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SCIENTIFIC PLAN FOR THE PROPOSED NANSEN DRIFT STATION,(U)
1976 N UNTERSTEINER, K AAGAARD, V ALEXANDER N00014-75-C-1162

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Scientific Plan for the Proposed Nansen Drift Station

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Committee for the Nansen Drift Station

Polar Research Board

Assembly of Mathematical and Physical Sciences

(6)

SCIENTIFIC PLAN FOR THE PROPOSED NANSEN DRIFT STATION,

(10) Norbert/Untersteiner, Knut/Aagaard,
Vera/Alexander, John/Anderson Donald/Barnett

Committee for the Nansen Drift Station

Polar Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

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NOTICE: The study that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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FOREWORD

This document, prepared by the Polar Research Board's Committee on the Nansen Drift Station, is a comprehensive multidisciplinary scientific research plan that can be carried out from an arctic research platform (i.e., the Nansen Drift Station).

The Committee for the Nansen Drift Station first met on August 11, 1975, and held a workshop and final meeting November 3-5, 1975. This document is based on the results of that workshop.

The Polar Research Board is deeply grateful to Norbert Untersteiner (Chairman) and members of the committee for their diligent efforts in putting this report together in the brief time alloted for the task.

James H. Zumberge, *Chairman*
Polar Research Board

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PREFACE

The desirability of repeating the historic journeys of the *Fram* (1893-1896) and *Sedov* (1937-1939) across the Eurasian Basin of the Arctic Ocean has been discussed in the scientific community on various occasions over the past 20 years. The scheduled decommissioning of the WIND-class icebreakers by the U.S. Coast Guard offers, for the first time, a definite opportunity to acquire a suitable platform to carry out a wide-ranging research program in a little known area of the Arctic.

In June 1975, the Polar Research Board (PRB) was invited to prepare a comprehensive plan for studies to be carried out from an icebreaker in the transpolar drift stream between the Laptev Sea and the Greenland Passage. To execute this task, the PRB established a Committee for the Nansen Drift Station Project, consisting of 14 members, each representing specific scientific disciplines and activities and including participants from Canada and Norway as well as representatives of several agencies of the United States Government. Ten major scientific areas were identified, and one member of the Committee was assigned the responsibility for drafting a scientific program for each of the subject areas that make up Chapters 6-15 of Part II. Drawing on the advice of a large number of experts outside the Committee, and on the results of an earlier workshop held during a meeting of the American Geophysical Union in December 1974 (see list of participants), the Committee prepared this report.

It should be noted that the scientific plan for the Nansen Drift Station Project describes a most comprehensive, balanced program, without regard to specific and actual funding prospects for commitments. Bearing in mind that mission-oriented agencies of the federal government, with a potential interest in the project, are not likely to have a uniform set of priorities, an attempt to identify priorities was made only within each discipline. Each chapter of the scientific program contains an estimate of costs and operational requirements, intended only for preliminary reference. If the basic funding for operational support can be secured (see Section III), specific proposals from the Community at large will be solicited according to funding agencies' procedures.

The report underwent extensive critical review by groups of the National Research Council: Assembly of Mathematical and Physical Sciences Executive Committee, Naval Studies Board, Ocean Science Board, Maritime Transportation Research Board, Committee on Solar Terrestrial Research, Committee on Seismology, U.S. National Committee for Geochemistry, U.S. National Committee for International Union for Quaternary Research, U.S. Committee for the Global Atmospheric Research Program, U.S. Geodynamics Committee, Marine Board, and the Committee on Atmospheric Sciences. The comments of the reviewers were especially appreciated.

The Nansen Drift Station Project offers a unique opportunity for international participation and cooperation, and the Station will be available to all nations interested in arctic research; all research data will be made public.

We wish to express our special appreciation to the Office of Naval Research, Arctic Programs, for providing financial support that made this document possible. The expert assistance in all phases of the work of the Committee provided by L. De Goes and W. Timothy Hushen of the Polar Research Board and other staff members of the National Research Council is most gratefully acknowledged.

Norbert Untersteiner, *Chairman*
Committee for the
Nansen Drift Station

CONTENTS

Page

I
INTRODUCTION

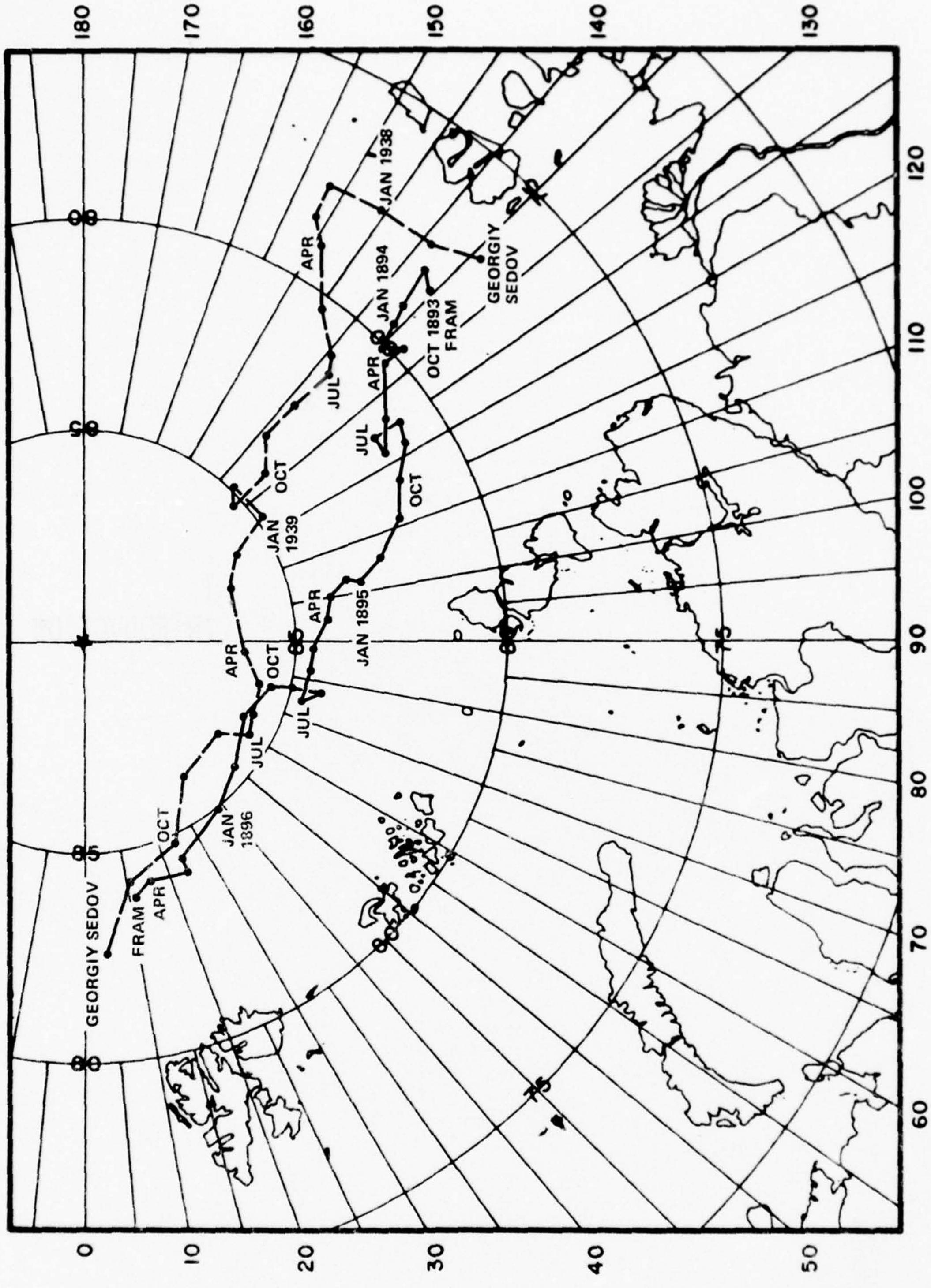

Figure 1.1. Drift of the *Fram* (1893-1896) and the *Georgiy Sedov* (1937-1939)

1.

FRIDTJOF NANSEN

In the summer of 1893, Fridtjof Nansen and his men set out from the Laptev Sea in their ship *Fram* to reach the north pole. For three years they drifted with the pack ice toward Spitsbergen (Figure 1.1). In early 1895, it had become clear that the ship would not reach the pole. Nansen and one companion tried to proceed by dog sled, but the ice drift was against them. After an arduous journey of more than 2000 km they reached Franz Josef Land and wintered there. Meanwhile, the *Fram* continued to drift while locked in the ice, coming free in 1896. In August 1896, both ship and sled party arrived safely back in Norway.

In the history of polar exploration, Nansen's journey remains an unparalleled feat of imagination, courage, scientific ingenuity, perseverance, and ultimate success.

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2.

BACKGROUND

while field stations on,

During the past three decades, drifting pack ice stations have been the operational mainstay of research in the Arctic Basin (see map inside back cover), culminating in the year-long four-station array of the Arctic Ice Dynamics Joint Experiment. While field stations of that kind will remain useful for special purposes, recent scientific and technological developments have fostered the idea to use or, ~~as it happens,~~ reuse with modern means, the icebreaker supported by aircraft as a research platform.

The project, entitled the "Nansen Drift Station" (NDS), ~~that we~~ is describe in this report and for which we propose a scientific plan is recommended for the following reasons:

The scientific program is planned to include:

(con't on p XV)

1. Extensive research programs have been conducted in the Canadian Basin and our knowledge of the Arctic has become strongly oriented toward that region. At the same time, the urgency to learn more about the Eurasian Basin has increased in connection with progress in global tectonics, climatology, resource geology, sea-air interaction, and other disciplines.

2. The Eurasian Basin with its vigorous ice dynamics is a region less suited for pack ice stations than, for example, the Beaufort Sea. The need to move into a new region with a multidisciplinary research program and a more secure research platform fortuitously coincides with the acquisition by the United States Coast Guard of two new icebreakers and the scheduled decommissioning of older ships that can be adapted for use as drifting platforms for science.

3. If realized, the NDS will overlap in time with at least two major international research programs: the International Magnetospheric Study, the Global Atmospheric Research Program (GARP), with the Polar Experiment (POLEX) as a subprogram, the International Geodynamics Program (IGP), and others. Great mutual benefit can be derived from coordinated planning and data acquisition among these programs (as explained in the respective chapters of Part II).

4. The NDS project is considered an ideal vehicle to engender and enhance international cooperation for the common good.

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3.

SCIENCE SUMMARY

In the opinion of the Committee for the Nansen Drift Station, an icebreaker and its corollary installations (temporary field camps, data buoys) afford such a wide range of research opportunities that it would be inappropriate to assign priorities to scientific disciplines. Giving primary emphasis to geophysics, geology, and ocean physics might be justified. However, the unifying concept of the NDS is that of a multipurpose operating platform, and individual research projects should be selected according to scientific excellence and policies of the prospective funding agencies, both in the United States and abroad.

Within each discipline it is, of course, possible to assign priorities. The sequence of specific studies described in Part II is meant to reflect, in general terms, an order of priority.

Marine geophysics and tectonics (Chapter 6)

Perhaps the greatest contributions that the NDS project can make to earth science are in the areas of tectonics and sedimentology. Two major deep-sea basins and three submarine ridges are the main tectonic features of the Arctic. Closest to Eurasia, the Nansen Ridge is a direct continuation of the globe-encircling active midocean ridge system. The spreading rate is of the order of 1 cm/year. The Nansen Ridge and Eurasian Basin are an ideal laboratory for studying the implications of different geodynamic models and the morphology and crustal structures produced at various accretion rates. By drifting across the region with a secure research platform, it will be possible to perform observations of bottom morphology, gravity, magnetics, seismic reflection and refraction, and heat flow, with unparalleled efficiency.

Marine geology and paleoclimatology (Chapter 7)

In addition to studies of the geologic structure and history of the Arctic Basin, extensive sampling of ocean sediments will provide new and crucial information on the climatic history of the Arctic. Theories of climatic change need to be tested against the climatic record preserved in the sediments (floral and faunal assemblages, stable oxygen isotope ratio, radioisotope concentrations, volcanic and other particle contents). Efforts by the Consortium of Scientists Studying Paleo-Climatology (CLIMAP) to establish this record in the North Atlantic have been highly successful. An extension of this kind of work in the Arctic Basin is most desirable.

Physical oceanography (Chapter 8)

Compared with the relatively stagnant waters of the Canadian Basin, those of the Eurasian Basin are in vigorous exchange with the Norwegian and Greenland Seas. In addition, roughly a third of the immense land mass of Asia discharges its runoff northward onto the wide continental shelf. The physical oceanography of the Eurasian Basin, once the inspiration for the fundamental work of Nansen and Ekman, is today less developed than that of any other ocean basin. The NDS program proposes to map the properties of arctic water masses, observe the water velocity fields, and investigate the modification of water masses that result from large-scale advection, sea-air-ice interaction, and freshwater influx from land. A better understanding of these phenomena will help to define the role of the Arctic Ocean in global climate, and it will provide the physical background information for studies of the marine ecosystem, bioacoustics, pollution baselines, and others.

Biology and biochemistry (Chapter 9)

Among the ecosystems of the world oceans, that of the Arctic Ocean occupies a special place: it is the least contaminated and the least productive and probably the least diverse.

The increased understanding of biological population, communities, feeding relationships, nutrient transport, the role of light, ice, and other environmental factors will broaden the knowledge base for comparative studies of ice and ecosystems. In addition, biological information is needed for the interpretation of certain acoustical phenomena and to relate present and past types of plankton populations in the paleoclimatic interpretation of deep ocean sediments.

Marine acoustics (Chapter 10)

The two features peculiar to the acoustic environment of the Arctic Ocean are the near-surface sound channel and the ambient noise generated by the sea ice. Virtually all available acoustic measurements over the past 20 years have been confined to the Canadian Basin. The NDS, with its surrounding array of data buoys, will enable us to extend these studies to the Eurasian Basin, where the warm core of Atlantic water lies close to the surface and where more vigorous ice dynamics may be expected to produce a different ambient noise regime. Better observations of propagation losses, backscattering, bottom reverberation, plankton scattering, sounds from marine mammals, and many other features of the acoustic environment, along with improved models and prediction methods, will provide both scientific insight and safer ship operations.

Heat and mass balance of the ice cover (Chapter 11)

In many theories and hypotheses concerning the evolution of climate, variations of sea ice play a critical role. Dramatic fluctuations of heat exchange between ocean and atmosphere occur associated with diverging sea-ice motion. These effects are especially great on the Eurasian side of the Arctic Ocean, where the sea ice moves rapidly and has a residence time of only a few years. The NDS will provide new and hitherto unavailable information on ice thickness distribution and regional heat balance. Along with data from the upper ocean and the lower atmosphere, this information will help us to understand mechanisms and magnitude of the polar heat sink and its effect on large-scale circulation systems.

Troposphere (Chapter 12)

An understanding of the transfer processes within the arctic troposphere is essential for development of reliable models of the general circulation and climate. The NDS provides a rare opportunity to investigate vertical transfers in regions of the Arctic that have been barely investigated. Topics to be addressed are the relation between vertical transfers of heat, momentum, and mass; the structure of the planetary boundary layer; and the characteristics of stratus clouds and haze and their effect on the radiation balance. The flat, uniform surface of the Arctic Basin, exposed to prolonged radiational cooling during the polar night, is the most suitable place in the world to investigate the stably stratified planetary boundary layer. During summer, stratus clouds, fog, and haze are persistent over the Arctic Basin. Observations during the NDS drift will elucidate poorly understood mechanisms governing the origin of these aerosols and their effect on radiative heat exchange.

Ice physics and engineering (Chapter 13)

The NDS program in ice mechanics is designed to test some of the recently developed ideas and models by means of a multipurpose network of data buoys and transponders (see Chapter 13, Figure 13.1). Appropriate instrumentation of the ship itself will make it possible to relate the stress in the surrounding pack to that extended on a rigid structure embedded in the ice. Since the ship will be traveling along with ice of different thickness and age, a study of its mechanical properties and their variation in the course of two annual cycles should be especially useful. The laboratory-like environment afforded by the ship will also make possible a number of carefully controlled experiments (e.g., *in situ* stress tests and remote sensing ground-truth observations) designed to improve our understanding of physical processes affecting properties of the ice cover.

Atmosphere-ionosphere-magnetosphere (Chapter 14)

The drift path of NDS between 70° and 80° geomagnetic latitude will provide a rare opportunity to observe some of the complicated phenomena of atmosphere-ionosphere-magnetosphere (AIM) interactions. High-energy protons and electrons from the sun distort the geomagnetic field, affect transpolar very low frequency and high frequency communications, control plasma motions in the magnetosphere, and influence the chemical balance of ozone and nitric oxide in the stratosphere. The AIM studies described in this report are closely related and complementary to the worldwide International Magnetospheric Study. Additional benefits could be derived from the fact that the "conjugate path" of NDS in Antarctica touches the Australian station Casey and the Soviet station Mirny.

Remote sensing (Chapter 15)

Technological advances in the field of automatic data and remote sensing devices during the past decade have greatly improved the efficiency of data collection. In addition, the new tools of remote sensing are providing entirely new kinds of data that have in the past been unobtainable in the polar regions: large-scale high-resolution views of sea ice fields and cloud systems, precise laser altimeter profiles of the ice surface, images of the passive microwave emission from different types of ice and water surfaces, to name only a few. The remote sensing program for the NDS is specifically designed to augment other projects by providing data on ice thickness distribution, roughness, and strain and to aid in the further development of remote sensing techniques by acquiring ground truth data. Special consideration has been given to making optimal use of specially processed data from operational meteorological satellites in polar orbit as well as from LANDSAT and the forthcoming SEASAT.

4.

OPERATIONAL SUMMARY AND PLANNING

The ship intended for use as the Nansen Drift Station is a WIND-class icebreaker constructed during World War II. The normal ship's operating crew of 200 will be reduced to less than 50. The number of persons on board, including scientists and technicians, should not exceed 110.

Aircraft support should consist of two Bell 205A-1 helicopters, both permanently stationed on the ship during the spring and autumn. A DeHavilland Twin Otter (turboprop) aircraft will be used for short- and medium-range flights (buoy deployment, temporary camps, surveys). Personnel rotation via Alert (Ellesmere Island) or Longyear Byen (Svalbard) will be accomplished by C-117 (Super DC-3) or, if possible, C-130 (Hercules). The use of other types of aircraft will be considered as operational requirements are specified.

The fuel capacity of a WIND-class icebreaker is large enough for approximately one year's operation, provided that the propulsion plant is not used. In view of the high cost of fuel resupply by air, a study is now under way to examine other possibilities of increasing the station's fuel storage capacity. A limited resupply by air or by another icebreaker *(Polar Star)* should be considered. Depending on the scientific programs to be supported, certain modifications to the ship will be necessary.

The following table lists a number of decision points, proceeding backward in time from the start of the ship's passive drift to the commitment of funds for the project. If this time scale could be expanded, the quality of all preparations could be enhanced. It should be noted that, under normal ice conditions, the month of September is the only time at which the ship can be deployed in the desired location.

		TIME
Ship commences passive drift	October	YEAR 2
Laptev Sea research cruise	August-September	
Arrival Laptev Sea	Late August	
Departure United States west coast	Late July	
Repairs and adjustments	Early June	
Shakedown cruise	June	
Installation of science equipment	May	
Ship modification completed	April	
Procure field-support equipment	December	YEAR 1
Negotiate air-support contracts	December	
Begin shipyard work	November	
Complete operations plans	November	
Issue RFP for air support	October	
Initiate procurement of science gear	October	
Issue RFP for ship modification	August	
Submit ship engineering change orders	August	
Decide funding of science proposals) Complete plan for ship modifications) Adjust operations plan to science program)	Summer	

A projection of the drift path of NDS, based on climatological averages and previous drifts, is shown in Appendix A.

5.
BUDGET SUMMARY

The following cost estimates are preliminary and approximate. The budgets given in Chapters 6-15 have been adjusted, assuming that no field project will last longer than two years. In all cases, the cost of data processing has been included.

The cost ratio of science versus operations in the core program of AIDJEX, integrated over five years, has been approximately 1:1. It seems noteworthy that the cost projections for NDS arrive at nearly the same ratio. It should be noted further that the cost of adapting the NDS platform cannot be reduced by more than 25 percent, even if it would support no scientific program at all. Therefore, the cost-effectiveness of NDS increases dramatically with the size of the science program. An upper boundary for the science program is set by the limits of ship space and air logistics. It is our recommendation that the total expenditure for science should approximately match that for operations.

Science	$ Thousands
Marine geophysics and tectonics	1270
Marine geology and paleoclimatology	950
Physical oceanography	2227
Biology and biochemistry	1163
Marine acoustics	2335
Heat and mass balance of the ice cover	350
Troposphere	1500
Ice physics and engineering	1610
Atmosphere-ionosphere-magnetosphere	1750
Remote sensing	1210
TOTAL	14,365

Logistics and Operations	$ Thousands
Ship conversion and operations	11,900
Aircraft operations	4,472
Personnel rotation	700
Support equipment	600
TOTAL	17,672

II
SCIENTIFIC PROGRAM

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6
MARINE GEOPHYSICS AND TECTONICS

1. BACKGROUND

1.1 Introduction

Since the earliest attempts to describe the tectonic evolution of the earth, the geological structure and the origin of the Arctic Ocean basin have been regarded as both a puzzle and a key to the satisfactory interpretation of ocean basin-continent relationships. The position of the Arctic Ocean between the major land masses of the northern hemisphere, its obvious but constricted connection with the Atlantic Ocean basin, and its position tangential to the ring of persistent orogeny and modern crustal activity surrounding the Pacific Basin, have given it a uniquely central position in attempts to explain the pattern and development of the major structures of the earth (Suess, 1904). Despite (and possibly in part because of) the lack of factual information about the characteristics of the Arctic Ocean basin, a large number of hypotheses sprang up about its origin. Most of these were put forth in an attempt to explain features of geology of the surrounding continents (Eardley, 1961); from the point of view of most researchers seeking to explain the origin of the ocean basins themselves, the Arctic Ocean was until recently ignored.

Modern considerations of the origin and structure of the Arctic Ocean basin date from the evidence that typical "oceanic" crust underlies at least part of the basin (Sykes, 1965) and from the discovery by Soviet researchers (Sachs *et al.*, 1955) (confirmed and extended by later American studies) that the geographical region of the Arctic Ocean was for more than half its areal extent underlain by continental shelves, which surround a well-defined "basin" of typical ocean abyssal depths crossed by three prominent ridges. The nature and origin of these ridges, and of the distinct basins separated by them, make the Arctic Ocean one of particular geophysical interest.

The Alpha Cordillera is the ridge farthest from the Atlantic Ocean. It is nearly inactive seismically at present but has irregular, subparallel magnetic anomalies and rough topography, and many researchers have considered it to be a former locus of sea-floor spreading (Vogt and Ostenso, 1970; Dawes, 1973). Other hypotheses view the Alpha Cordillera as a former subduction zone or as subsided continental crust (Herron *et al.*, 1974).

About 500 km distant from the Alpha Cordillera and like it extending across from the Eurasian to the North American continental masses is the Lomonosov Ridge, the most prominent topographical feature in the Arctic Ocean basin. This ridge is a sinuous single feature rising 3000 m above the surrounding plain with a smooth profile. It has no recorded earthquake activity and appears to be devoid of small-scale magnetic irregularities. Seismic refraction investigations suggest a three-layer structure (Gramberg *et al.*, 1974). The Lomonosov Ridge appears to be composed of continental material and may be a sliver split from the Eurasian shelf edge by the development of the Nansen Ridge and Eurasian Basin (Roots, 1969).

The Nansen Ridge is a direct continuation of the globe-encircling midocean ridge system. It is still active, with earthquakes occurring along a well-defined rift and is the site of present crustal activity in the Arctic Ocean basin. It is remarkably linear, for 2000 km from the Greenland Sea to the Laptev shelf, of uniform width, with a crest about 500 m deeper than the typical mid-Atlantic ridge and axial rifts whose bottoms are in places more than 1000 m below the flat sediment-covered floors of the adjacent abyssal plains. Magnetic anomalies approach 1500 gammas and in places are apparently too low to be detected but show the linear patterns typical of active spreading ridges (Demenitskaya and Karasik, 1966, 1969).

The Eurasian Basin, bisected by the Nansen Ridge, is the part of the Arctic Ocean about which there is least information. Reconnaissance bathymetric, gravity, and aeromagnetic data show a basin of relatively simple form, smooth-floored, bounded on the southern and eastern sides by a well-developed continental rise leading to a relatively steep, complex slope to the edge of the Laptev, Kara, and Barents continental shelves (Michajlov, 1969) but on its northern side abutting the Lomonosov Ridge without conspicuous "rise." Aeromagnetic data show apparently relatively widespread linear anomalies of low amplitude offset by a few apparent fracture zones (Karasik, 1974). Recent aeromagnetic surveys over the "Atlantic" portion of the basin should throw valuable light on its character.

1.2 Significant Problems

The Nansen Ridge and Eurasian Basin have a number of unique aspects that are of great potential significance to the understanding of global dynamics and the processes of ocean basin formation and continental tectonics. The Ridge is one of the few crustal plate boundaries that approaches its own locus of rotational opening, from an apparent pivot between two continental cratonic blocks whose relative movements over geological time have been well recorded in the continental geology (Gramberg and Kulakov, 1975). The basin apparently began to open about 60 million years ago (Vogt *et al.*, 1970; Pitman and Talwani, 1972). The consequent low spreading half-rates (0.5-0.8 cm/yr) and the likely significant change of rate with increasing distance from the locus make the Eurasian Basin-Nansen Ridge an ideal laboratory for studying the implications of different geodynamic models and the morphology and crustal structure produced at various accretion rates. At the same time, the existence of the Alpha Cordillera as either an apparent former axis of spreading between the same continental masses (National Academy of Sciences, 1970; Dawes, 1973), upon which motion appears to have stopped about 40 million years ago (Vogt and Ostenso, 1970), or as a fossil subduction zone inactive for 80 million years (Herron *et al.*, 1974) and the evidence of a still earlier spreading axis along the side of the present Arctic Ocean (Yorath and Norris, 1975) provide comparative examples of various stages of the dynamic process.

The very slow rate of sedimentation in the Eurasian Basin should make it possible to observe the physiographic expression of different parts of the ridge system and to make measurements of heat flow and magnetic characteristics uncomplicated by the insulation of a thick sedimentary blanket. The slow sedimentation may have contributed to the preservation of deep rifts available for direct study.

Some of the most important tectonic and geodynamic problems for which there is a unique opportunity for study in the Eurasian Basin-Nansen Ridge area include the following:

1.2.1. What are the manifestations of crustal strain and density redistribution near the termination point of an actively spreading ridge where it abuts a continental block?

1.2.2. What is the pattern of fracturing by which an accreting sea floor adjusts to rotational opening at very low spreading rates?

1.2.3. How does the crust-mantle boundary adjust to the continent-ocean floor boundary at the end of a slowly spreading ridge?

1.2.4. What is the fine structure of a very slowly spreading ridge in terms of intrusion sequence and spacing, pattern and magnitude of geothermal heat release, magnetic characteristics, and morphological development under conditions of very slow sedimentation?

1.2.5. What are the longitudinal changes along the axis of the ridge with distance from the locus as a function of increased rate of spreading and/or increased time of spreading?

1.2.6. What are the characteristics, both crustal and sedimentological, of the junction of the ocean's crust with the main mass of the continent (e.g., the Eurasian block at the edge of the Kara and Barents continental shelves) as compared with its junction with an isolated and splayed submerged fragment of continental crust (the Lomonosov Ridge)?

1.2.7. What is the internal structure and nature of the "basement" of the Lomonosov Ridge, and how does it terminate against or near the North American continent?

1.2.8. What is the sequence and magnitude of motion on the fracture systems bounding the Svalbard block, the Yermak Plateau, and the northeastern part of Greenland, and what is their relation to the fault systems of the midocean ridge system as it passes through the junction between the Greenland Sea and the Arctic Ocean?

1.2.9. What was the configuration of the continental masses around the north Atlantic Ocean area prior to the development of the Alpha Ridge and prior to the opening of the Eurasian Basin; and what were the characteristics of the sedimentary basin in which the rocks now underlying the arctic continental shelves were formed?

1.2.10. What are the relationships between the geosynclinal belts and fold systems of northeastern North America and those of Svalbard, Franz Josef Land, and Novaya Zemlya? For example, the fossils of East Greenland Mesozoic rocks are related both to Europe and the rest of North America, except during the Cenomanian stage, when there appeared to be direct affinities to Europe but not to fossils in strata of the same age in nearby Canada, (Johnson *et al.*, 1975); however, Innuitian and Greenland orogenic belts appear to have counterparts (or continuation?) in Svalbard and Novaya Zemlya (Harland, 1975).

1.3 Critical Information Needed

Given the unique and almost ideal situation presented by the Arctic Ocean for study of ocean-basin tectonics and the lack of detailed geophysical and geological information, data are needed not so much to fill gaps but to enable a start to be made at obtaining an understanding of the relationships and processes at critical localities that bear on the above problems. The information most urgently needed from the Eurasian Basin-Nansen Ridge area includes the following:

1.3.1. A comparison of the geophysical fabric from (a) near the junction with the Eurasian continental shelf; (b) across the central part of the basin; and (c) near the Svalbard-Greenland "entrance." Magnetic patterns, gravity surveys, and measurements of plumbline deflection are most important to allow determination of relative spreading rates, tectonic stability, and density distribution. Heat-flow data and structural information from reflection and refraction seismic studies are highly desirable and essential in at least two or three places.

1.3.2. Information on the structure and composition of the Lomonosov Ridge and its relationship to adjacent structural units. Most important data from this region are density distribution and patterns (plumbline deflection and gravity, seismic refraction, if feasible), heat flow, and magnetic character.

1.3.3. Crustal thickness and geological structure under the abyssal plains, the Lomonosov Ridge, and the edges of the continental masses enclosing the basin. This will require reversed refraction measurements.

1.3.4. Detailed information across and along the Nansen Cordillera: precision bathymetry; measurements of gravity, magnetism, heat flow, and seismic reflection; sediment and out-crop sampling; and bottom photography (see Chapter 7).

1.3.5. Detailed bathymetric, magnetic, gravity measurements, and, if possible, heat flow and microseismicity information from the complex of midocean ridge segments and fracture zones between Svalbard and the Yermak Rise on the east and Greenland and the North American end of Lomonosov Ridge on the west.

2. PURPOSE

2.1 Characteristics of the Ship-Ice Station Combination

Given the variety and major importance of the structural problems to be solved in the Eurasian Basin area, and the need for additional data from nearly all parts, the research program of the Nansen Drift Station must be selective so that the best information can be obtained from the limited scientific and logistics resources and time that will be available on a single passage by a single ship. Only those programs should be considered that (a) must be carried out in that part of the Arctic or (b) are not place-specific but can be done much better from a ship in ice (supplemented by surface traverses and ice camps) than from a ship in open water.

The proposed program takes advantage of the following factors:

(a) If the drift track goes according to the most likely predicted route, it will traverse the full length of the Eurasian Basin, crossing the median Nansen Ridge at least twice.

(b) The very slow drift rates characteristic of most pack ice movements (expected to average 3 to 6 km per day most of the time but as low as 1/2 km per day at times), with periodic but uncontrolled sharp changes in direction, make possible observations in close detail, not easily accomplished in the open ice-free ocean.

(c) The relatively stable and complete ice cover for large parts of the year makes possible a variety of repeated and multiple measurements, simultaneous measurements from a number of stations that can be a known and relatively constant distance apart (for periods of days), and measurements from a stable and acoustically and electrically quiet base difficult to duplicate on the ice-free ocean.

(d) At the "Atlantic" end of the drift, the station will be in a good position to carry out experiments in cooperation with shore stations or near-shore parties on both sides of the basin.

(e) The self-contained characteristics of a modern vessel equipped as a research station eliminate much of the housekeeping inefficiency, cost, and hazard of aircraft-dependent camps on the floating ice and make possible more effective immediately available computer facilities, laboratories, etc.; while the stable ice platform for most of the year, with opportunity for over-ice and helicopter travel, temporary camps, depots, and surface-mounted structures, makes possible the deployment of extensive measurement arrays, locally isolated measurement stations, simultaneous separate measurements, etc., in a manner not feasible aboard ship. It is thus possible to capitalize on the advantages of both ice stations and shipboard techniques.

The program must, however, make allowance for the fact that both the directions and rate of drift cannot be controlled, and that on the basis of the known tracks of past drifts there is a possibility that the ship would be carried far to either side of the basin or be held in the ice an extra year or more before reaching the Greenland Sea. The program must therefore not be dependent on reaching any specific part of the basin but must be able to turn unexpected deviation of the track to good scientific advantage.

2.2. Specific Program Objectives and Locations

In order to obtain as much information as possible on the major problems described in Section 1.2 above, with a geophysical specialist complement of six to eight persons (including coopted geologists and oceanographers), the proposed studies in geophysics and tectonics have been divided into a number of separate programs related to the areas of critical information outlined in Section 1.3. Each program comprises work in several disciplines. The proposed geographic positions of these programs are sketched on Figure 6.1. For reference, the programs are numbered GP-1 numbered GP-1 to GP-7.

2.2.1. Program GP-1

To obtain as complete a cross section as possible of the physiography, density distribution, magnetic characteristics, geothermal heat flow, and, if possible, seismic velocities of sedimentary formations and structural elements across the margin of the Eurasian continent at its junction with the Nansen Ridge and Eurasian Basin.

2.2.2. Program GP-2

To obtain systematic and regular physiographic, density distribution, magnetic, electric field, heat-flow, earthquake, and seismic velocity structural information on an accurately located but irregular longitudinal section of the Eurasian Basin and its median ridge system by continuous or close-spaced measurements along the ship's drift track.

2.2.3. Program GP-3

To determine the geophysical characteristics and structural fabric of the Eurasian Basin and Nansen Ridge along a transverse swath at about Long. 90° E. This, together with aeromagnetic survey results

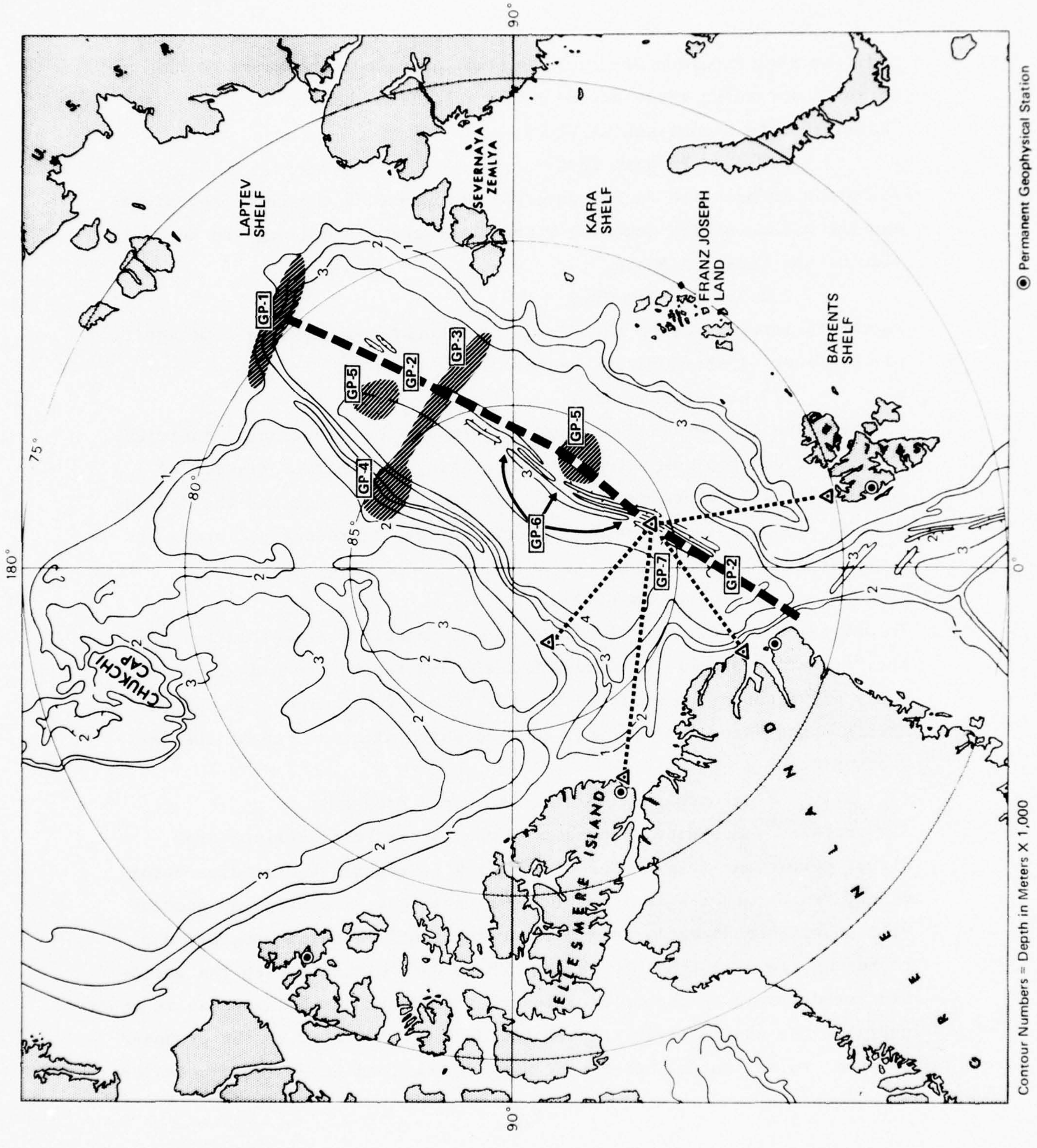

Figure 6.1. Location of Proposed Geophysical Program GP-1 to GP-7

and data from Programs GP-1 and GP-2 may provide information on the relative spreading rates of the Basin and the mechanism of its "advance" into a continental block.

2.2.4. Program GP-4

To obtain information on the internal structure of the Lomonosov Ridge and the nature of its junction with the Hakkel Plain along the northern side of the Eurasian Basin.

2.2.5. Program GP-5

To obtain information on the crustal thickness and physical homogeneity of the floor of the Eurasian Basin.

2.2.6. Program GP-6

To determine the detailed morphology, density distribution, seismicity, heat flow, outcrop composition, age, origin, and characteristics of sedimentary fill where present, across the Nansen Ridge and the median rift by close-space traverses and grid surveys of restricted areas at a number of locations along the ridge.

2.2.7. Program GP-7

To determine the structural relations and crustal characteristics of the "Atlantic" end of the Eurasian Basin and the Nansen Ridge, specifically with respect to Svalbard and the Yermak Rise, Greenland and the Morris Jessup Rise, Nares Rift, and the North American end of the Lomonosov Ridge.

2.3. Relationships with Other Research Programs

The proposed geophysical programs of the Nansen Drift Station are directly relevant to a number of on going researches and studies being undertaken by other agencies. In some instances, the proposed studies will contribute directly to major international research programs and represent the only feasible way to obtain data without which the world-wide study would be incomplete. Furthermore, studies by agencies in other parts of the Arctic or in related fields can be related to the proposed program, to the mutual benefit of both if they can be so coordinated or made compatible.

Examples of major international programs to which the geophysics and tectonics studies of the Nansen Drift Station are directly related include the following.

2.3.1. International Geodynamics Program (IGP)

This program, to which more than a dozen nations are contributing under the auspices of the Inter-Union Commission for Geodynamics of the International Council of Scientific Unions, is aimed at solving major questions of tectonic processes and structural evolution of the earth. Both the United States and Canadian National Committees on Geodynamics have drawn attention to the critical importance of the Arctic Ocean area and in their reports have recommended that acquisition of data from the Arctic Basin be given high priority. All programs, GP-1 to GP-7, will contribute directly to the IGP.

2.3.2. International Magnetospheric Study (IMS)

The IMS is an international cooperative enterprise, coordinated by the International Union of Geodesy and Geophysics and the International Union of Radio Science (URSI) to make coordinated observations of the geomagnetic field in order to understand its dynamic behavior. The observational phase of the program, to be undertaken in 1976 to 1978, will include special magnetic stations in Greenland and a detailed program in northern Canada. Geophysical Programs GP-1, GP-2, GP-3, and GP-6 of the Nansen Drift Station will contribute to the IMS by providing surface-based background information on the variations in magnetic field and electrical and magnetic characteristics of the crustal and mantle rocks under the Arctic Basin.

2.3.3. World Seismic Network

Programs GP-2, GP-5, and GP-7 will be of direct assistance to the analysis of earthquakes undertaken by the worldwide network of earthquake observatories, coordinated by the International Association of Seismology and Physics of the Earth's Interior (IASPEI). Program GP-2 (and GP-6, if lucky) will provide nearby detection and measurement of seismic shocks from an active fracture that so far has only been studied from a distance; and Programs GP-5 and GP-7 should enable the Arctic Basin to be calibrated seismically, thus enhancing the accuracy of teleseismic observations made outside the basin (see Section 3.1.6).

2.3.4. International Geological Correlation Program (IGCP)

A satisfactory reconstruction of the age and history of development of the Eurasian Basin (see Sections 1.2.9 and 1.2.10) will be of direct aid to the solution of some major problems identified by the International Geological Correlation Program of the International Union of Geological Sciences, with regard to the correlation and nomenclature of rock units and geological events between northern North America and Eurasia. Because of the potential for economic resources in the rocks of the northern parts of the continent in each area, improved correlation and understanding of the sequence of events is of high practical interest. All geophysical programs, but in particular GP-1, GP-2, GP-3, GP-6, GP-7, and the aeromagnetic surveys will contribute to the IGCP.

2.3.5. Tectonic Map of the World

The compilation of a Tectonic Map of the World is a continuing activity of the Commission for the Geological Map of the World (CGMW) of the International Union of Geological Sciences. Its purpose is to produce periodically the best available interpretation of the tectonic record of the planet. To date, information from the Eurasian Basin has been meager and the interpretation speculative; and yet, for reasons given above, the region is of critical importance. All geophysical programs will contribute to this project, and it can be expected that among the most visible results of the Nansen Drift Station will be a revision of the arctic sheet of the Tectonic Map of the World and the associated Geological Atlas of the World.

2.3.6. General Bathymetric Chart of the Oceans (GEBCO)

The geophysical programs of the Nansen Drift Station will contribute, along with the marine geology program, to the General Bathymetric Chart of the Oceans, a continuing activity of the International

Hydrographic Bureau and the Scientific Committee on Oceanic Research. Geophysical and geological information are essential to the correct interpretation of the morphology of the floor of the Arctic Ocean. In the absence of such information, charts based on reconnaissance bathymetric data alone have to date been highly speculative. Programs GP-1, GP-2, GP-3, GP-4, and GP-6 will be directly relevant.

In addition to the multinational programs coordinated and endorsed by international scientific unions or associations, there are research programs carried out by other agencies that would be aided by the Nansen Drift Station or with which collaboration would be of mutual benefit. Examples of these studies are described in Section 3.6.

3. OBSERVATIONAL PROGRAMS

In the following section the specific observations comprising the elements of Programs GP-1 to GP-7 (see Section 2 above) are described in greater detail.

3.1. Specific Observations

3.1.1. Bottom Morphology and Shallow Subbottom Structures--Needed for Programs GP-1, GP-2, GP-3, GP-4, GP-5, and GP-6, as well as for Marine geology, Oceanography, and Biology

Information on the undersea topography, while not a geophysical observation, is the most important single parameter for geophysical as well as other studies. Continuous information is required along the drift track; spot depths are needed at all gravity, magnetic, and heat-flow stations and at suitable intervals (to give slope control) along lines of seismic experiments. The precision depth recorders should have the narrowest practical beam and sensitivity corresponding to 10-m depth accuracy or better, for slope and scarp discrimination. A hull-mounted 3.5-kHz system is desired, as it will serve as a shallow seismic reflection system and provide information on the structure and morphology within or beneath the sediments to shallow depths below the sea floor.

The best bathymetric equipment would be a multibeam Harris array or equivalent, to chart a broad continuous swath beneath the ship. Such a system would give information many times more valuable than that obtained from a single fathometer profile and would greatly enhance the scientific value of the drift. If a multibeam array is not possible, the use of paired, dangled side-scan sonar sets to be operated close to the bottom in the vicinity of the median ridge, supported from ice stations about 1 km apart, should be carefully considered in conjunction with the marine geology program. Low-angle sonar imagery of parts of the ridge would give additional information on its character. Such equipment will also contribute to the backscatter experiments of the marine acoustics program.

Underwater television equipment, suitable for operation near the bottom at abyssal depths, would be a valuable supplement to the geological and geophysical tools, as well as to biological studies.

3.1.2. Gravity--Programs GP-1, GP-2, GP-3, GP-4, and GP-6 Gravity observations should be taken continuously from the ship during Program GP-1, if it can be done by ship, and during the whole course of the drift on Program GP-2. Particular attention must be paid to those areas where, from aeromagnetic surveys, the character of the magnetic signature changes noticeably. On Programs GP-3, GP-1 if it is done on the ice, and GP-5, gravity readings should be taken at intervals not greater than 3 km on two parallel lines about 5 km apart. Given the limited time and logistics support available, it will be better to have two parallel lines with somewhat more widely spaced readings, to establish directional trends of anomalies, than one line with more closely spaced readings.

In Program GP-4, in areas of significant gravity gradient, a grid survey with station spacing of 3 km should be attempted. The minimum data aimed at should be a surveyed strip 20 km wide across the lower ridge slope and the junction with the Hakkel Plain and across the crest of the ridge; about 300 spot readings on this program appears feasible, in locations guided by aeromagnetic pattern, bathymetry, and observed gravity gradient.

In Program GP-6, spot gravity readings should be taken in as much detail as possible and, as the data obtained appear to warrant, to supplement those obtained from the ship along the drift track. This may require readings every 100 m or so in places. Such work will best be done in winter, using light over-ice surface vehicles to supplement the helicopter. The ideal circumstance will be if the ship is drifting over the Nansen Cordillera each winter.

3.1.3. Plumbline Deflection--Programs GP-2, GP-4, GP-5, and GP-6

A study related to the gravity investigations and capable of providing information of value for interpreting geological and crustal structures is the continuous recording of the deflection of the plumbline as the station drifts across the ocean bed. The deflection is determined by comparing the difference between astronomically determined and satellite-determined geographical position of the moving station, coupled to a fixed bottom referencing system. An experiment of this type has been carried out near the Lomonosov Ridge at the North Pole, using conventional astronomic observing techniques (Lillestrand and Weber, 1974), where it was found that observations of ±1 second of arc were feasible and gave results of significance for geophysical interpretation. The method provides a powerful tool for aiding the interpretation of gravity anomalies and for providing information on the shape of the geoid (see Section 3.1.9).

The drifting station will be routinely providing NAVSAT position and acoustic bottom referencing. Thus a plumbline deflection study can be accomplished by obtaining regular and accurate astronomic fixes. These are best done by an automatic astronomic positioning system (AAPS), prototype models of which can determine stellar positions to +0.75 second of arc over a 2-hour period while the sun is 10 degrees below the horizon. Thus, the AAPS is ideally suited to winter arctic operations and would make skilled precise conventional stellar observations unnecessary during much of the drift.

3.1.4. Surface Magnetic and Electric Field Observations--Programs GP-1, GP-2, GP-3, GP-4, and GP-6

Measurement of the magnetic field in three components should be an integral part of all field studies and traverses on the above programs. Magnetic measurements should be taken at each station where gravity and bathymetric data are obtained. This will provide referencing and detail to the aeromagnetic surveys and aid greatly in the correlation of regional aeromagnetic patterns with interpretations of gravity, physiographic, seismic, and heat-flow data.

Use of a portable gradiometer will eliminate problems of undetermined diurnal variations when working away from the ship. Sediment cores will be needed from representative locations to provide near-surface magnetic stratigraphy. These can be provided by the marine geology program.

The ship will be expected to tow--dangle may be a better word--a standard seagoing magnetometer during the entire drift (Program GP-2). Consideration should be given to the degree to which the ship can be equipped as a magnetic observatory, in view of its construction and the power demands of other experiments. At the very least, variometers and gradiometers must be available to establish on the ice, at a suitable distance from the ship, a "base station" to obtain magnetic data compatible with that routinely recorded at Alert and Ny Alesund, during the traverses of Programs GP-1 and GP-3 and the detailed aeromagnetic flights (see Section 3.6.2.1).

The Nansen Drift Station provides a first and excellent opportunity to measure electric and magnetic fields in the lowermost atmosphere and in sea ice and to observe the secular changes attending ionosphere dynamics and fluctuations in atmospheric ion loads (e.g., concentrations of SO_x). The Arctic Ocean environment provides an extensive area of uniform earth surface with minimum electric-field disturbances and maximum exposure to magnetic storm phenomena. Two additional questions could be attacked:

(a) Electric field relationships of migrating solute ions in the water films within sea ice;

(b) Contributions to electrification of the atmosphere by particles injected into the atmosphere by bubbles in the sea (see Blanchard, 1963).

To aid in meeting these objectives, and objectives in marine biology and biochemistry (see Chapter 9, Section 1.8) relating to electric and magnetic fields, we recommend electric fields and VLF wave detector measurements as follows:

(a) Atmospheric electric field (vertical) from 0 to 1 Hz.

(b) Three-component vector magnetic field using standard magnetometer.

(c) Three-component magnetic pulsation detector up to ∿50 Hz.

(d) Broadband VLF radio receiver from 100 Hz to 100 kHz.

Additionally, attention should be given to methods and instrumentation for measuring electric potential generated by the freezing process in sea ice.

3.1.5. Heat Flow--Programs GP-1, GP-2, GP-3, GP-4, and GP-6

The Nansen Drift Station project provides a unique opportunity to obtain close-spaced heat-flow information along an active spreading axis and at critical locations in a young but well-developed ocean basin.

If Program GP-1 can be done by ship, a heat-flow station should be established whenever feasible, but, in view of likely ice conditions and the urgent need to keep moving for the oceanographic and gravity programs, it is possible that desired heat-flow measurements may have to be sacrificed.

Throughout Program GP-2 an attempt should be made to establish one heat-flow measurement per day, in conjunction with the geological coring program. This should give readings less than 5 km apart down much of the length of the basin. Representative sediment cores must be measured for thermal conductivity.

In Program GP-1, if it is necessary to do it on the ice, and for Programs GP-3 and GP-4, determination of heat flow should be made at about every fifth station (e.g., about every 15 km) on a routine basis and at closer intervals in critical regions if time and logistics permit. Particular attention should be given to obtaining representative heat-flow measurements at the margins of the Eurasian Basin, as well as near the median ridge. This work should be coupled with studies by the geological team and oceanographers of the rate of sedimentation and the stability of sediments and the activity of bottom currents at the foot of the Eurasian continental slope and of the Lomonosov Ridge.

For Program GP-6 and as a supplement to Program GP-5, heat-flow measurements should be taken as frequently as possible. In areas of detailed survey it will be advantageous to have duplicate equipment so that staggered readings can be taken from two or more locations on the ice a kilometer or so apart, one station being established while the other is reaching thermal stability.

3.1.6. Earthquake seismology--Programs GP-2, GP-3, GP-5, GP-6, and GP-7

The earthquake seismology studies should be aimed at locating the precise center of activity and characteristics of energy release by earthquakes along the Nansen Cordillera and at obtaining data on the crustal structure of the Arctic Ocean region by interpreting energy from more distant earthquakes that passes beneath part of the basin.

As part of Program GP-2 and a contribution to Program GP-6, it is proposed that the ship suspend a seismometer a few hundred meters above the bottom throughout the entire drift. This will not be able to record shear waves but will give a complete record of first arrivals and maximum compressional waves for the duration of the cruise. The suspended seismometer should be supplemented by bottom seismometers left in selected places, either acoustically telemetering or tethered to the ship by a slowly unwinding cable. The bottom seismometers would have to be considered expendable, although with good fortune some may be recoverable. For initial planning, it is suggested that four such units may be considered for deployment on the floor of the Eurasian Basin. The positions would be determined from a study of present seismic activity and the rate of ice drift; they would be most useful (and have best chance of recovery) in areas where the ice drift rate is slowest. It would be desirable to have two bottom seismometers near the median ridge during Program GP-7.

The study of earthquakes from the Arctic Ocean area and of the arctic continental and oceanic structures in general would be greatly facilitated if seismic calibration explosions were released during the drift (Program GP-2). To date, the earthquakes along the Nansen Ridge (and elsewhere in the Arctic) have to be studied only by teleseismic observations because of lack of recording stations within the polar basin itself. As a result, there is uncertainty of location for all past events in the area, and thus, teleseismic methods have not been as valuable in the Arctic as in other parts of the world in contributing to the study of the crustal structure and tectonic development. A controlled explosion within the region and observed at teleseismic distances will render travel-time and amplitude corrections of great importance for the crustal studies for the whole area.

The study of the upper mantle under areas that have no local seismic network is also difficult until some calibrating shots have been fired. The most important studies in question are concerned with the depth functions for the seismic velocities and for the energy loss coefficients.

The size of explosion necessary to be recorded at teleseismic distances has been proved to be of the order of 10 tons of TNT if exploded at the optimum depth as a simple charge. Equivalent teleseismic signals to those of a single 10-ton charge can be obtained by explosion of four one-ton dispersed charges (Jacob, 1975). The large explosions can also contribute to the seismic reflections and acoustic programs.

The multipurpose seismic array proposed for seismic reflections studies (see Section 3.1.7) will also be useful in detecting and locating earthquake shocks. In particular, it will provide a possibility for differentiating earthquakes originating on ridges from those on fracture zones (Program GP-6).

If a complementary ice station program can be established on the Lomonosov Ridge near 87° N (North American side), it should also have a bottom-mounted seismometer to sample, however briefly (two weeks seems optimistic for staying within low-power acoustic range), for microearthquakes.

The Nansen Drift Station must have communication capacity to exchange seismic data whenever required with Alert and other observatories in the world network.

3.1.7. Reflection Seismology--Programs GP-1, GP-2, GP-3, GP-4, GP-5, and GP-6

Seismic reflection measurements can provide much valuable data on the nature and thickness of the sediments (Marine geology program) as well as the underlying rocks and structures, but in view of its high manpower and logistics requirements compared with other geophysical studies, it must be employed sparingly and where the data obtained are particularly valuable.

The principal seismic reflection studies will be carried out near the ship, as a contribution to Programs GP-2, GP-5, and GP-6. It is proposed that a crossed or V-array of about 30 detecting elements, centered on the ship and with legs 15 to 40 km long depending on local transport and telemetering equipment, be set out as soon as the ship gets well frozen into the ice. At each detecting site, two hydrophones would be suspended at different depths beneath the ice, attached to buoys with UHF telemetering equipment, which would send data to a central processing station on the ship. An air gun on the ship would provide the seismic energy.

It will be necessary to determine the position of each detector station in the main array on at least a daily basis as the array changes shape because of ice movements. This can be accomplished by a "sing-around" calibration system using each hydrophone as both transmitter and receiver to give distances between all instruments, which can be reduced to a daily configuration of the array. With hydrophones at two depths at each location, it should be possible to locate the direction and vertical angle of energy wave paths and to differentiate earthquake waves arising from below from ice fracture noises originating on the surface.

This array should provide information on the thickness and structure of the sedimentary and near-surface igneous rock units throughout the Eurasian Basin and, in particular, provide a three-dimensional picture of the ridge and fracture system and sediment-igneous relationships in considerable detail for representative parts of the Nansen Ridge. With proper selection of frequency range and dynamic range of the detecting equipment, it can also contribute directly to the earthquake detection, refraction seismology, and marine acoustics programs.

For reflection profiling from the ship, an air gun would be satisfactory. At times of considerable ice movement, however, a variety of energy sources and hydrophone/geophone frequency filters should be available. Under some conditions it may be desirable to use directional energy sources operated near the sea floor.

In the programs undertaken on the ice away from the ship, the highest importance for seismic reflection studies should be given to (a) determination of the structures at the edge of the Eurasian continent (Program GP-1, if it cannot be done by ship); (b) the midslope and west of the Lomonosov Ridge, if it can be reached (Program GP-4); and (c) the central cross section of the basin (Program GP-3).

Seismic reflection equipment operated away from the ship (e.g., on Program GP-1, if not done by ship, Program GP-4) will have to be portable, simple, and rapid in operation. This limits it to relatively high-energy, nondiscriminating measurements. Traverses in midocean under heavy ice conditions, using proven six-channel recorders and shot points 15 km apart using two helicopters and a six-man team have been able to cover 100 km per day, which would appear adequate with good safety margin for the proposed studies. The work could be done with a single helicopter, at a slower rate and greater net fuel consumption. Experienced crews are essential. Telemetering seismometers are an operational advantage, provided they possess adequate reliability under arctic conditions but to date have proved little saving in logistics requirements.

On-board computer capacity should be able to handle first reduction of data, for immediate modification of field programs.

3.1.8. Refraction Seismology--Programs GP-5, and GP-7

Refraction seismic measurements are necessary to establish the dimensions, form, and likely composition of the major structural units and the underlying crust. Because of the heavy materials requirements and the manpower involved, the studies must be few and carefully prepared. The seismic reflection measurements (Section 3.1.7) and most of the other geophysical studies should be designed and scheduled to be supportive of the refraction experiments where appropriate.

No refraction data appear to be available from the Eurasian Basin. The most important places for these studies appear to be (a) the floor of the Basin near the Eurasian end but outside the continental rise (Program GP-5, supplemented by Program GP-1); (b) the floor of the Basin somewhere near its middle but not immediately adjacent to the active central ridge (Program GP-5); and (c) the "Atlantic" end of the Basin (Program GP-7).

At each location, Program GP-5 should comprise crossed or two armed reversed refraction profiles at least 80 km long to give unit thickness, velocity profiles, and anisotropy information for the crust and to determine the depth and slope of the crust-mantle boundary. Large explosive charges (1000 kg plus) will likely be necessary.

Program GP-7 is a reversed seismic refraction experiment, utilizing the ship, three stations near shore, one station on the Lomonosov Ridge if possible, and, ideally, cooperation from Soviet observers on Franz Josef Land. At least two sets of shots and recordings should be made, with the ship in different positions, ideally at least 100 km apart as it drifts toward the Greenland Sea. The two sets might therefore have to be scheduled as much as three weeks apart. As shot-recorder distances are up to 800 km, shots of up to 3000 kg may be needed. A good quality, dedicated communications network is also required.

The experiment will depend on the active collaboration of shore parties operating out of Svalbard, Greenland, and Arctic Canada. It would be undertaken in the second (last) spring, preferably during April.

3.1.9. Navigation and Geodesy--All programs, Particularly GP-2, GP-4, GP-5, and GP-6

The highest possible positional accuracy is needed for all bathymetric and geophysical information. On-track relative distance accuracy should be 200 m with geographical accuracy of profiles and spot stations to 500 m. Surface magnetic observations will require azimuth determinations accurate to within one half of a degree.

It will be convenient for most of the routine positions and relative positions to be recorded on a terrestrial-based coordinate system through calculated satellite orbit. However, because of the lack of information about crustal density and thickness in [illegible] Arctic Ocean area, the lack of regional gravity information, and the absence of pendulum measurement stations, the fit of the geoid is not known in the area of the drift. It is, therefore, important that positions based on celestial coordinates be established along the course of the drift and the satellite-based coordinates be referred to them for absolute positioning. Comparison of astronomic and satellite positions is essential for plumbline deflection studies (Section 3.1.3) in conjunction with gravity studies and will enable geoid corrections to be determined.

An automatic astronomic positioning system, accurate to 1 second of arc or better (Carroll, 1969) will be able to provide celestial positioning on a routine basis except during the summer when the sun is continuously above the horizon. As a backup, for use in summer and on traverses over the ice (especially Program GP-4), a good quality theodolite, reading to 0.5 second of arc, is adequate. Away from the ship, geodetic observations and navigation will be the responsibility of a geophysicist, who should develop in advance the necessary observational skills.

During the summer, persistent stratus cloud will prevent astronomic observations on many days.

3.2. Instruments

The major items of equipment needed for installation on ship or prepared for ice stations are listed in Section 5.2.

3.3. Program Schedules

The geophysical programs outlined in Section 2.2. are closely constrained in timing by the severe seasonal changes in the arctic environment and the uncontrollable rate of progress of the drifting station itself. Extensive traverses away from the ship can only be made when ice conditions, average weather, daylight, and temperature permit a reasonably safe and efficient operation; near-ship studies can only be carried out when the ship has drifted to an appropriate geographical location at a time of sufficient daylight for useful field work.

It is proposed that bathymetric, gravity, plumbline deflection, towed (suspended) magnetometer, heat-flow, and suspended seismograph measurements will be taken continuously or at frequent intervals during the entire course of the dirft (Program GP-2). This may not be possible during parts of the cross-basin traverse (Programs GP-1 and GP-3), the Lomonosov Ridge studies (Program GP-4), and the seismic refraction studies (Program GP-5), because of manpower shortages, but the losses during these periods will be short and compensated by increased data from critical areas.

Program GP-1: It is desired that this program be carried out from the ship, prior to its insertion into heavy ice, while the ship is still mobile. The ship should plan to reach the survey area about September 10. The heat-flow element of this program may have to be sacrificed in the interests of maintaining mobility. If the ship cannot reach the survey area in reasonably light ice, or becomes beset before completing the program, the traverse should be completed by helicopter-supported stations on the ice rather than risk delay or expenditure of excessive fuel in ice-breaking.

If the program is to be carried out from stations on the ice, it should take about two weeks, depending on the amount of seismic reflection work, if the crews and pilots are already experienced in ice-station geophysics. Operationally, this program will be a race between delaying the start to enjoy more dependable ice conditions and speeding the finish before decreasing daylight and winter storms make operations impractical and unsafe.

Program GP-2: The longitudinal traverse through the Eurasian Basin will be carried out during the whole time the ship is in the ice.

The approximate work load will be as follows:

Bathymetry and bottom morphology: continuous
Gravity: continuous
Plumbline deflection and geodesy: continuous September to March, once daily March to September when sky is clear or broken.
Magnetometry: continuous or daily
Heat flow: once daily except for when in conjunction with GP-6, then as frequently as possible
Seismic array: several times daily when ice conditions are suitable

Program GP-3: This traverse must be considered one of the main efforts of the Nansen Drift Station geophysics program, and much of the preparation and scheduling should be devoted to it. It can be done most effectively during late March, April, and early May. Logistically and from the point of view of timing it should be combined with Program GP-4. Three to four weeks should be devoted to the traversing parts of this program. It is important that this program not be curtailed by the "spring airlift" and crew rotation or demand for the helicopter and STOL aircraft.

Program GP-4: The studies of the Lomonosov Ridge are best carried out at the northern end of the traverse of Program GP-3 and would require an ice-station satellite camp, fuel depot, and navigation beacon to support both programs. Two to three weeks, preferably late April, should be planned for this study.

Program GP-5: Studies of the floor of the Eurasian Basin should be undertaken in periods of good weather when the ship is in a good position as apparent from bottom physiography and aeromagnetic survey information. About five days will be needed for each complete "shoot." Preferred times, assuming average ice drift rates, appear to be early winter and late winter of the first overwintering period; and autumn of the second year. Related information will, of course, be picked up in the spring of the final year if Program GP-7 is carried out. If Program GP-7 does not materialize, Program GP-5 should be continued in the spring of the final year.

Program GP-6: Studies of the Nansen Cordillera will be undertaken whenever the ship is in an appropriate position, subject to the temporary prior claim of Programs GP-3, GP-4, and GP-7 on personnel. Depending on where the ship is inserted into the ice and the course of the drift, this program will be active any time after late spring of the "drift year."

Program GP-7: This must be carried out between late March and mid-May, subject to the schedules of the cooperating stations.

Delay caused by slow drift: It is possible, although statistically the chances do not appear to be high, that the ship would not drift across the Arctic Ocean from the Laptev Sea to the Greenland Sea in just under two years but would remain in the ice for a third winter.

In that case the seasonal timing of the geophysical programs would not be changed, but Programs GP-3, GP-4, and GP-5 would be repeated during the additional year, with positions of the studies changed according to the progress of the drift. It is also possible that Program GP-7 could be run twice, first from a position more centrally in the Basin and again the following spring, provided it was possible for the collaborating agencies to mount two successive programs. However, preference should be given to Program GP-7 in the spring period when the ship is in the optimum position to obtain structural and crustal information on the Greenland Sea end of the Eurasian Basin (Figure 6.1).

Sufficient supplies, particularly helicopter fuel and seismic explosives, should be carried to ensure that maximum scientific benefit can be realized from a delay in the drift progress.

Changes due to Unexpected Drift Course: It is entirely possible, although not likely that after being frozen in the ice in Laptev Sea, that the ship would not drift down the axis of the Eurasian Basin but could be carried widely to either side. In this event, the programs proposed (except GP-6 and possibly GP-4) should still be possible. The timings would not be likely to change.

General Calendar: A generalized calendar and schedule of the principal geophysical programs, based on a two-winter drift crossing of the Basin is given in Figure 6.2. If the drift were to take a year longer than expected, the schedule shown in the middle "drift year" would be repeated with little change in timing.

3.4. Personnel Required

Personnel demands are most critical on over-ice work away from the ship (Programs GP-1, GP-3, GP-4). Three persons (one of whom can be the helicopter pilot if he is willing to work as technical field assistant) can handle the portable depth sounding, gravity, and surface magnetic data; two additional persons are required for heat-flow measurements. Explosion seismology measurements will require a minimum of six persons and preferably six plus two pilots who double as field assistants.

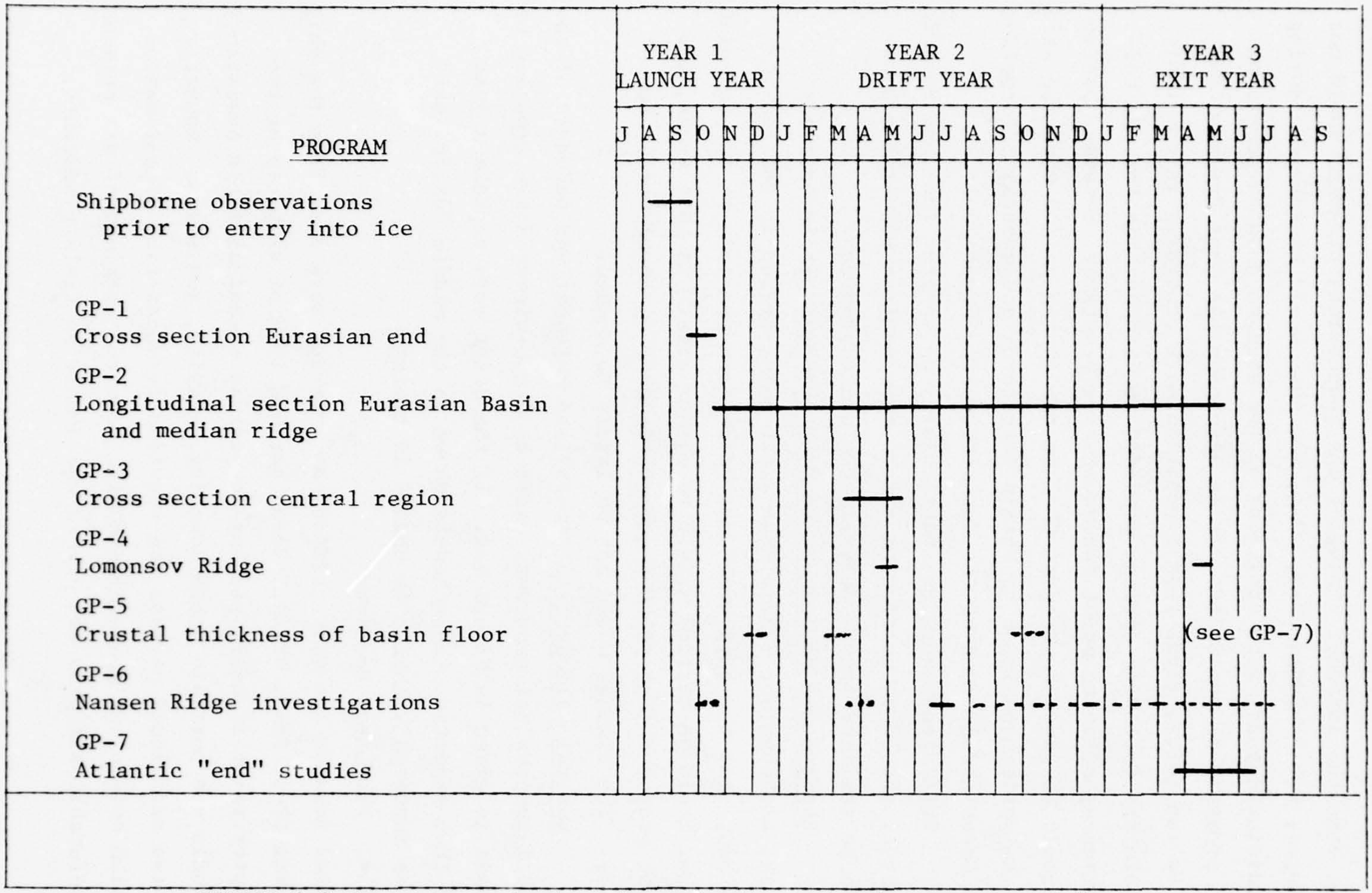

FIGURE 6.2 Tentative calendar of geophysics-tectonic programs of Nansen Drift Station, based on assumption of two-year drift crossing.

Geophysical observations on board or alongside the ship can be handled by the same crew as that for work away from the ship, provided geodetic skills are available for the plumbline deflection work. To avoid shutdown of on-board observations during over-the-ice programs, one experienced technician should be assigned to the ship at all times. It is assumed that ship fathometer operation and positioning will not be the responsibility of the geophysics team.

As in all operations of this type, the field personnel must be versatile, skilled in their own disciplines, and able and willing to assist as a matter of routine with other disciplines. On the basis of cooperation and shared workload, a minimum but feasible geophysics team appears to be as follows:

	Investigators	Technicians or Assistants
Gravity/surface magnetics/portable bathymetry/plumbline	2	1
Heat flow	1	1
Seismic experiments	2 or 1	1 or 2
TOTAL	8	

Of this number, at least one can be a pilot and at least one shared with the marine geology group. Personnel may have to be "borrowed" from the geology or oceanography group for seismic experiments and could be "lent" to that group to help with long cores and dredging, monitoring underwater TV, and the like.

Two of the team must be properly trained and licensed to handle explosives.

Program GP-7 can be handled from the drifting station with the team available. It will also require a minimum of four persons plus logistic support at each of the three or four cooperating stations.

3.5. Data Management

All significant data will be submitted to the appropriate national or international data banks one year after delivery from the ship or station. Data such as seismic refraction measurements for which no generally recognized bank exists will be stored for distribution to interested scientists by the principal investigators. Information on the type of data, its format and referencing, location, and accession will be filed with the project central director or committee by each principal investigator.

3.6. Collaborative and Cooperative Studies and Activities

For maximum scientific effectiveness and to obtain the greatest operational efficiency and economy, the above programs must be coordinated with and extended by related studies in other fields, which are undertaken during the drift, and by collaboration or cooperation with programs in the Arctic Ocean region undertaken by other research groups and programs.

3.6.1. Other Studies Undertaken from the Drifting Station

When the basic scientific objectives and major elements of the plan have been approved, it will be necessary, for maximum scientific effectiveness and to ensure that the design of shipboard facilities and scheduling of their uses is optimized, that careful attention be given to the planning of joint and cooperative studies between different teams and major disciplines during the course of the drift. The need for cooperative and collaborative planning between the various studies prior to finalization of schedules and even where possible prior to the decisions of the location of electrical outlets in the ship's laboratories can make a vital difference to whether the drift experiment runs smoothly and is a coherent integrated study or whether it is a collection of disparate individual investigations.

Areas where active collaboration between the marine geophysics and tectonics program and other identified programs proposed on the drifting station include:

Marine geology and paleoclimatology:

- physiographic interpretation; bottom photography;

- density, magnetic stratigraphy, and thermal conductivity of near-surface sediments;
- geochemistry of igneous rocks and their detritus;
- rate of sedimentation, past and present;
- paleontological record of source of sediments and past conditions of sedimentation;

Physical oceanography:

- bottom currents and temperature gradients;

Marine acoustics:

- elastic characteristics of bottom materials;
- morphology of bottom features;

Atmosphere-ionosphere-magnetosphere:

- variations in electric and in magnetic fields, on the surface, at shallow and moderate depths, within and under the ice;
- crustal conductivity;

Marine biology:

- observations of planktonic behavior in possible relation to electromagnetic fields

3.6.2. Collaborative Studies with Other Research Programs

Some geophysical studies currently under way are essential to an effective geophysical program of the drift station. Parts of the program are dependent on, or would be greatly enhanced by, collaborative or associated studies undertaken by other agencies in different parts of the Arctic. The most important of these are outlined below.

3.6.2.1. Aeromagnetic Surveys

An effective means of resolving the major sequence of crustal motions and relating the Nansen Ridge dynamics to the broader Arctic Ocean dynamics is through regional aeromagnetic surveys supplemented by detailed aerial magnetic study of selected sites where specific boundary conditions exist. Regional magnetic surveys with track line spacings of between 5 and 20 km can define the structural fabric of the Eurasian

Basin and serve to identify and locate optimium areas for detailed study from the drift station in a number of other disciplines such as gravity, heat flow, and seismic reflection. The resultant magnetic anomaly patterns, also under certain widely accepted assumptions, provide age control for interpretation of the development of the Arctic Ocean. They can, in addition, provide regional integration for the interpretation of bathymetric, side-scan sonar, and reflection seismic data by outlining fracture zones, which are often steep scarps or valleys, seamounts, and spurs on subsea ridges.

It is essential that the results of the regional aerial magnetic survey of the Eurasian Basin be available prior to the initiation of the drift. This information is needed for on-board planning of Programs GP-1 to GP-7, whose precise locations will depend on the rate and course of the drift and thus the position of the ship at the suitable times for each program. Three-component measurements of the magnetic field are desirable, with recorder sensitivity at least to one gamma. Flight lines should whenever possible be perpendicular to the main linear tectonic elements with frequent cross-lines as ties to allow for discrepancies in positioning. Relative positioning (line to line) should be justified to within 1 km, and absolute geographical positioning to within 5 km. Care should be taken to ensure that fixed-base-station magnetic variation data in the surrounding area--at Ny Alesund, Nord, Alert, and Mould Bay--are compatible and calibrated to allow correction of temporal magnetic characteristics at the time of the survey.

The regional aeromagnetic surveys should, if possible, be supplemented by surveys in greater detail, at the lowest practical flying altitude, over critical areas of the median ridge and flanks and the Lomonosov Ridge. It would be most desirable if these surveys could be carried out at the same time as the drift, using the ship (more probably a station on the ice nearby) as a base station and tying in with surface magnetic measurements obtained during Programs GP-2, GP-3, GP-4, and GP-5.

3.6.2.2. Seismic Refraction Studies

Program GP-7 represents a unique opportunity to attach one of the most important tectonic problems of the northern hemisphere (National Academy of Sciences, 1970; Dawes 1973). Its success depends on the establishment of a complementary and coordinated program of seismic refraction shot points and recording stations on the ice north of Svalbard, north of Greenland, north of Ellesmere Island, and if possible on the Lomonosov Ridge or over the Makarov Basin at about 87^{o} N latitude, plus observations at the geophysical observatories at Ny Alesund, Nord, Alert, and Mould Bay. Using the drifting station as a central station, this experiment would permit reversed seismic refraction profiles to be run across the Atlantic end of the Eurasian Basin and obtain information on its contained and bounding structures and underlying crust. If at the same time it was possible to undertake coordinated recording and shooting from Franz Josef Land or Novaya Zemlya, the value of the experiment would be still further enhanced.

3.6.2.3. Complementary Studies on Lomonosov Ridge or Makarov Basin

At intervals since 1967, Canadian researchers have undertaken studies of the Arctic Ocean basin and crust between the northernmost Arctic Islands and the North Pole, under the auspices of the Earth Physics Branch and the Polar Continental Shelf Project of the Department of Energy, Mines and Resources. Field studies have been carried out when manpower and resource commitments permitted; to date there have been two programs near the North Pole, over the Eurasian Basin close to the foot of the Lomonosov Ridge, concentrating on geodetic, gravity, and ocean-tilt measurements. The next studies planned in the series, to be undertaken when resources are available, will include gravity, heat-flow, plumbline deflection, magnetic, and seismic investigations across the crest of the Lomonosov Ridge and the North American end of the Makarov Basin and Alpha Cordillera. The value of both this work and of the Nansen Drift Station (NDS) studies would be greatly enhanced if the ice station over the Lomonosov Ridge (necessarily occupied in the spring) were to be established while the NDS was in the appropriate part of the Basin (i.e., during the second spring of the drift). Each station could thus use the other as a logistic and navigation base and carry out complementary and joint programs. NDS Programs GP-3, GP-4, and GP-7 apply; also studies in marine geology and oceanography. The safety factor of critical off-ship traverses during this period of the drift will also be increased by the presence of another midocean station, with attendant air support and communications system. It will be essential that both operations have a compatible navigation system.

3.6.2.4. Conjugate Point Studies

Consideration should be given to the desirability of undertaking coordinated magnetic measurements from the ship and from its geomagnetic conjugate point in the southern hemisphere, if and when the drift track passes through an area conjugate to an observing station in or near Antarctica. Because of the uncontrollable course and rate of the drift track, only approximate and once-only experiments can be expected; but because of the absence of geomagnetic behavior measurements from this part of the planet and the extreme difficulty of obtaining more sophisticated data, any information would be valuable. On the NDS, the observations could be carried out through cooperation between the geophysics and atmosphere-ionosphere-magnetosphere teams on Program GP-2. What is needed is to prepare, in advance, for coordination and collaboration with observing stations in the southern hemisphere.

4. REMOTE SENSING

Not applicable in the usual sense of "remote sensing" programs. Two special types of "remote sensing" are, however, essential to the geophysics program here proposed:

(a) Aeromagnetic surveys (see Section 3.6.2.1), and

(b) Satellite orbit calculations, for regional interpretation of the gravity field, for plumeline deflection, and for geoid observations (see Sections 3.1.3 and and 3.1.9).

5. LOGISTICS

5.1. Movement of Staff to and from the Drifting Station

It appears essential that the drift begin with as experienced a crew as possible, so that the critical program GP-1 can be carried out with dispatch and success from the start without having to learn as one goes and miss the only chance for information from this unique location. At least half of the GP-1 team should be prepared to spend the winter on the ship and take part in Programs GP-2, GP-3, and GP-4.

From an operational point of view, the most suitable times for staff rotation coincide with the best (or only feasible) periods of away-from-the-ship studies. Careful thought should be given to plans for personnel exchange, to ensure that the demands from other disciplines, whose studies are not so critically dependent on seasonal ice conditions, do not curtail the effectiveness of the geophysical field investigations.

Continuity and the passing on of local experience and methods of dealing with idiosyncratic equipment are essential if the data are to be consistent. Thus complete turnovers of crew are to be avoided. The best times for crew exchange are early summer and autumn (see Figure 5.2).

5.2. Needed Installations or Facilities

5.2.1. On Ship

Shipboard gravity meter
Precision depth recorder
Deepwater side-scan sonar and winch
Deepwater television
Towed (suspended) magnetometer, winch and recorder
Magnetic and electric field detectors, three-component, for use on the ocean surface at shallow and moderate depths, within and under sea ice, with recorders

Suspended seismometer, winch and recorder

Storage for explosives; charge preparatory space

Data-processing equipment

Automatic Astronomic Positioning System

Satellite navigational equipment

Communications equipment for ice parties, for helicopters, and for scientific data exchange

Drummed helicopter fuel storage or drumming facilities

5.2.2. On Ice

Portable camps and emergency depots as needed

Fuel storage (drummed or airlifted containers)

Portable aircraft navigation beacons and power supplies

5.3. Power

(To be compiled when specific equipment selected; likely to be less than 10 kw, with peak drain up to 20 kw)

5.4. Communications

a. Ship to base station in North America: regular ship communication facilities

b. Ship to field station and aircraft: four sets HF - SSB portable with frequencies suitable to polar summer conditions

c. Ship to shore geophysical station: may need two dedicated voice channels for synchronization of experiments and instrument calibration

5.5. Flight Support

5.5.1. Helicopter

Helicopter minimum capacity 2500-lb disposable load or 1200-lb payload over 100-mile radius of operation. Practical capacity should be 2000-lb payload with range of 400 miles

Backup (emergency) two-man helicopter for safety, minimum range 300 miles

Dedicated use of helicopters: for Program GP-1 (3 weeks);

for Programs GP-3 and GP-4 (together 5 weeks); as available for Programs GP-2 and GP-6

Estimated total helicopter flying time for geophysics program (2 years): 500 hours

5.5.2. STOL Fixed-Wing Aircraft

Minimum capacity 2000-lb payload with 600-mile working range, gross landing weight 12,000 lb (Twin Otter type)

Full IFR and inertial navigation equipment

Belly hatch 24-inch-diameter minimum, side port or opening window

Estimated use for geophysics program (2 years): 300 flying hours

Not required to be based at ship except during Programs GP-3 and GP-4

5.6. Surface Transportation

Two tracked over-snow vehicles, tracked truck type, approximately one-ton payload, one with open box and one heated van, each equipped with front and rear winches, each capable of being lifted on deck, would be useful, especially for Programs GP-2 and GP-5. Flotation equipment should be available.

Small personal over-snow vehicles, one- to four-man capacity would be useful for local work near the ship. At least two should be amphibious.

5.7. Items Requiring Special Handling

Seismic explosives, 80 tons

6. COST ESTIMATES

The following estimates are based on a two-year program:

Salaries

Principal Investigators 5 @ 2/3 time @ $24,000	$150,000
Technicians or Assistants 4 @ 2/3 time @ $10,000	30,000

Premium, bonus, 20%	30,000	
Fringe benefits, 20%	40,000	
Overhead for university and institute personnel, 30%	50,000	
	300,000	$300,000

Travel and Shipping

Equipment to embarkation and return estimate	$30,000	
Personnel (not including rotation) 10 @ $1200	12,000	
Rotation, costs to arctic point only (Alaska, Canada, Svalbard) 30 x 1500	45,000	
(say)	87,000	$100,000

Equipment

(to be worked out in detail)

First cut, assume 1/2 borrowed at net cost -- Instruments	$200,000	
- Field operational equipment	100,000	
- Vehicles, etc. (shared)	100,000	
	400,000	$400,000

Supplies

Explosives	$100,000	
Fuel (purchased in United States)	200,000	(plus transport)
Other supplies	50,000	
	350,000	$350,000

Operational costs

Helicopter, 500 hours

STOL aircraft, 300 hours

Ship navigation and astronomic observations

Ship computer technician

Data processing	
Salaries, supplies (computer costs not included)	$100,000
Distribution of specimens and records	$20,000
Rough total	$1,270,000

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7

MARINE GEOLOGY AND PALEOCLIMATOLOGY

1. BACKGROUND

1.1 Existing Information

There has been no geologic work by the United States in the Eurasian Basin. Some sediment samples have been taken from icebreakers in the shallow marginal shelf areas, and one drifting ice station (Arlis II) obtained data from the margin of one corner of the Basin. This, plus aerial magnetic surveys over parts of the Eurasian Basin, constitutes the United States investigations to date. While U.S.S.R. ice stations probably have collected at least some geologic data, little has been published (e.g., Gramberg and Kulakov, 1975). Since the drift of the *Fram* (1893-1896), other countries have not studied the geology of the basin. Thus, it is not possible to interpret the origin and geologic history of the Arctic Ocean satisfactorily because there are no data available for almost one half of this deep basin.

From studies in the adjacent Amerasian Basin (based on ice-island T-3 work), from aerial geophysical investigations, and from comparisons with the North Atlantic Basin, some inferences can be made. We assume that the deeper Arctic Basin originated and developed by processes of sea-floor spreading similar to those in other oceans. We assume that the crustal structure and sediment blanket of the Eurasian Basin have developed in a manner at least partially similar to that elsewhere but with differences because of the geographical and geophysical setting and the polar oceanographic environment. Unanswered are questions of the sedimentological and paleontological history of an ocean that has been mainly ice covered since at least the Miocene. In addition to helping answer questions of origin and geologic history of the area, the sediment holds evidence of the environmental evolution of the Arctic. Because of the profound effect of a polar ice cap on the world's climate, knowledge of its origin and development, recorded in the sediment, is vital to long-term climate understanding, an important factor in the CLIMAP project.

1.2 Information Gaps and Their Significance

Geology and climatic history of the Arctic Ocean, particularly the Eurasian Basin part, are poorly known. Among the significant problems to be dealt with are the following.

The arctic environment during Pleistocene glacial periods is especially important. A range of opinion from an open Arctic Ocean to a thick cover of glacial ice during the period has been expressed. The sediments carry the information needed to determine the environmental history. One problem has been that the deposition rates in the areas studied are so low and the dating of samples of known stratigraphic or structural relations are so dubious that definite conclusions have proven elusive. The spreading ridge should be the best place to do these studies. The ridge is probably to a large extent protected from turbidity currents, and it is possible that Fe-Mn emanations from the rift may increase the rate of accumulation to the point where less ambiguous results can be obtained.

On the basis of topography and geophysical signature, the Arctic Ocean floor can be divided into basins and intervening ridges. The most important element in the geologic development of the Eurasian Basin is the Nansen Ridge, most likely an extension of the globe-encircling midocean ridge system. This ridge forms the "backbone" of the Eurasian Basin, is tectonically still active (Karasik, 1974), and will be the focus of the geology-geophysics program. Not only is a knowledge of this ridge important to interpretation of the origin and development of the entire Arctic Basin, but it is important because it is the only segment of the world system of midocean ridges that essentially is unstudied. Pertinent questions are: What is its precise structure, age, and composition? How does its sediment blanket differ from that of other ridges and from the sediment of the Amerasian Basin? In the unique environment of an ice-covered midocean ridge, how has the marine life of the past 60 million years been influenced in its development? What geologic factors are involved in the transition of the Nansen Ridge to continental structure as it merges with the Laptev Shelf? All of these factors point to this area as a unique segment of the earth's crust, and yet its origin and history can at present only be inferred from aerial geophysics and from assumed correlations with other areas.

In addition to the Nansen Ridge, another geologic structure of great importance in the Eurasian Basin is the Lomonosov Ridge. Study of this structure should be possible from the Nansen Drift Station (NDS). The Lomonosov Ridge has been interpreted to be a unique part of the arctic continental shelf that has been separated from its original position by spreading along the Nansen Ridge. Its origin and history have not been investigated in detail, yet it may be considered the most prominent ridge in the Arctic Ocean. It separates the Arctic into unequal halves. How it has affected the sedimentation and marine life in the basin that it divides may be answered from bottom samples and coring in the Eurasian Basin.

Abyssal plains underlain by thick sedimentary sections exist on both sides of the Nansen Ridge where it bisects the narrow Eurasian Basin. The rift axis is in places deeper than the flanking abyssal plains. A number of small fracture zones on the ridge are indicated in the Soviet literature, but the evidence for these is not clear. If the fracture zones or other gaps exist in the rift mountains, it appears possible that sediments may enter the median rift valley, as they do in the case of the Gorda Ridge rift valley in the eastern North Pacific. If this occurs in the Arctic, it may explain the anomalously low or discontinuous magnetic amplitudes, for basalt magmas would then form more slowly with lower magnetizations than normal. In fact, the Nansen Ridge crest is about 500 m deeper below sea level than the typical mid-Atlantic Ridge. Whether this anomalous depth is due to the slow spreading rate or to some other process is unknown.

The principal obvious problems of the Arctic Ocean basins relate to the sedimentary processes that clearly control the form of the relatively smooth floor. The abyssal plains, which occupy the deepest portions of the Arctic Basin, appear to have been formed by ponded sediments apparently carried to abyssal depths by downslope flow. Fans of sediment that stretch out from the continental slope have been shaped by both downslope movement and, probably to a greater extent, by the deep circulation pattern of the arctic waters.

2. PURPOSE

The geophysical part of the marine geology-geophysics program (Chapter 6) is designed to answer the question of how and why the Eurasian Basin formed. Geological studies will provide the history of this formation, the sedimentary processes at work, the development and relationship of arctic life and sediment, and the history of the arctic water column above the bottom sediment and its relationship to climate change during the past 40-70 million years.

The scientific objectives of the marine geology-paleoclimatology programs are designed to take advantage of the fact that this is a unique segment of the earth with a spreading ridge center below an ocean that is covered more or less by a continuous ice platform. Utilizing the ice cover, it will be possible to do more thorough, closely spaced sampling than possible or economical in other midocean ridges and deep-sea basins. The following objectives are designed to elucidate the geological history and the sedimentological and paleontological factors that have modified the ocean floor, but their realization will also contribute to clearer understanding of the dynamics of the processes that function in the crust and upper mantle of the earth (see Chapter 6).

Answers obtained from the study, together with studies in the Amerasian Basin (Hunkins *et al.*, 1971; Clark, 1969, 1970, 1971, 1974) may answer questions concerning the origin of the Arctic Ocean basin structure and provide sound geologic data for the whole Arctic Basin. This work will directly supplement work done from ice-island T-3 during the past 15 years in the Amerasian Basin.

2.1. Specific Objectives Are:

2.1.1. To analyze and describe the regional geological framework and structural and sedimentological history of the Eurasian Arctic in terms of shelf, slope, rise, basin, and midocean provinces.

2.1.2. To define the arctic Mid-Ocean Ridge geometry, tectonic style, and history of the adjacent arctic basins and intrabasinal tectonic elements through the integration of ocean floor and subsurface geological information obtained through geological mapping and studies of cores and dredged samples, together with information from geophysical profile.

2.1.3. To increase the scientific knowledge of the formation and history of oceanic basins and adjacent continental margins and the characteristics of interaction between oceanic plates, continental plated and upper-mantle regions in the Eurasian Basin.

2.1.4. To analyze the depositional, structural, and paleontologic history of the Eurasian Arctic shelf, slope, rise, and basin.

2.1.5. To define the nature and recent sediments on the Lomonosov Ridge. To shed further light on the questions of whether this structure is a piece of the Eurasian shelf split off by the Nansen Ridge.

2.1.6. To aid the interpretation of the nature of the junction of Nansen Ridge with the Eurasian continental block. To define the junction of Nansen Ridge with the Mid-Ocean Ridge in the Greenland Sea and to determine whether the junction is affected by one large fracture zone or a series of small echelon fracture zones and ridge segments.

2.1.7. To obtain information on paleoclimatology of the Eurasian Basin and adjacent areas.

2.2. Paleoclimatological Considerations

Considerable concern exists with regard to regional and global consequences of a reduction in ice cover of the Arctic. It has been postulated that such a reduction could be triggered either by the increase in atmospheric CO_2 content generated by the burning of fossil fuels or by a reduction of freshwater supply to the Arctic Ocean caused by reversing the flow of the major rivers in the Siberian-Arctic drainage basin. As the sensitivity of arctic ice cover either to atmospheric CO_2 content or to the rate of freshwater input is poorly known, the magnitude of the ice-cover reduction resulting from these changes currently cannot be reliably assessed. One of the major thrusts of the Arctic Ocean research program must therefore be the development of a quantitative understanding of the factors controlling the extent of arctic ice cover.

Although the most obvious approach to an explanation of the change in ice cover is through direct modeling of the arctic energy and water balance (see Chapter 8-11), these exercises need to be tested against direct observation. The historic records are not sufficiently complete and cover too short a duration to provide such a test. Fortunately, nature keeps her own records. The composition of the sediments on the floor of the Arctic Ocean record in various ways the extent of ice cover. Interpretations of this record should make it possible to state what the arctic environment was during periods when global climate was different than it is today. One of these times was the peak of the last glacial period (18,000 years ago), and the other was the time of minimum ice during the last interglacial period (124,000 years ago). If the ice cover during these two periods could be reconstructed, we would be in a much better situation with regard to testing arctic models. As the CLIMAP program is making reconstructions of the sea-surface temperature through much of the world's oceans for these two times, the ice-cover record could be placed in global context. Whole-earth meteorological modeling for these times of extreme earth climate, using the CLIMAP inferred sea-surface temperatures and continental ice-cover maps as inputs, is now being attempted.

Unfortunately, the available sediment cores from the Arctic Basin only give partial answers with regard to the ice cover during the last glacial and interglacial periods. One reason is that these sediments come from areas of very low deposition rates. Possible vertical mixing of these sediments on the sea floor through bioturbation or possible erosional episodes render reconstruction of climatic history highly tenuous. There is a possibility that depositions of volcanogenic oxides along the ridge crest may have raised the sedimentation rate so that sampling and stratigraphic interpretation may be more reliable.

Despite the poor quality and doubtful stratigraphy of the sediments sampled to date, we do have some important clues to the conditions prevailing in the Arctic 18,000 years ago. Sediments deposited during postglacial time (i.e., the last 11,000 years) are rich in the remains of planktonic foraminifera. By contrast, glacial-age sediments have fewer plankton. The most likely explanation for this difference is that during the Wisconsin (Würm) glacial time the extent and thickness of ice cover in the Arctic Ocean was greater than it is today. With an extensive and continuous ice cover, plant productivity was essentially nil. Without a food source, the herbivorous planktonic foraminifera did not thrive, hence the shells of these organisms are not so abundant in glacial sediments.

Sediments corresponding to precise intervals during the pre-Wisconsin interglacial age have been difficult to identify. It is hoped that a better preserved record of arctic history will be found along the NDS track.

Even if a better sedimentary record is recovered, problems still exist in "reading" this record. The techniques used in other parts of the ocean are either inapplicable in the Arctic or applicable with much difficulty. For example, the CLIMAP group reconstructs ocean surface temperatures from faunal or floral assemblages. In today's Arctic only two species of planktonic foraminifera are abundant. The best information we can get from arctic cores is a rough index of biological productivity from the rate of accumulation of Globorotalia pachyderma.

Another key source of climatic information in deep-sea cores comes from $^{18}O/^{16}O$ ratio in the shells of planktonic (surface-dwelling) and benthic (bottom-dwelling) foraminifera. The record in benthic forams provides a good index of global climate. This is because the $^{18}O/^{16}O$ ratio in the oceans changes with global ice cover. The ice that forms is deficient in ^{18}O relative to surface seawater. The "left behind" ^{18}O makes oceanic oxygen heavier, and in turn the benthic calcite precipitated by benthic organisms dwelling in water subject to surface freezing is richer in ^{18}O than that of organisms living where there is no freezing. Thus, although the ^{18}O record in benthic forams tells us little about conditions in the Arctic itself, it does mark global climate events on the record of arctic sediments, allowing them to be correlated with sedimentary records from other places in the world. The $^{18}O/^{16}O$ relationship in planktonic forams does, however, offer a means of obtaining environmental information about the Arctic itself. In addition to the global ^{18}O enrichment effect imprinted in the benthic calcite, the ^{18}O content of planktonic shells will vary because of changes in water temperature and changes in the salinity of arctic surface waters. The quantitative aspects of these variations needs to be tested against direct observations.

Because of the rarity of the remains of the hard parts of living organisms in Arctic Ocean floor sediments, other means of deriving ice-cover information from the sediments will have to be explored. One promising method is the rate of accumulation of the isotopes ^{230}Th and ^{231}Pa. These isotopes are generated within the water column by the decay of uranium. Because uranium is well mixed throughout the ocean, the production rate of these daughter isotopes in the arctic water column will be the same as that in the remainder of the ocean. In most parts of the ocean these isotopes are removed within months of their formation onto particulate matter and carried to the bottom. This removal is partly through absorption onto suspended particulate matter and partly by incorporation into living organisms. The amounts of both suspended particles and living organisms will be inversely related to the extent of arctic ice cover. If the particle content of arctic waters is sufficiently low, then the extraction efficiency will fall and the newly produced isotopes will remain in solution long enough to "escape" from the Arctic by lateral mixing and reach the open Atlantic, where the necessary particles exist for their removal. In such situations, the rate of delivery of these isotopes to arctic sediments would be reduced. By studying the distributions of isotopes ^{230}Th and ^{231}Th with depth in a core over more than one complete climatic cycle, it should be possible to learn about sedimentation rates, the absolute rain rate of these two isotopes, and also the relative degree of ice cover.

If there is a substantial component of iron and manganese oxide in the sediment, then these materials could be of considerable benefit to studies of sedimentation rate changes. It has been shown on the East Pacific Rise that the rate at which these oxides accumulated did not change over the course of the last climatic cycle. As the generation of iron and manganese oxide should depend on crustal and subcrustal conditions, the quantity deposited should be independent of the degree of ice cover. If so, and if the rate of generation is constant, the amount of Fe + Mn to a given depth in the sediment should be proportional to the age of the sediment. Thus the presence of manganese and oxide-rich sediment will be important not only from the standpoint of the preservation of the climatic record but also from the standpoint of obtaining a chronology. By radiocarbon dating of the upper foram-rich layer, the rate of Fe + Mn oxide accumulation in postglacial time can be calibrated; and assuming that the rate of accumulation has not changed significantly, it will provide the needed proportionality factor to relate total Fe + Mn oxide above a given horizon to the age of the horizon.

In summary, an ice-cover chronology can be inferred from a study of Arctic Ocean sediment samples.

3. OBSERVATIONAL PROGRAM

The following activities will comprise the main elements of the marine geology and paleoclimatology program; additional contributions to the program will come from marine geophysics and tectonics (Chapter 6), physical oceanography (Chapter 8), and biology and biochemistry (Chapter 9).

3.1. Specific Observations to Be Taken

3.1.1. Long Sediment Cores

The most important part of the sediment program will be the recovery of long cores. The cores should be piston cores capable of recovering approximately 20 m of sediment. Two core barrels and a winch with cable capabilities up to 5000 m will be necessary. Because of weight problems, it will be practical to take long cores only from the ship. If a suitable portable coring apparatus can be obtained, cores "of opportunity" as well as six cores from each of six helicopter traverses perpendicular to the main drift station would be desirable. These cores would be used to obtain information on the rate of spreading, as well as the influence of turbidities in the Barents Abyssal Plain. Magnetic stratigraphy will be necessary for age determination and will supplement detailed faunal analysis of the cores.

Shorter cores should be taken from helicopter traverses associated with heat-flow studies. This will provide supplemental data on age, origin, and paleoclimatic development of the ocean.

3.1.2. Box Cores

Box cores will be taken from the main station in order to recover as large as practical a three-dimensional piece of the ocean floor for sediment studies and bottom epifaunal and infaunal analysis. Half of the box cores will be preserved as permanent library material; the other half will be consumed in the study. Sediment recovered in these boxes, as well as from the longer cores, will be used to extend and refine the map of Arctic Ocean sediment, now in preparation. Box core recovery from the Eurasian Basin can be taken by the team that handles the coring, but a separate winch probably will be necessary.

3.1.3. Bottom Samples and Dredging

Bottom grab samples will be taken during helicopter traverses if short cores are not obtainable. This program probably can be coordinated with heat-flow and geophysical traverses. Up to six traverses across the ridge with 10-20 samples on each traverse should be prepared for. Bottom sediment grab samples should be taken as often as possible from sites away from the main station.

Dredging will be possible from the main station only. Systematic dredging should be undertaken at 20- to 50-km intervals along the axial zone and will be invaluable to identify trace elements and isotopic compositions of basalt erupting along its length. Dredging is an essential supplement to coring, for it may reveal phase or chemical inhomogeneities in the mantle otherwise unobtainable. It may also provide evidence of melting conditions and locations of asthenospheric mass movements such as hot spots. The Svalbard region is suspected to be influenced by a hot spot, and basalts from the Nansen Ridge in this region may be of the iron-titanium (FeTi)-rich type. Inferences on upper mantle flows may also be obtainable by identifying and sampling equivalents to the basaltic layer across the mid-Atlantic ridge (MAR).

During parts of the drift where the ship is not over the Nansen Ridge, dredging will provide information of the representativeness of tube cores, box cores, and grab samples. Less closely spaced hauls may be necessary over the abyssal plain and the spacing will be determined by the evidence of geophysical and topographic heterogeneity.

3.1.4. Laboratory Studies of Materials Recovered

Listed below are those categories of observations and/or measurements that should be made routinely on the largest possible number of suitable hard-rock samples recovered:

(a) Petrographic observations
(b) Electron probe studies of phase mineralogy
(c) Major-element chemistry by x-ray fluorescence spectroscopy, atomic absorption spectroscopy, and colorimetric methods
(d) Minor and trace-element chemistry by x-ray fluoresence spectroscopy and mass spectrometric isotope dilution
(e) Rb-Sr and U-Pb isotopic analyses
(f) O, S, and D/H isotopic analyses
(g) Rare-gas analyses

In addition, the following should be carried out on either particularly suitable and/or selected samples:

(h) Petrofabric analysis
(i) Melting experiments

There are various scientific objectives embodied within each category above and other objectives that depend on measurements made in more than one category. An indication of these various objectives will be given below.

(a) Petrographic Observations Detailed petrographic observations (in both reflected and transmitted light) should be made of representative hard-rock samples. To provide textural and phase description, determine alteration products and indications of secondary or phase-change mineralogenesis that may relate to depth of origin and extrusion history.

(b) Electron Probe Studies of Phase Mineralogy After detailed thin-section studies, samples should be subjected to electron-probe analysis. Major and minor silicate phases and oxides should be quantitatively analyzed to provide information on fractionation of low-pressure phase assemblages and, where possible, the range and sequence of crystallization temperature and metamorphism.

(c) Major-Element Chemistry A representative suite of samples from each site where igneous and/or metamorphic rocks are obtained should be examined to assess the extent of major element variation and degree of evolution representative of Nansen Ridge basalts and to examine the variation in major-element chemistry along the axis of the Ridge using phase-chemistry data obtained by electron-probe studies (see above). It may be possible to examine to what extent major element variations are caused by fractionation of the phases stable at low pressures. The degree of higher pressure evolution of the magmas may then be assessed. Samples that show significant hydro-thermo metamorphism may give evidence on the mobility of major elements. Special studies should be undertaken on any unaltered aphyric sample to assess precisely the erupted liquid compositions and thus test as far as possible whether they are primary magmas. Such studies may warrant subsequent experiments on melting relationships (see [i] below).

(d) Trace-Element Chemistry A number of trace elements, particularly large-ion elements, should be measured. Rb, Sr, Ba, and rare earth elements could be determined by mass spectrometric isotope dilution; and other elements, notably Y, Zr, and Ni, could be determined by x-ray fluorescence spectroscopy. In addition to adding to our basic knowledge of the chemistry of the earth, such studies may evaluate the possibility that different magma types are related via crystallizing differentiation and provide an indication of the degree of heterogeneity that existed in the mantle source region at the site of magma genesis. Such information may be essential in determining the chemical setting in which mass transfer and magma plume generation can be interpreted for the Nansen Ridge.

(e) Rb-Sr and U-Pb Isotope Studies High-precision analyses of Sr and Pb isotopes and determination of Rb, Sr, U, and Pb abundances should be made on representative samples from each site at which igneous and/or metamorphic rocks are recovered. Results of such analysis will not only add to the basic framework of isotope ratio distribution in oceanic crustal rock but may provide unique information on the fractionization sequence near the point of a slowly spreading ridge and the junction with a continental plate. It should also provide information on the role of oceanic water in the hydro-thermo alternation of subseafloor volcanics.

(f) O, S, and D/H Isotopic Studies Determinations of $^{18}O/^{16}O$ ratios should be made on igneous and/or metamorphic rocks from each dredge. Such studies should add to the knowledge of crustal chemistry and the factors that affect the various isotope ratios in specific ocean crust situations.

(g) Rare-Gas Analyses Determination of rare-gas abundances would be helpful in further assessing their contents in ridge magmas. $^{40}Ar/^{36}Ar$

ratios could yield information ultimately on degassing of the earth.

(h) Petrofabric Analyses If samples recovered show the evidence of strain, they should be subjected to petrofabric analysis. From such measurements it is hoped to gain information concerning the magnitude and orientation of stress fields in relationship to position in the oceanic crust.

(i) Melting Experiments Selected samples, such as those that are close to liquid composition, should be studied with 1 atmosphere gas and/or solid media apparatus to (1) determine the melting relationships and (2) assess the depth of last equilibration with the mantle.

3.1.5. Ocean-Floor Photography

Documentation of coring and box coring sites can be supplemented by bottom photographs. This is an important dimension of seafloor study. Although it may be possible to accomplish photography from the main station only, it will be necessary in order to document the bottom sedimentary structures and *in situ* sediment-fauna relationships.

In addition, photomosaics of the axial valley will be invaluable in comparing axial processes with the FAMOUS studies. More or less continuous photographs should be taken of long sections whenever possible. This will provide a quantitative record of the distribution of microfeatures of the topography, textural variations of the sediments and rock fragments, faunal habitats, and the like.

3.1.6. Sediment Traps--Atmospheric Dust Collections

In order to document quantity and variety of atmospheric contribution to arctic sediment, sediment traps should be installed on the ice away from contaminating factors of the NDS. Snow samples should be taken on helicopter traverses as well.

3.1.7. Continuous Bottom Profiling

The bottom topography of the drift course should be determined by use of a high-resolution (3.5 kHz or equivalent) narrow-beam reflection profile system. This will determine bottom structure and will complement geophysical and sediment investigation concerning the floor of the Nansen Ridge. A detailed reference to accurate position, azimuth, rate of drift of the ship at all times is absolutely essential, to enable geomorphological and structural interpretations to be made from the recorded profile.

3.2. Instruments

3.2.1. Sampling Equipment Required

3.2.1.1. Coring tubes capable of 20-m recovery. Special considerations should be given to select the best available methods of recovering, storing and handling of these cores. A quantity of core liners should be available but may not be necessary.

3.2.1.2. A large winch capable of spooling 5000 m of 3/8 in. to 1/2 in. cable and 5000-lb breakout pull will be required to support coring activities. An adequate provision must be made for convenient handling of long cores over the side and on deck in subzero temperatures, bearing in mind the large amount of over-the-side and dangling equipment from other programs.

3.2.1.3. Shorter coring tubes, winch, and motor to be used from the helicopter traverses must be portable, capable of being dismantled into units that can be lifted by hand. 5000 m of wire will be needed, preferably tapered for lightness.

3.2.1.4. A box-coring device and a winch capable of 2000-lb lift will be required. This should be separated from the long core winch but should have the same wire capacity.

3.2.1.5. Bottom dredge for consolidated rock, especially on the Nansen Ridge, with suitable winch and crane installed on deck.

3.2.1.6. Bottom samplers (Eckman, etc.) for grab sampling during helicopter traverses.

3.2.2. Underwater Camera and Rigging

This will be necessary for photography. The same winch as that used with box cores can be used.

3.3. Frequency, Times, Schedules

The geologic and sedimentologic work will proceed daily throughout the course of the drift. Long cores should be taken at least every other day (4-5 hours work) and shorter cores "of opportunity" should be taken from as many of the traverses perpendicular to the main drift station (helicopter) as possible.

Box cores and bottom photography will be linked together and proceed on a daily or alternate day basis with the long cores.

Bottom samples will be taken from helicopter traverses. Six traverses across the ridge with 12-20 samples per traverse are considered a minimum. Longer traverses should be taken across the basin on either side of the Ridge when possible. Bottom samples should be taken as often as the opportunity arises.

Dredging should be done at 20- to 50-km intervals for petrologic work, whenever the drift is over rough seafloor topography and at representative intervals 100-200 km over the abyssal plain.

Sediment traps for atmospheric dust should be used as an ongoing project for the duration of the drift.

3.4. Personnel Required

The long-core program will require two persons continually. Bottom sampling and dredging will require one additional person continually. Box core and bottom photography team may be the same as the long-core team. One additional person for atmospheric dust monitoring and core sample preparation will be necessary.

4. LOGISTICS

4.1. A staff of four will consist principally of graduate students who, ideally, would stay for two- to three-month shifts corresponding with the semester schedule of the university.

4.2. A large winch on board is needed for long-coring activities Box cores and bottom photography could be done from shipboard or ice and, if necessary, use the same winch. A separate winch located on the ice for this work, plus dredging, would be ideal. A small portable winch for helicopter transport for bottom samples at right angle to drift is necessary.

4.3. There will be a requirement for 6000-7000 W for motor drive on a helicopter and at least the same on the ice.

4.4. There will be no special communications other than those normally available on ship.

4.5. Helicopter support with a 100-mile working range for bottom samples and dust collection, with weekly to bimonthly flights, could satisfy requirement. At least six special traverses across the ridge for sampling during the course of the drift should be planned.

4.6. Surface transportation (snowmobile?) will be necessary for daily monitoring of atmospheric dust sites that will be located away from the main station.

4.7. Assuming that the major winch is part of the ship's equipment, special handling will involve a second winch (and motor) for the helicopter, another one for the ice, coring tubes, packing cases, box cores, cable, dredge, and bottom samplers plus miscellaneous equipment, approximately 2000 cubic feet.

4.8. The reflection profile system may be available on the ship, and this section (as well as the budget item) may not be necessary. If installation is necessary, the system should be installed above the hull plates in a sea chest. A 3.5-kHz capability is necessary.

4.9. Shipboard chemistry laboratory will be valuable for reduction of snow-dust data. A small laboratory with vacuum pump, microscope, and filter system will be necessary.

4.10. Storage space should be provided for 300 20-m cores and 2500-cubic-feet box cores, short cores, and grab samples.

5. COST ESTIMATES

Salaries

4 Research Assistants
Technician
Premium pay
Principal Investigator
Petrology laboratory
Indirect Costs

TOTAL SALARIES $300,000

Travel and Shipping

Equipment
Personnel

125,000

Equipment (Assumes Winches Provided)

2 coring tubes	
2 box corers	
2 bottom samplers	
1 camera and casing	
10 dredges	
1 3.5 kHz high-resolution reflection profile system	
TOTAL EQUIPMENT	175,000

Supplies and Laboratory Material

(Geochemistry) 2 years on ice	150,000

Data Processing and Publication

Salaries, expendable supplies, etc., 2 years	200,000
APPROXIMATE TOTAL (2-year program)	$950,000

(Not included is estimated cost for helicopter support for sampling away from station.)

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8

PHYSICAL OCEANOGRAPHY

1. BACKGROUND

The Eurasian Basin is a distinct and unique region of the Arctic Ocean from the point of view of physical oceanography. Atlantic water from the Norwegian Sea enters the Eurasian Basin through the Greenland-Spitsbergen passage, while the arctic surface water exits from the Basin through the same passage. The exchange of mass, heat, and other properties between the Arctic and other oceans is most vigorous in the Eurasian Basin, where the Atlantic water is 1 to 2°C warmer than it is in other parts of the Arctic Ocean (Coachman and Barnes, 1963). Here the warm core of this layer is closer to the surface, also, and the vertical heat flux may be one or two orders of magnitude greater than in the rest of the Arctic Ocean (Aagaard and Griesman, 1975). The largest influx of freshwater into the Arctic Ocean occurs in the Eurasian Basin, with an estimated residence time for freshwater of only two to three years (Aagaard and Coachman, 1975). Despite this large influx, the overall stratification is relatively low in this Basin (Coachman and Barnes, 1962). The Arctic Ocean is considered a key factor in several theories of climatic change that invoke feedback mechanisms between ocean and atmosphere involving sea-ice albedo and exchange of heat and water between the Arctic Ocean and the North Atlantic. The Eurasian Basin is the most important area of exchange for the Arctic Ocean, and hence an understanding of its dynamics is essential to an assessment of these ice-age theories.

The first oceanographic measurements in the Eurasian Basin were made by Nansen (1902), during the drift of the *Fram*. A number of fundamental discoveries were made in physical oceanography as a result of the *Fram* expedition. These include the first observations of internal waves, along with proper explanation of their behavior. Ekman drew upon observation, theory, and model experiments to explain the internal waves generated by the ship when a thin layer of freshwater lay over a deeper layer of salt water. Ekman's theory of wind-driven currents, still a cornerstone of physical oceanography, also developed from observations during the drift of the *Fram*. Still another result was the recognition of the importance of adiabatic effects in deep basins, where *in situ* temperatures increase steadily toward the bottom. After a long hiatus, oceanographic research in the Eurasian Basin resumed with the drift of the Soviet ice station North Pole-1 during 1937 and 1938. Since that time, the Basin has been investigated almost exclusively by the Soviets, with additional drifting ice stations and with spot landings of the High-Latitude Air Expeditions. Soviet data in this Basin prior to 1960 have been summarized by Timofeyev (1960). Some more recent interpretations of Arctic Ocean circulation have been given by Treshnikov and Baranov (1972) using mostly data gathered prior to 1960. Most of the data are presented in a generalized form so that reinterpretation by other investigators is difficult.

The Arctic and sub-Arctic seas constitute the northern extremities of the global ocean. An understanding of their wind-driven and thermohaline-driven circulation is an important oceanographic goal, as is their interaction with other oceans and with the atmosphere. The sea ice that covers the polar and subpolar seas at least part of every year has a large effect on circulation and air-sea interactions. Perhaps the most critical problem for the arctic seas is their relation to world climate and climatic fluctuations. The thin ice cover has a strong influence on radiation exchange and the energy balance of this region. The cover of pack ice may exert a considerable influence on climate through any of several proposed ocean-atmosphere feedback effects.

We are now faced with the curious situation of knowing that the Eurasian Basin is critical to certain major scientific problems, while at the same time having less available information concerning the physical state of its water and the associated processes, than is probably the case for any other part of the world's oceans. We have only primitive mappings of the large-scale temperature and salinity fields, essentially no information about currents, and can only hypothesize the physically important processes.

In summary, the Eurasian Basin is the least-known portion of the Arctic Ocean but very possibly the most important with regard to climate and interaction with the rest of the world's oceans. Furthermore, it is a part of the world's oceans in which an ice cover provides not so much a barrier to experiments as it does a unique stable platform for careful studies of many oceanographic processes that can still only be studied with difficulty in the open sea.

2. PURPOSE

The goal of the physical oceanography program is to provide high-quality measurements of those oceanographic parameters that will enable us to understand the circulation, heat exchange, and mass exchange of the waters of the Eurasian Basin.

The objectives are to:

2.1. Map oceanographic properties of the Eurasian Basin on a large scale. These fields include temperature, salinity, density (a derived quantity), and certain chemical parameters, including a number of radioisotopes. This mapping will provide basic information on the Basin's circulation and will also establish a climatic baseline.

2.2. Make direct measurements of the velocity field in the Eurasian Basin. Continuous measurements of currents over time periods as long as possible will help to define the mean circulation as well as the fluctuations.

2.3. Investigate the processes that modify the waters of the Eurasian Basin. The processes include vertical exchange with the ice and the atmosphere and mixing between layers, as well as horizontal exchange around the margins of the Basin. Mesoscale eddies are believed to play an important role in these exchange processes (Hunkins, 1974).

A problem peculiar to the Arctic Ocean is its extremely stable upper layer (Hunkins, 1974). It is caused by a poorly understood combination of heat and salt exchange with the overlying ice and freshwater advection from the surrounding continents. Stability, convection, and heat balance of Eurasian Basin waters affect the seasonal and secular variations of sea ice and hence deserve special attention in the context of climate research.

3. OBSERVATIONAL PROGRAM

The first objective (2.1 above) requires frequent oceanographic stations with continuous profiles of temperature and salinity, as well as sampling of selected chemical parameters (e.g., oxygen, nutrients, tritium) at the icebreaker site. These continuous profiles should be calibrated with water samples and reversing thermometer readings taken on the same cast. The stations will extend to the bottom when appropriate.

These shipboard oceanographic stations should be supplemented with a complete set of chemical and isotope measurements to be obtained at two locations during the course of the drift. These stations will be patterned after those taken during the GEOSECS program and will provide a northern extension of the longitudinal geochemical sections already taken in the North and South Atlantic Oceans. They will be used to study the renewal rate and mixing dynamics of Arctic Ocean waters.

3.1. Tritium-helium dating of intermediate depth (thermocline) waters should prove very useful in arctic waters.

3.2. $^{18}O/S$ and/or D/S diagrams should add important information regarding the origin of the low-salinity components in arctic thermocline waters.

3.3. ^{14}C measurements will allow the residence time of deep arctic waters to be defined.

3.4. ^{228}Ra and ^{222}Rn profiles in near-bottom waters will allow the rate of vertical eddy diffusion in arctic waters to be defined.

3.5. "PO" ($^{135}P + O_2$) and "NO" ($^{9}NO_3 + O_2$) measurements add yet another dimension to water mass studies.

3.6. Si, Ba, Ra, ΣCO_2, $\underline{p}CO_2$ data provide the information necessary to define the rate of dissolution of organic hard parts ($CaCO_3$ and opal) and of the flux of ^{226}Ra from arctic sediments.

3.7. ^{222}Rn and ^{14}C measurements in arctic surface/mixed-layer waters will allow limits to be placed on the rate of gas exchange across the arctic surface. Because of the extensive ice cover, this rate is difficult to assess in the absence of direct measurements.

3.8. ^{32}Si and ^{39}Ar are trace radioisotopes with half-lives more suitable to arctic turnover than ^{14}C. An attempt should be made to develop means of measuring these isotopes in the deep Arctic.

Oceanographic sections composed of intermediate-depth stations should be made across the Eurasian Basin on lines perpendicular to the Mid-Ocean Ridge axis and expected drift track. Aircraft landings will be made for a period of several hours while an ice well is cut and the oceanographic cast is made. It is desirable that these sections extend out to both sides of the Basin. An effort should be made to obtain selected stations extending to the bottom on each side of the Mid-Ocean Ridge. These may include parameters other than temperature and salinity. The spacing between stations will be a compromise between resolving power for small features and economic realities that dictate the number of possible stations. It is believed that for the large-scale mapping a station spacing along each line varying from 20 to 50 km and a spacing of the section lines at intervals of about 200 km along the ship's track will be adequate. The oceanographic sections should be logistically coordinated with the geophysical section (see Chapter 6).

The second objective (2.2. above) will require arrays of current meters. The arrays will be of two types: either suspended from the ice or anchored to the bottom. A mesoscale array of ten current meters suspended from the ice should be centered on the icebreaker with an initial separation of approximately 10 km and extending in depth to at least the core of the Atlantic water. This array will require positioning with an accuracy of ±10 m. It will be coordinated with the seismic-acoustic array and depend for positioning on the acoustic ranging or radar fixing used in that array (see Chapters 6 and 10). This array is designed to detect eddies of the sort recently observed in the Canadian Basin and should, during selected periods, be complemented by small-scale temperature and salinity charting of the same region. We expect that the mesoscale array will be repositioned from time to time to cover a range of spatial scales from 5 to 50 km. Some continuously operating sensors for temperature and possibly conductivity should be placed near the ship at intermediate depths to monitor internal wave activity. Profiling current meters and high-frequency echo sounders operated at or near the ship will provide additional information on behavior of internal waves and on the mixed layer.

A large-scale array of three elements will provide information on the spatial pattern of mean currents. This array will be a part of the RAMS buoy system at a radius of 200 km from the ship. Each buoy should have two current meters, one in the surface water and one in the Atlantic water mass. A positioning accuracy corresponding to a velocity resolution for the ice of at least 1 cm/sec on a daily mean is considered adequate for these long-term measurements.

Bottom-anchored current-meter observations should also be made to investigate circulation with particular emphasis on monitoring the Atlantic water. Because of difficulties in recovering instruments from beneath pack ice, serious consideration should be given to the engineering of the current-meter system to ensure that the data are recovered. This will probably involve acoustic data telemetry, as well as release of the mooring and recovery. Preliminary tests are presently being conducted in the Bering Sea on such a system.

Several different problem areas and processes are involved in meeting the third objective (2.3. above). One is the vertical flux of heat from the Atlantic water, both within the deep basin, along the continental margin, and in an area of semipermanent open water such as north of Spitsbergen. Another is the complex set of processes occurring in the upper layer. This includes the effects of freezing and melting of ice, solar radiation, and direct transfer of heat and water through leads and polynas.

These problems can be treated indirectly through measurements of temperature and salinity profiles or directly through eddy-correlation measurements. The former methods may include measurements of certain chemical parameters, while the latter require measurement of the turbulent velocity, salinity, and temperature fields in the ocean using special small sensors with rapid response time. Velocity and temperature sensors for these measurements are presently available, but an appropriate *in situ* salinometer will probably require special instrument development. These measurements will be coordinated with the heat and mass balance of the ice cover program (Chapter 11).

Investigations of mixing at the continental margins will require special attention to the role of canyons. The high-resolution profiles should include an appropriate grid of stations near and within one of the major canyons, e.g., the Svyataya Anna or Voronin canyons, along with temporary current-meter deployments within the canyons. It may also be desirable to include turbidity measurements in and near a canyon. These experiments will probably require establishing a temporary ice station supported by helicopters, or fixed-wing aircraft.

Investigation of the upper-layer processes should include radiation measurements within the water under conditions of ice and snow coverage (including open water).

4. REMOTE SENSING

Certain remote imagery and meteorological observations are necessary to meet the oceanographic objective. These include airborne infrared, microwave, and visible sensing. The need will be greatest during the cold season. Weather and micrometeorological observations and ice thickness determinations will be needed. The amounts of open water and thin ice are particularly important in heat-budget calculations. Included in the required meteorological observations are frequent atmospheric pressure determinations sufficient to enable construction of the large-scale wind field that drives the ocean.

Flight support in the form of at least one aircraft will be required for 5 to 15 days each month while the oceanographic section is made. Special flight support will also be required for installation of the bottom-anchored array of current meters and for acoustically monitoring the meters every three months thereafter.

Aircraft support will be required for all the oceanographic programs away from the icebreaker. The mesoscale current-meter array will require one aircraft for two days per month. The large-scale array will be maintained and serviced in coordination with other groups using this array. The oceanographic sections require one aircraft for a period of from one to three months. The bottom-anchored current meters will require an aircraft for an average period of two days per month.

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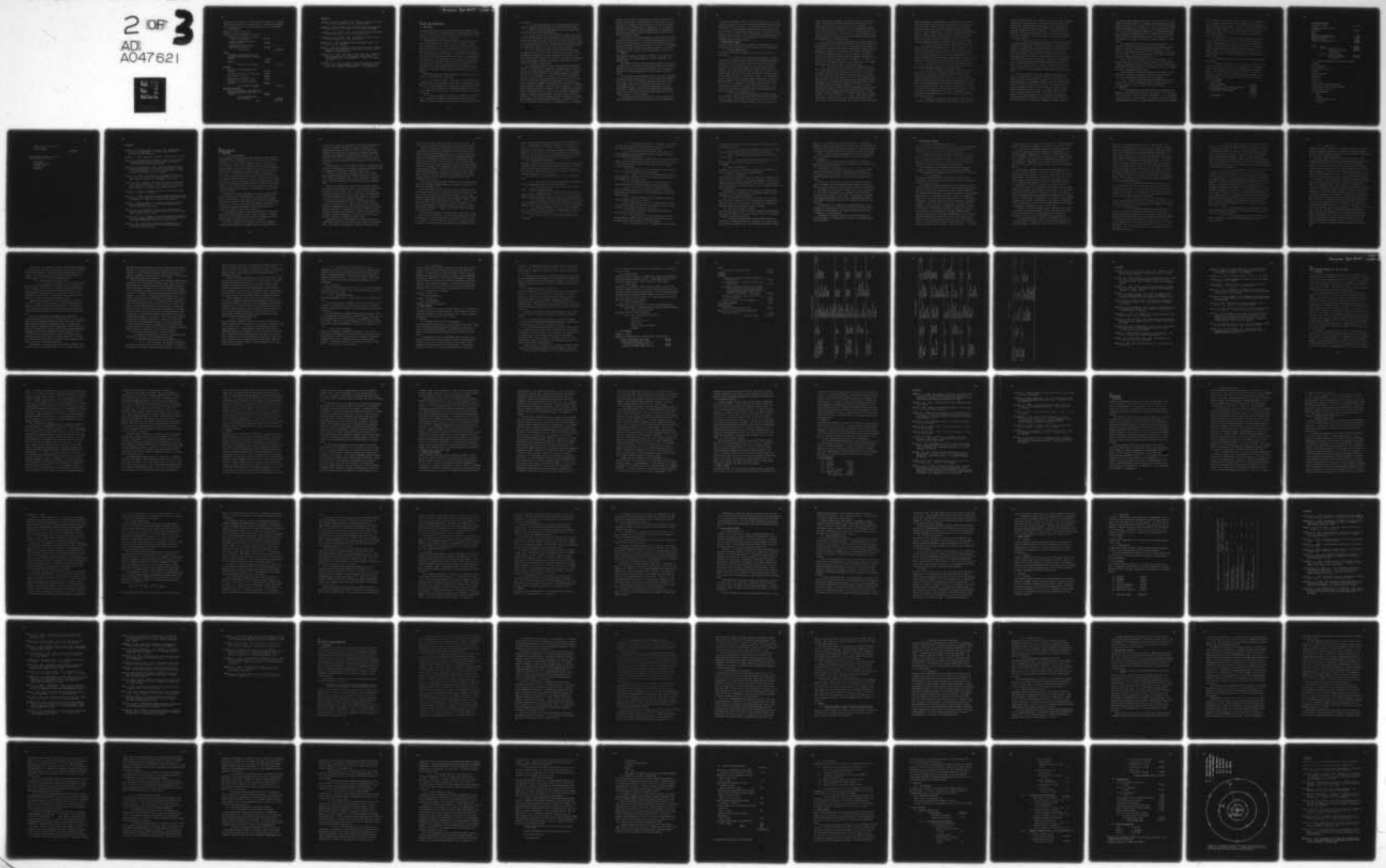

The special program on the continental margin will need one or possibly two dedicated aircraft for a one-month period. Other special programs call for about one week of aircraft time every three or four months.

6. COST ESTIMATES

Budget for 2-year field program.

Salaries (Including overhead and ice bonus)		
4 persons for oceanographic program, full-time with overlap	$250,000	
4 persons for temporary camp and special projects	200,000	
3 persons, data processing and administrative services	150,000	
Total Salaries		$600,000
Travel		
50 roundtrips from United States to icebreaker and attendance at scientific meetings	75,000	
Shipping	40,000	
Total Travel and Shipping		115,000
Equipment		
STD, winch, and oceanographic gear for ship	187,500	
Current meters for ship-centered array	225,000	
Instruments for sections	150,000	
Instruments for temporary station	150,000	
Current meters for bottom-anchored moorings	450,000	
Total Permanent Equipment		1,162,500
Miscellaneous Supplies		
Data-processing analysis and publication (Will extend beyond two-year field program)	250,000	
Total Miscellaneous and Data Processing		350,000
TOTAL		$2,227,500

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BIOLOGY AND BIOCHEMISTRY

1. BACKGROUND

The opportunities offered by the Nansen Drift Station (NDS) are rare, so it is desirable that a broad biological research program be realized. The drift track crosses an area that has received little study in any discipline and none in biological oceanography.

Although there has been biological work in the open water of the Barents and Norwegian Seas, usually related to fisheries, there is little understanding of the marine ecosystem of the Eurasian Basin. For several reasons, American and Canadian work in the Arctic Ocean has been concentrated on the Canada Basin. Long time-series have been obtained from the drift of the manned ice floe stations and Fletcher's Ice Island (T-3), and models have been developed on nutrient and photosynthetic effects from observations along the margin of the Beaufort Sea (English, 1961; Hopkins, 1969a). The transfer of this knowledge to the different conditions represented by the ice dynamics, the proximity of the large Eurasian shelf, and the intrusions of Atlantic water can be expected to produce important contributions to oceanic biology.

The Eurasian Basin has several advantages and features of special interest to the biological oceanographer:

1.1. In terms of the Atlantic water layer, it is upstream to the Amerasian Basin, or Canada Basin, so that effects measured in the latter Basin will be better understood by measurements in the Eurasian Basin.

1.2. It will be possible to estimate the suggestions by Soviets of the import into the Arctic Ocean of "biogenic" materials from oceans to the south.

1.3. It will be possible to increase our knowledge of the Arctic Ocean as a whole in a condition approaching the "before pollution" ideal or at least to measure the extent to which pollutants have entered the Arctic.

1.4. It offers the possibility of settling the question of the extent of plankton exchange between the Atlantic and Arctic Oceans.

1.5. There is little work published on the flora and associated fauna in and on ice in the Eurasian Basin.

1.6. It will be the first real opportunity to study, over a large area and extended time, the ecosystem dynamics of the least productive ocean in the world and one that offers a fairly simple system for study--at least the simplest available. The NDS offers an opportunity to attack the controversial question of the relation between environmental stability (deep arctic water), productivity, and ecosystem diversity.

1.7. It will allow us to study the very low light fluxes under the permanent polar ice as they affect (a) primary production, (b) the distribution and behavior of various components of the biota in the water column during the annual light cycle, (c) the chemical constituents in the water column as mediated by biological processes, and (d) the biomass and diversity of the benthos.

1.8. Biological phenomena, such as seasonal and diurnal vertical migration or reorientation of planktonic organisms within and beneath the sea ice, should be investigated in space and time series correlated with electric field and ULF, ELF, and VLF wave phenomena (see Chapter 6. Section 3.1.4 and Chapter 14, Section 3.1.6). The availability of portable sensitive (to about 10 microvolts, response time of 1 second) electric-field meters recommends such measurements in relation to specific biological communities and habitats for the purpose of evaluating the degree of influence of electric fields on organisms. The Arctic Ocean environment provides an extensive area of uniform surface materials, minimal ionized particles (e.g., $SO_{\underline{x}}$) in the atmosphere, and maximal exposure to magnetic storm phenomena (including ionizing radiation). Relations of electric-field strengths and fluxes to navigation of birds, marine mammals, and fish deserve investigation, as remote as the connection may seem at present writing. At a detailed scale, the changing electric fields should be investigated in relation to migrations of mineral ions and minute organisms within the water films of the ice pack and the responses of these organisms to the electric potential generated by the freezing process. Additionally, microbiologists should look for magnetotropisms and magnetotaxis in microorganisms and lesser invertebrates, since the demonstration of magnetotactic bacteria (Blackmore, 1975).

Selectivity in the program elements is necessitated by space and financial considerations, so the proposed program includes work best suited to the unique nature of the platform and excludes work that can be done equally well from other types of stations. The biological program is designed to explore the essential features of the marine biosphere and relate them to the total environment of the Arctic.

2. PURPOSE

The research problems of interest to biologists on the NDS focus on contributing to our understanding of the marine ecosystem of the Eurasian Basin.

The proposed biological work is important because it will be in an unknown area of the ocean, and the interpretation of the biological observations will be facilitated and enhanced by the wide range of physical and chemical measurements of the environment provided by others.

The biological and environmental results can be used to describe relatively undisturbed conditions in the least productive ecosystem in the world ocean. The biological baselines drawn from the drift can document present levels of pollutants and the status of rare and endangered species. The increased understanding of special populations, communities, feeding relationships, and environmental controls and interactions will broaden the knowledge base for comparative studies of ocean ecosystems.

The biological results are inseparably related to the work of other disciplines that will measure aspects of the environment such as insolation, submarine radiation, ice thickness and ice cover, ocean currents and water masses, water chemistry, suspended materials, bottom sediments, and marine acoustics. The biological results from the drift are relevant to the International Decade of Ocean Exploration, Earthwatch, the Outer Continental Shelf Energy Program of the Bureau of Land Management and the National Oceanic and Atmospheric Administration, and programs within the Office of Polar Programs of the National Science Foundation and other federal agencies.

3. OBSERVATIONAL PROGRAM

A variety of observational programs should be undertaken as part of a broad biological investigation during the course of the NDS project.

3.1. Specific Observations

The several observational programs can be presented as questions to be answered.

3.1.1. What are the distributions and abundance of plants and animals in the water column: What are the most abundant organisms, and what are their life cycles? What are the relations between the organisms of the three main water layers? A study of the macrozooplankton of the Canada Basin (Dunbar and Harding, 1968) showed, for instance, that there were very few species that were confined to the Atlantic layer and that the deep water contained its own fauna fairly rich in endemic species (see also Hopkins, 1969b). It is important to know the extent of faunal exchange between the layers in the Eurasian Basin, the extent of the vertical migrations, and their breed cycles. It is not clear, for example, to what extent the life cycles are environmentally controlled in the upper waters and the nature of the cycles in the highly stable and perpetually dark environment of the deep water (Yingst, 1974; Kobayashi, 1974).

3.1.2. What sound-scattering layers of biological origin exist, and what organisms cause them? What species provide individual acoustic targets? Some pioneer work has been done on this matter in the Canada Basin from T-3 (Hansen and Dunbar, 1970), but there seems to be nothing in the literature on scattering layers in the Eurasian Basin. Considering the different structure of the two basins, the scattering layers in the latter Basin may be very different. The scatterers in the Beaufort Sea were found to be concentrated roughly at the top and the bottom of the Pacific water intrusion, which is lacking in the Eurasian Basin. On the other hand, it is possible that the density pattern there may be such as to cause biological concentrations equally marked but at different depths.

3.1.3. What is the pattern and magnitude of primary productivity by photosynthesis in the water column? What is the range of production/biomass ratios in the Arctic layer? Primary production measurements throughout the drift will be required to answer this question with light measurements adequate for this purpose; also, the routine measurement of nutrients (phosphate, nitrate, silicate, ammonia). The carbon dioxide cycle should be monitored and also zooplankton biomass and dissolved and particulate organic matter (see Kinney *et al.*, 1971). Is the model of light-limited primary production developed for the Canada Basin adequate to describe events *in the Eurasian Basin?*

3.1.4. What are the relations between the communities in the water column and those associated with the ice? What are the patterns of vertical and horizontal distribution of the in-ice flora in the NDS region, and how do they compare with what is known of the Canada Basin? We have little information on ice biota from this region. The work of Hoshiai (in press) in the Antarctic has shown markedly uneven distribution of the diatoms both vertically and horizontally. As for the normal plankton in the water beneath the ice, there are many problems to be settled concerning the interplay between the two floras, which present interesting general ecological aspects and for which solutions require information both from nearshore and oceanic regions (Clasby *et al.*, 1973; Alexander *et al.*, 1974). When seawater freezes, there begins a separation of the ice system from the water system; when ice melts, the two systems fuse. The details of these interesting events are unknown. Another question to be answered is that of the part played by the in-ice primary production in the total production of the Arctic Ocean. There is also the possibility that biological particles, both in the ice and over open water, act as ice nuclei in the air; air over blowing snow, for instance, should be sampled for this purpose. Finally, efforts should be made to determine whether ice flora, in the lower levels of the ice, have any acoustic effect; intense diatom growth may have a dampening effect on sound echoing. And sonar methods of measuring the growth intensity might be tried.

3.1.5. How do the nutrients cycle? What is the nutrient content of the Atlantic layer and how does it affect nutrient levels in the upper (arctic water) layer, if at all? Nutrient profiles from the Eurasian Basin would be most useful for comparison with the profiles in the other Basin and toward a greater understanding of the relation between the arctic and Atlantic layers and the formation of the mixed layer. There seems little doubt that the density structure of the Arctic Ocean is not the primary cause of its low productivity; but it is also clear that the arctic layer must itself be formed by the modification and upward movement of the Atlantic water.

3.1.6. What are the range and variation of microbial biomass and activity in the water column and along the time line, and to what extent are the bacteria cryophilic? This is a basic microbiological study and will involve the measurement of ATP and of particulate and dissolved carbon; the NDS offers a unique opportunity for this study. The same measurements should be made at higher trophic levels, in order to model the energy flow through the whole system. The study also relates the benthos to the water column as a whole, and it relates to the process of sedimentation. The study of the decomposer phase should include the marine fungi, which may be the first invaders into dead tissues and cells.

3.1.7. What is the composition of the benthos? How diverse is it? What is its degree of endemicity? The benthos is not at all well known in the Arctic Ocean, very largely for lack of the sort of platform proposed in the present program. The benthos should be sampled both with box-core samplers and with hyperbenthic sledges (there will undoubtedly be times when the relative speeds of ice and seafloor are different enough for the use of such gear). The objectives here are manifold: How recent is the benthic arctic fauna? Has partitioning of the depth developed, and to what extent? How does the fauna relate to the past climate?

3.1.8. In general, what can the Arctic Ocean system teach us of the relations between environmental predictability, ecosystem stability, diversity, and production? It would be difficult to find a more predictable environment than the deep arctic water, but its fauna is not likely to be very diverse; the opposite of what is found in warmer parts of the world. The deep arctic water may well be a very old environment, and yet its diversity is probably low; again, the reverse of what other parts of the world suggest. Production is undoubtedly low, a condition associated elsewhere with high diversity; again the reverse of the arctic situation. A study of these properties in the Arctic Ocean, therefore, in the detail made possible by the NDS program, is likely to contribute important additions to general ecological theory.

3.1.9. How does the Arctic Ocean compare with other oceans in terms of marine chemistry in general? Biologists are greatly concerned with chemical oceanography, and there is a clear need, within the NDS program, for a professional chemical input that the biologists themselves are not in a position to provide. The Eurasian Basin is virtually unknown chemically. With the exception of the unreleased Russian chemical data that may exist, even common chemical variables such as dissolved oxygen are unknown. Only sparse data along the fringes of the Basin, gathered by U.S. icebreakers, are available; the deepest penetration being the recent *Southwind* track to 83° north of Franz Josef Land. Reasonable but fragmentary coverage exists on the southern shelves (Barents, Kara Seas, etc.) but very little in the region of the shelf break or the submarine canyons indenting the shelf. Chemical techniques are now powerful tools for the solution of problems in physical oceanography, marine biology, climate, and man's perturbation of large-scale phenomena, and good sets of chemical measurements must be made in this large unknown area. Chemical tracers are useful in many contexts, including mixing processes, the identification of water masses, the flushing of deep basins, and the influence of large rivers.

The measurement of nutrients has already been discussed. In addition to these, and the CO_2 system, frequent measurement of special elements, including selected radiochemicals (tritium, ^{14}C, radon, ^{32}Si, for example, and trace metals will add considerably to the usefulness of the data. Good spatial distribution of stations is essential, especially covering interesting mixing areas.

3.1.10. How patchy is the distribution of the plankton? Is it possible that there are separate plankton stocks, in the same sense as there are separate stocks of fish species? Early work on the patchy distribution of plankton was done in the Antarctic, but we lack similar work in the oligotrophic Arctic Ocean.

We should observe plankton populations in water films of sea ice in relation to mineral ion migration and electric field changes, especially during episodes of especially active freezing.

3.1.11. Finally, sounds produced by sea mammals should be monitored. These are of considerable intrinsic interest and have an obvious bearing on acoustic studies in the sea in general.

4. LOGISTICS

4.1. The observations and time schedules for the various components of the biological program cannot be discussed as an integrated whole, since there is much variation in requirements. It is anticipated that there will be a need on board for six persons, of which four would require laboratory space for a large proportion of their time. Sampling can be divided into ice, water column, and benthic. For some parts of the program, as phytoplankton and ice community studies, high-frequency sampling will be necessary at times of intensive activity (biological spring and summer), with less frequent monitoring at other times; whereas for other programs, such as deeper water column and benthic assessment, frequency of sampling may be determined geographically rather than seasonally.

4.2. Hydrocasts, vertical tows, benthic sampling with sledge and box cores, and divers (for under-ice work) will be employed as needed. A hydrographic winch for Niskin bottle sampling and winch capability for trawling and coring will be required. A considerable array of instrumentation is included below as an addendum to the budget estimate. The biological program will need a hydrohut to itself and access also to a large winch on board for the deep-water and benthic work.

4.3. Schedules will be determined by individual program element requirements.

4.4. Some six investigators, each in charge of a portion of the program, will interact to fulfill the requirements of the scientific design. Each program part will have one representative involved in the field phase in addition to shorter-term visits by the senior personnel. Cooperation will be essential between the members of the biological party, so that operations requiring more than one person can be accomplished.

5. COST ESTIMATES

Salaries and Wages	1st Year
6 persons for 1 year (shipboard personnel)	$120,000
Principal Investigators' Salaries	20,000
Fringe Benefits and Overhead	100,000
	$240,000
Transportation	$ 25,000

Expendable Equipment	
7 programs @ $2000	$ 14,000
Equipment (see attached list)	
(Estimate)	150,000
Other	
Shipping and Communications	10,500
Report and Publication Cost	3,500
Contract Services	100,000
Secretarial and Engineering	20,000
	134,000

TOTAL	(Year 1)		563,000
	(Year 2)	Same as Year 1 $20,000 for Increments and Equipment	400,000
	(Year 3)	Estimate without Travel or Equipment 50% Personnel	$200,000

5.1. Equipment Requirements for Biological Program

Autoclave

Spectrophotometer

Scintillation counter

pH meter

Balance and scale

Glucrometer

Centrifuge

Drying oven

Walk-in temperature-controlled room

Corning Glass still, deionizing columns

Echo Sounders, sonic gear

Collecting equipment

- Nets
- Dredges
- Niskin bottles and rack
- Box cores

Pumping system for filtration

Diving equipment

$150,000

Other equipment, probably supplied by participating institutions:

- Microscopes
- Hyperbenthic sledges
- Attenuance meter
- Photometers
- Incubators

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10
MARINE ACOUSTICS

1. BACKGROUND

1.1. Existing Information

The two features of the polar environment that most strongly influence underwater sound are the permanent ice cover and the velocity structure in the water. Ice deformation at pressure ridges is the principal source of ambient noise. The ice modifies propagation, particularly at high frequencies, by scattering waves from the rough ice boundaries. Sound velocity is generally increasing with depth from the surface to the bottom. In sufficiently deep water, sounds are transmitted to great ranges in this sound channel by upward refraction in the water and repeated reflection from the ice canopy. The surface sound channel of the Arctic is the polar extension of the deep sound channel or SOFAR channel of the nonpolar oceans (Ewing and Worzel, 1948), but the arctic signals are often quite different in character from those observed in the deep channel, largely because of the predominance of low-frequency waves in the Arctic.

Virtually all acoustic measurements in the central Arctic Ocean have been confined to the Amerasian Basin. These measurements span nearly a 20-year period. They reveal a strong spatial and temporal variation of propagation loss, ambient noise levels, and reverberation levels, but it is only recently that experimental and theoretical investigations of under-ice propagation loss have been made to unscramble the causes of some of these variations.

A wave theoretical model of long-range propagation in deep water has been developed (Kutschale, 1969). Using this model, the normal-mode structure of explosion signals detected by geophones on the ice and hydrophones at depth has been accurately predicted.

Coincident measurements of propagation loss and ice roughness (Diachok, 1974) suggest that reliable estimates of propagation loss as a function of range can be obtained from airborne measurements of surface-ice roughness combined with computer modeling of loss. A phenomenological model of under-ice reflection loss based on the assumption that ridges may be represented as randomly distributed elliptical half-cylinders has been developed (Diachok, 1975). Predictions of the reflection loss model have been verified at small grazing angles and at frequencies above 200 Hz and to some extent below 50 Hz.

Reflection loss at a flat ice-water interface at frequencies above 10 kHz has been measured at a few angles of incidence (Langleben, 1970) and compared with theoretical computations (Mayer, 1974).

Velocities of longitudinal and shear waves in sea ice show a marked seasonal change, which are largely attributable to variations of ice temperature (Hunkins, 1960). Limited absorptivity measurements in ice have been made at frequencies above 10 kHz (Langleben, 1969).

Under-ice reverberation levels measured using omnidirectional sources have been qualitatively related to the observed "roughness" of the topside ice cover (Milne, 1964). Qualitative backscattering measurements using directional sources have shown that ridges, which are generally spatially well defined and far apart, are the primary scatterers of sound at high frequencies (Berkson *et al.*, 1973).

Absorption measurements at 10 kHz in near-freezing seawater (Greene, 1966; Garrison *et al.*, 1975) indicate that the relaxation frequency is considerably lower than that given by generally accepted absorption equations. At frequencies well below 10 kHz, an excess absorption has been found in laboratory studies to be caused by boric acid with a relaxation frequency of 1 kHz and to be affected by the carbonate concentration (Simmons and Fisher, 1975).

Reverberation levels from biological scattering layers in ice-covered waters exhibit an annual rather than a diurnal cycle (Hunkins, 1965). This character is apparently a response of the scattering organisms to the unique light conditions present in the Arctic. The layer occurs at a moderately shallow depth of between 50 and 100 m.

Ambient noise has been measured under various sea-ice and other environmental configurations. Qualitative differences between the characteristics of noise measured under pack ice in the central Arctic, fast ice in the Canadian archipelago, and ice interacting with waves and swell in the subarctic have been reported. Noise levels under pack ice have been related to wind velocity (Greene and Buck, 1964; Mellen and Marsh, 1965); noise levels under fast ice have been related to the rate of change of air temperature with time and to wind velocity (Ganton and Milne, 1965). A quantitative model of the noise spectrum resulting from thermal ice cracks has been developed (Milne, 1966). Noise levels at the Arctic Ocean-open ocean boundary have been empirically related to sea state and to the period of incident swell (Diachok and Long, 1974).

Signals from a few marine mammals indigenous to ice-covered waters have been investigated qualitatively (Ray and Watkins, 1975; Ray *et al.*, 1969; Fish and Mowbray, 1962).

The Eurasian Basin is expected to be different from the Amerasian Basin because the warm core of the Atlantic water lies relatively close to the surface and because of the Basin's proximity to a very large freshwater input and the rapid salt exclusion during freezing of exposed waters in dynamic conditions anticipated for the area. The drift will be in an area of rather rapid ice motion. Hence the ambient noise level can be expected to be markedly different from that of the less dynamic Amerasian Basin. In addition, the Eurasian Basin has significant seismic activity.

The particular advantage of the Nansen Drift Station (NDS) is that it allows collection of data in a new area from a platform that affords the opportunity to conduct experiments that would be difficult to conduct elsewhere. Much of the present data taken in the Amerasian Basin is limited to the spring and summer months when the properties and behavior of the ice are significantly different from the remainder of the year. The high degree of variability requires the acquisition of a large set of data in order to derive a suitable set of statistics. The presence of helicopters and fixed-wing aircraft associated with NDS will allow the mobility needed to make meaningful acoustic measurements over the entire year, while the complementary set of scientific observations vastly enhances the value of the acoustic data.

1.2. Gaps and Their Significance

Virtually no acoustic data exist from the Eurasian Basin. We are unable to predict acoustic propagation loss, ambient noise levels, reverberation levels, and array performance versus time and space in the Eurasian Basin. Predictability of acoustic properties is required for underwater operations in the Arctic Ocean.

Specifically the following important gaps exist at the present time:

1.2.1. There exist no concurrent measurements of propagation loss and environmental factors in the Eurasian Basin.

1.2.1. Propagation loss in the infrasonic frequency band from 2 to 10 Hz has not been measured.

1.2.3. Propagation loss to geophones in the ice has been measured only in the Amerasian Basin. The effects on loss due to geophone location near pressure ridges and leads have not been measured.

1.2.4. The under-ice reflection loss model requires validation at low frequencies, with under-ice ridge characteristics extracted from submarine sonar under-ice profiles coincident with the loss measurements.

1.2.5. A theoretical model of under-ice sound propagation that can accommodate spatial variability of sound velocity structure, ocean depth, and surface reflection loss has not yet been tested.

1.2.6. Bottom loss in ice-covered waters has not been investigated.

1.2.7. The midwater absorptivity at frequencies of the order of 1 kHz has not been accurately measured nor has it been related to the chemical composition of water masses in the field.

1.2.8. The strong bottom reverberation in the band 4 to 20 Hz commonly observed in long-range explosive propagation has not been investigated quantitatively.

1.2.9. No measurements of ambient noise exist in the Eurasian Basin; in the Amerasian Basin experiments have been carried out in connection with the AIDJEX Program to relate ambient levels to large-scale ice deformation.

1.2.10. The source levels and radiation patterns of various types of ice deformation have not been determined.

1.2.11. Acoustic signals emitted by marine mammals have not been quantitatively related to the behavior and migration patterns of marine mammals in ice-covered waters.

1.2.12. Only limited experiments on the horizontal and vertical directivity of the ambient noise field have been made.

1.2.13. The effects of anisotropy of ambient noise and signal incoherence on the array gain of large-aperture, low-frequency arrays have been measured only in limited experiments and only in the Amerasian Basin.

1.2.14. Only limited under-ice backscattering measurements from directional sources have been made.

1.2.15. Reflectivity at the flat ice-water interface needs to be measured virtually continuously with angle, for several different ice types. The seasonal variability is not known.

1.2.16. Spatial and temporal signal fluctuations and coherence have not been investigated.

1.2.17. The existence of the deep scattering layer in the Eurasian Basin is unknown, and no quantitative volume reverberation measurements have been reported for the Eurasian Basin.

1.2.18. Vertical profiles of the longitudinal and shear-wave velocity in sea ice have never been measured as a function of temper- and salinity in the ice.

1.2.19. The velocity and absorptivity of sound in the "slush layer" at the ice-water interface have never been determined.

1.2.20. No backscattering measurements from the seafloor have been made.

1.2.21. Coupling of propagation from shallow to deep water and vice versa has not been investigated quantitatively.

2. PURPOSE

2.1. What is the Problem?

In general, we are unable to predict propagation loss, ambient noise levels, reverberation levels, and array performance.

2.2. Why is It Important?

Predictability of acoustic properties is required for underwater operations in the Arctic Ocean. The operation of submarines in the Arctic requires sophisticated sonar equipment. The design of such equipment requires knowledge of the acoustic properties of the underwater medium and the boundaries.

The purpose of the proposed investigations is to measure these properties in order to understand the interrelation between acoustic properties and environmental parameters.

The use of the drift station serves two needs: (1) to investigate the acoustic conditions in the central Arctic as encountered by the drift station and (2) to provide a convenient and long-duration platform from which to investigate acoustic phenomena.

2.3. What Can We Do with the Answer?

We can develop models of under-ice acoustic properties from measurable environmental parameters, and in some cases we can infer environmental parameters from acoustic properties.

2.4. How Does the Answer Relate to Other Research Projects?

Development of fundamental models of propagation loss, signal fluctuations, under-ice reflection loss, and reverberation requires realistic models of (1) the spatial and temporal variability of temperature, salinity, currents, and internal waves in the Arctic; (2) the geometrical, statistical, and physical properties of sea ice; (3) physical properties of sediments and underlying basalt as a function of depth and location.

Models of sea ice require consideration of not only static properties of ice and water but also the effects of currents and winds on ice properties.

Predictability of average under-ice parameters, from above-ice measurements, requires answers from specialists involved in remote sensing from aircraft and satellites.

Predictability of sound velocity structure and currents requires inputs from specialists involved in modeling and hydrodynamics of water masses in the Arctic Ocean. Predictability of the absorptivity requires knowledge of the chemical composition of the various water masses.

Models of the sound velocity, density, and absorptivity versus depth in sediments and the underlying basement requires information extracted from cores and seismic reflection and refraction measurements.

Development of useful models of ambient noise requires development of a theoretical understanding of ice dynamics and ice deformation processes, their frequency of occurrence in time and space, and their corresponding ambient noise source levels. Phenomenological ambient noise models will probably be based on ice properties observable from satellites.

Predictability of the temporal and spatial variability of the frequency of occurrence and the level of bioacoustic signals requires a fundamental understanding of the migration patterns and behavior of mammals in ice-covered waters.

Development of fundamental models of volume reverberation requires knowledge of the distribution of biological scattering layers in time and space.

3. OBSERVATIONAL PROGRAMS

3.1. Specific Observations to Be Taken

The objective of the acoustic program is to collect acoustic information that (a) is peculiar to the region or (b) can be done best by the facilities that are peculiar to the ship and its drift.

The observational program is designed to provide basic acoustic data of propagation loss, signal and noise field coherence, ambient noise, reverberation, and array performance in a largely unexplored portion of the Arctic Ocean, as well as to help provide answers to fundamental problems of sound propagation in the ocean.

The observations are conveniently divided into four groups: propagation, ambient noise, reverberation, and array performance.

The experiments are summarized in Table 10.1 in order of priority.

3.1.1. Propagation

The acoustic propagation would be measured as a function of the oceanographic, bottom, and under-ice parameters, scaled appropriately to the frequency involved.

Low-frequency propagation measurements in the frequency band 2 to 1000 Hz would employ standard explosive sources *launched* from Twin Otter aircraft or at helicopter landing points along a line extending 150 km or more from the icebreaker. Listening could be done from hydrophones and geophones of the proposed seismic buoy array of the geophysics group. This array would provide listening devices up to 30 km from the icebreaker. Ice-surface laser profiles over the acoustic track would be measured from the Twin Otter or helicopter, coincident with the propagation. The measurements of propagation loss would be extended to long ranges, up to 1500 km, using Navy P-3 aircraft or other aircraft suitable for the measurements. Explosive charges would be launched coincident with laser profile measurements of the ice surface. These measurements would be extended by use of large acoustic projectors at the ship with reception at remote buoys. The icebreaker provides a unique opportunity to deploy large transducers. The frequency band would cover 10 to 200 Hz. Lower frequencies to 5 Hz would be investigated if such a source is made available. The cw measurements would be compared with propagation from shots launched near the breaker.

The low-frequency propagation experiments would be coordinated closely with investigations by the geophysical, oceanographic, and sea-ice programs. Propagation as a function of source and receiver depth, shadowing by bottom features, composition of the subbottom, surface roughness, bottom roughness, and changing thermal profiles would be investigated. Propagation loss to ocean-bottom sensors would be measured by the special ocean-bottom seismic stations of the geophysics group.

High-frequency experiments (above 1 kHz) would measure the absorption of sound in seawater. In most water, the transmission is so badly distorted at a range of 1 km that an average sound level cannot be determined. However, deep arctic water, with a large portion of the water column near the freezing point, may be sufficiently uniform to permit absorption measurements of heretofore unobtainable accuracy.

Experiments on acoustic fluctuations in the Arctic offer an opportunity to isolate and investigate oceanographic-acoustic phenomena that are not separable in experiments in other oceans. The sound speed field and its perturbations are such that ray paths can be resolved that have comparatively small sound-speed perturbations in the vicinity of their turning points. Coordination of the acoustic and oceanographic experiments will correct a shortcoming of many previous oceanographic-acoustic measurements that did not have comprehensive and simultaneous oceanographic measurements to support acoustic data.

In general, a properly designed acoustic experiment would require bottom-mounted positioning systems to measure and account for source and receiver motion, but, for some measurements, it may not be necessary to account for the anticipated slow relative motions.

The proposed experiments could be accomplished by the use of a real-time coherent processing system designed around a general-purpose mini-computer. Software for such a system is currently being developed. This approach allows the use of a wide variety of test signals that probe various characteristics of the propagation channel. Coherent processing has been used with success on fixed-system experiments in the Florida Straits and between Eleuthera and Bermuda. The channel probe signal can be so selected that many characteristics of the propagation channel can be measured simultaneously. The transmitted signal would be a linear maximal pseudo-random sequence. Each digit of the coded sequence consists of perhaps eight cycles of the carrier frequency (possibly 400 Hz). Thus, the digit and duration (20 milliseconds) determines the pulse resolution of the signal. The sequence must be sufficiently long to resolve all the pulse arrivals; that is, the number of digits in the sequence times the duration of each digit must be greater than the total spread in travel times of the multipath arrival. Such a signal will allow for the simultaneous measurements of the following channel properties:

3.1.1.1. cw Phase and transmission losses. Statistics of cw fluctuations aid in the evaluation of sonar system performances and operational analysis. Phase rate and coherent processing time can be predicted with cw data. Long-term slow fluctuations in phase are thought to be related to slow fluctuations of oceanographic phenomena such as internal tides and inertial oscillations.

3.1.1.2. The cw carrier line also can be used to measure time-varying Doppler spectra. Scattering from turbulence along the path of propagation will be responsible for the Doppler broadening of the observed spectral lines.

3.1.1.3. Broadband transmission loss and ambient noise. By using comb-filter processing, the average power of the spectral lines composing the pulse spectrum can be computed continuously. This measurement provides information on the bandwidth of fades and estimates of the broad stability of the channel for communication. The same filter computations can be used to measure ambient noise over the same bandwidth by placing teeth of the comb between the spectral lines of the signal. Thus, the signal-to-noise ratio can be computed with the same bandwidth and gain.

3.1.1.4. The pulse response of the channel can also be measured. By selecting experimental geometry, it will be possible to identify pulse arrivals and associate them with ray paths. At ranges of approximately 120 km, the spread of arrival times will be of the order of 200 to 300 milliseconds, which can easily be resolved with the proposed 20-millisecond digit. Thus, it becomes possible to observe the phase and transmission loss fluctuations of the individual paths. Path splitting can be observed. Statistics of the single-path phase and transmission loss can be compared with simultaneous measurement of the multipath fluctuations.

3.1.1.5. For some transmission channels, it is possible to resolve simultaneously both the pulse response and the Doppler broadening. This is accomplished by a scattering-function measurement. The scattering function is the intensity as a function of travel time and Doppler frequency. Scattering-function measurements are not always possible, since the particular channel may be overspread; that is, the spread in arrival times from multipath exceeds the Nyquist period of the Doppler broadening to be measured. If one has control over the experimental geometry, it is possible to avoid overspread channels. For typical arctic conditions, the scattering function could be measured out to ranges of 30 km. The scattering function would determine Doppler broadening from turbulence along an individual path. Since successive arrivals have reduced depths of penetration in the water column, it may be possible to infer turbulent velocities as a function of depth from acoustic results.

3.1.1.6. Spatial coherence would be measured by simultaneous pulse response observations at hydrophones with various horizontal and vertical separations.

3.1.1.7. Pulse response measurements from shots and any other conventional incoherent processing techniques can also be readily included.

3.1.2. Ambient Noise

Ambient noise would be measured as a function of frequency, directionality, and seasonal correlation to environmental parameters such as meteorological, ice dynamics, biological, and oceanographic observations made by others during this experiment.

Some buoys could be deployed along the track en route to the freeze-in point and could thus provide missing ambient noise data over a very large region of the Arctic Ocean. However, the principal application of these buoys would be to monitor the noise field along the drift track of the frozen-in ship, where knowledge of the environmental parameters from the other investigations greatly increases the value of the noise observations. Such buoys would be deployed in two three-buoy triangles about the ship at ranges of about 100 and 200 km.

The acoustic buoys would provide long-term measurements of ambient noise in selective third-octave bands covering the frequency band from about 3 Hz to perhaps 10 kHz. These data would be telemetered to satellites along with position data derivable from interaction with the satellite. The position accuracy requirement should be dictated by the requirements of the ice deformation program, since these buoys will also serve as elements of the large-scale strain net for that program. Buoys suitable for the acoustic task have already been developed and used in the Arctic. Somewhat similar buoys using VHF radio telemetry to the ship or internal tape recording, which have the capability of determining low-frequency noises as a function of both vertical and horizontal direction, would be highly desirable. A modification of the Arctic Data Buoy employed in the AIDJEX program may be applicable. These buoys could be incorporated in the proposed seismic array for measuring earthquake waves. The satellite communicating buoys will function automatically throughout a nominal two-year period. The buoys for measuring low-frequency directional noise will require periodic servicing by helicopter throughout the entire drift of the ship.

Source levels of ice deformation would be measured by instrumenting an active pressure ridge near the icebreaker with an array of standard Navy AN/SSQ-57 sonobuoys. Signals would be recorded aboard the icebreaker. This effort would be coordinated with the measurements of ridge dynamics by the ice physics and engineering group.

3.1.3. Boundary and Volume Reverberation

3.1.3.1. Boundary scattering. The effect of the boundaries on acoustic transmissions take several forms, each applicable to both the surface and the bottom: (a) forward reflections, where the surface is sufficiently smooth that the specular reflection is distinguishable; (b) backscattering, or reverberation, measured at the transmitter location; and (c) scattering in all directions other than that of the forward reflection and the backscattering.

Measurements are needed of the acoustic reflections from the ice that can be examined and characterized. The reflective quality may change as ice forms or melts on the under-surface. The exclusion of salt, with some brine trapped during freezing, and the early melting of such brine during thawing, add to the complexity of the under-surface.

Under ice, reverberation measurements would be made with directional projectors covering the frequency band from 1 kHz to about 80 kHz, possibly employing a parametric array for the lower frequencies. These boundary reverberation measurements would be concentrated in regions where ice morphology has been established. Observations of the under-ice topography made along the acoustic path are highly desirable. An Unmanned Arctic Research Submersible System (Francois, 1973) is available to provide these functions, as well as to collect other oceanographic data of horizontally distributed phenomena. Coincident top and bottom ice profiles might be obtained using a parametric sonar system installed on the unmanned submersible.

Low-frequency reverberation from the ice would be measured from explosive sources by a standard method (see, for example, Milne, 1964).

The measurements would be made at helicopter landing points in areas of different ice conditions and would be correlated with surface profiles measured by a laser aboard the helicopter and with measurements of under-ice topography and high-frequency backscattering coefficients from a portable side-scanning sonar (Berkson *et al.*, 1973).

The NDS provides an opportunity to make long-range, high-resolution sonar scans of the seafloor over a midocean ridge. This could be accomplished employing a three-dimensional array of hydrophones suspended from the ice near the breaker. Such an array designed for the range 1 to 4 kHz would permit steering in the vertical as well as the horizontal direction. Processing of the backscattered energy from small explosive charges (1/2 lb of TNT), a repeatable broadband sound source, or a 3.5-kHz transducer would be accomplished by beamforming with the aid of a minicomputer aboard the ship. The experiment would be repeated on a three-to-six hour interval along the entire drift of the ship. The output of each horizontal beam would be displayed on a plan position indicator giving a true horizontal distance presentation. Processing by digital computer would be done during the interval between acoustic transmissions. The calibrated equipment would quantitatively display backscattering strengths of the seafloor. The array could be employed to investigate in detail reverberation returning from a particular direction in the three-dimensional medium. The small displacements of the platform between acoustic transmissions could be exploited to increase resolution of features on the seafloor by coherently processing outputs from each transmission to form a synthetic aperture.

The array could serve experiments in two other areas:

(a) Vertical and horizontal directivity of the ambient noise field with the ship noise nulled by adaptive beamforming.

(b) Long-range backscattering from the underside of ice.

3.1.3.2. Volume Scattering. An important consideration in the design of active acoustic systems is the strength of volume reverberation of the medium in which the system operates. In ocean waters, this parameter is a function of the biological population density. The density of biological scatterers is usually very low in the Arctic during the winter. The arrival of long hours of sunlight in the summer, however, brings a plankton bloom with an accompanying increase in organisms of all sizes.

Volume reverberation measurements at frequencies from about 15 kHz would be made and coordinated with the biological program. The volume reverberation measurements would be of two types: first, a high-frequency, continuous vertical scan of the water column to provide qualitative information on the depth distribution of the biological scattering layer(s) and, second, a quantitative series of measurements that would yield volume scattering strengths at several frequencies, as a function of depth, at selected time intervals (typically, one week).

A special underwater camera should be used to photograph the scatterers. Triggered acoustically by the organism, the camera would record visual evidence of the scatter and would improve identification, particularly of the larger species, which can avoid nets used in the biological sampling program. These investigations would provide input to a biological prediction model that could provide more accurate forecasting of correlated conditions of volume reverberation than could a statistical sampling program alone.

3.1.4. Array Performance

This experiment is designed to measure the effects of anisotropy of ambient noise and signal incoherence on the array gain of large-aperture, low-frequency arrays. The icebreaker's projectors would provide a unique opportunity. The measurements could be made with a portable narrowband beamformer at a temporary ice camp at least 600 km from the ship. Array gain would be measured directly and continuously over a period of about six weeks by measuring the signal-to-noise ratios both of the beam and also on a single hydrophone in the array. Signal coherence would be measured separately, using hydrophone pairs at right angles to the wavefronts.

3.1.5. Special Project on Shallow-Water Acoustics

Presumably, the start of the drift will be over the continental shelf. During the period that the icebreaker is in this relatively shallow water, a concentrated program in shallow-water acoustics should be undertaken using helicopters. Since this is by nature a short-range project, the helicopters would be particularly valuable in this undertaking.

3.2. Instruments

The information is summarized in Table 10.1, but it is worth elaborating on the buoys and sound sources because some preliminary work should be done before the drift begins.

3.2.1. Buoys--Ambient Noise

The NIMBUS 6/SYNRAMS system is a useful technique for accomplishing this work.

It is not certain that the NIMBUS 6 will still be in orbit during the period of the NDS project, but even if it is not, the follow-on satellite, TIROS N, will be similar in its processing and data-handling capabilities.

Two items should be accomplished before the drift begins. These are (a) improvement, simplification, and modification to lower the costs of the SYNRAMS data buoy and extension of its capabilities to handle more acoustic frequencies and (b) improvement of the hydrophone suspension system to increase performance at the very low frequencies of 2 to 5 Hz.

3.2.2. Buoys--Propagation

Buoys will be needed for propagation experiments. Some of these buoys could be integrated into the proposed seismic buoy array. Others will emphasize the low-frequency band and be located at considerable distances from the ship. Propagation buoys are currently being developed. A preparatory project for the NDS should include an arctic trial of various types of these data buoys.

3.2.3. Sound Sources

Accurate energy source levels of various sizes of underwater explosive charges will have to be investigated before and perhaps during NDS project. The availability of a good cw projector system on the icebreaker will enable some of this work to be done. These measurements are especially important for the extremely low frequencies, where it may be necessary to use source-level values of underwater explosions below the first bubble pulse frequency. Preparatory development that should be conducted before the NDS project will include the design of explosive sources of various sizes to be detonated at various depths.

3.3. Frequency, Times, Schedules

Presented in Table 10.1.

3.4. Personnel Required

Presented in Table 10.1.

3.5. Data Management

Format of data will be specified.

4. REMOTE SENSING

The laser profiling system must be aboard the aircraft or helicopter used for making the acoustic transmission runs. There should be a capability aboard the helicopter for strip photography of ice. Remote sensing by existing satellites should be used if possible.

5. LOGISTICS

5.1. Movement of Staff to and from Icebreaker

The noise-measuring buoys require a two-man team for installation. Three people rotated at four-month intervals would remain on the ship to conduct the hydroacoustics experiments, including the short range Twin Otter and helicopter-supported propagation and reverberation measurements.

The high-frequency acoustic measurements should be made during a period in which uniform sound propagation conditions (negligible microstructure) exist from the surface to depths of the order of 300 m, estimated for this region to be in March and April. This work will require five people for a four-week period during the first year of the drift. The measurements should be repeated, in part, during the autumn in order to assess the property changes of the water-ice interface during the summer and their effect on the acoustic properties of the interface.

Four people are required for a two-month interval each year to conduct the experiments on fluctuations. The timing of these experiments would be coordinated with the oceanographic program. Five people for a six-week interval are required to conduct the experiments on array performance.

5.2. Needed Installations on Ship or Ice

WIND-class icebreakers are poor platforms for acoustic research, because the ship's service electric generator is "hard mounted" and diesel-driven. At least one of these must be in operation at all times. It is strongly urged that the icebreaker assigned be equipped with a gas-turbine-driven generator placed in the superstructure on sound isolation mounts. This generator would provide vital power for the ship and science program during periods when acoustic experiments are being carried out.

A derrick is required for lowering large transducers (up to 2000 kg in air), such as a large cw source and a low-frequency parametric array.

One or two laboratories are required for the special equipment for monitoring the buoys and data-processing equipment. Desk space and an electronics shop aboard the icebreaker are required.

The acoustic measurements sensitive to ship noise should be made from a camp at least one kilometer from the icebreaker. The distance is dependent on the noise level of the icebreaker. The distance should be large enough to reduce mechanical and electrical noise below the ambient level. The huts should be portable so that they can be easily moved in case of ice breakup. Two buildings are required on ice with electrical power (10-kW generator).

A total of five or six buildings are required for temporary remote camps, with a 6-kW diesel generator to power equipment at each camp.

The overall power requirements will be largely determined by the type of transducers installed aboard the icebreaker, but 15 kW appears to be sufficient.

5.3. Communications

Portable radios are required for communication between the ship and any ice station several kilometers distant. Longer-range systems are required for communications to remote camps up to 1000 km away.

5.4. Flight Support

Helicopters are required to plant recording stations on the pack away from the icebreaker, as well as to service the local hydroacoustics camp and remote camps for short-term experiments. The short-range propagation and reverberation experiments would be made by Twin Otter or helicopter. The distant camp for the experiments on fluctuations and array performance will require Twin Otter support.

5.5. Surface Transportation

A snowmobile and sled are required to provide local transportation.

5.6. Total Volume of Equipment and Items Requiring Special Handling

5.6.1. Total volume of equipment

The weight estimate is about 40,000 lb.

5.6.2. Items requiring special handling

Explosives
Acoustic projectors
Remote buoys
Acoustic measuring equipment
Computers

6. COST ESTIMATES

Budget for 2 years

Salaries (Including Overhead, Fringe Benefits, and Ice Bonus)

2 Senior Investigators (full time)	$ 180,000
2 Senior Investigators (half time)	90,000
3 Technicians on icebreaker (full time) rotated at 4-month intervals	240,000
4 persons for temporary camps, 4 months	70,000

Travel	
40 roundtrips from United States	60,000
Shipping	40,000
Equipment	
20 ambient noise buoys including development and installation	200,000
10 propagation buoys, including development and installation	175,000
Outfitting icebreaker and local camp with hydrophones, explosives, projectors, reverberation, ambient noise and propagation measuring equipment, high-frequency echo sounders, acoustic bottom reference, and computers	400,000
Equipment at temporary camps including shallow-water experiment	150,000
Unmanned underwater research submersible	250,000
Miscellaneous supplies	50,000
Data Processing	
Computer modeling and publication	300,000
Navy P-3 aircraft with laser profiling system	
8 two-week intervals	120,000
TOTAL FOR 2 YEARS	$ 2,325,000

TABLE 10.1 Summary of Experiments

Title of Experiment	Frequency	Observation	Instrument	Platforms	Personnel
1a. Low-frequency, short-range transmission (max. range: 200 km)	1/Month	Ice roughness Temperature/salinity structure Transmission loss Bottom loss Absorptivity Chemical content of water Sediment velocity and thickness Bottom cores Bottom reverberation	Laser profiler AXBT Explosive charges Buoys Ocean-bottom seismic station Hydrophones Geophones	Twin Otter or helicopter Icebreaker Local camp	3
1b. High-frequency transmission	1/day to 1/week	Under-ice profile Currents Temperature/salinity Internal waves Chemical content of water Sound levels	Transducer Hydrophones Submersible	Icebreaker Local camp	2
1c. High-frequency transmission. Several frequencies, several ranges (0.5 to 30 km)	5 weeks/year March and April September and October	Under-ice profile Temperature/salinity Currents Internal waves Chemical content of water Sound levels	Transducer Hydrophones Submersible	Local camp Icebreaker Helicopter	5
2. Ambient noise	Continuous source level of pressure ridges 2/month	Ambient noise Currents Wind Ice Deformation Occurrence of marine mammals	Buoys High-frequency listening equipment Three-dimensional array near icebreaker Hydrophones Geophones	Twin Otter Helicopter Icebreaker Local camp	3
3. Reflection loss/ reverberation (max. range: 10 km)	1/week	Ice profile Reverberation Reflectivity Ice cores Temperature/salinity profile Air temperature	Directional sonar Submersible	Icebreaker Local camp Helicopter	3

TABLE 10.1 (continued)

Title of Experiment	Frequency	Observation	Instrument	Platforms	Personne
4. Signal fluctuations	8 weeks/year	Temperature/salinity Currents Internal waves Arrival structure Coherence	Special equipment Acoustic bottom references	Twin Otter Icebreaker Local camp Remote manned camps (up to 120 km)	4
5. Long-range transmission loss (max. range: 1500 km)	4 times/year (2 week each time) and 1/day to buoys	Ice roughness Temperature/salinity structure Transmission loss cw Fluctuations	Laser profiler AXBT Explosive charges cw Source Hydrophones Buoys Ocean-bottom seismic station Geophones	Shore-based aircraft Icebreaker Local camp	3 2
6. Array performance	6 weeks	Array gain Coherence Temperature/salinity Currents Internal waves	Array Portable beamformer cw Source	Twin Otter Icebreaker Remote manned camp (600 km from icebreaker)	5
7. Volume reverberation	Continuous echo soundings Quantitative measurements 1/week	Volume reverberation Biological samples Temperature/salinity profile Echograms Photographs	Directional sonar Net Echosounder Camera	Icebreaker Local camp	2
8. Depth dependent ice properties	1/week	Density Longitudinal and shear-wave velocity and absorptivity vs depth	To be designed	Local camp	2
9. Long-range, high-resolution back-scattering from the seafloor	8 times/day	High-resolution bottom reverberation	Source Three-dimensional array Beamformer (minicomputer) Display	Icebreaker Ice	3

TABLE 10.1 (continued)

Title of Experiment	Frequency	Observation	Instrument	Platforms	Personnel
10. Low-frequency under-ice reverberation	1/month for 5 months/year	Ice profile Reverberation Temperature/salinity	Explosives Hydrophones Sidescanning sonar	Helicopter Ice	2
11. Shallow-water experiment	2 weeks	Propagation loss Ambient noise Reverberation Temperature/salinity Bottom properties Ice Roughness	Explosive charges Hydrophones Geophones Special equipment for measuring volume and surface Reverberation Laser profiler Portable seismograph	Icebreaker Remote manned camp Helicopter	4

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11

HEAT AND MASS BALANCE OF THE ICE COVER

1. BACKGROUND

Sea ice interacts thermodynamically with both the atmosphere and the underlying ocean. The high albedo of the ice cover and its insulation of the ocean from the atmosphere give rise to a climate over the polar oceans that is more characteristic of the continental ice sheets than of a marine environment. The presence or absence of sea ice in the polar oceans is clearly a primary factor in the overall heat exchange at high latitudes and thus may affect global climate.

While sea ice accounts (in areal extent) for approximately two thirds of the earth's ice cover, it is only a thin veneer that can undergo large changes in area in response to relatively small changes in thermal forcing. Because of the inherent instability of sea ice, variations in its areal extent have frequently been mentioned as a possible source of climatic change (e.g., Brooks, 1949; Ewing and Donn, 1956, 1958; Budyko, 1966, 1972; Fletcher, 1969). It is not yet clear how sensitive hemispheric circulation patterns are to the state of the polar ice pack; however, it is generally accepted that sea ice is an important component in the climatic system because it has the potential to amplify small changes in climate through a variety of positive feedback mechanisms (Kellogg, 1975). For this reason, simple treatments of sea ice have been incorporated into a number of general circulation and climate models (Bryan, 1969; Sellers, 1969, 1973; Williams *et al.*, 1974; Gates, 1975).

In the past, calculations involving the ice pack have generally assumed it to be horizontally homogeneous and several meters in thickness. The real ice pack, however, is a complex mixture of many different thicknesses of ice, all temporarily coexisting under similar thermal forcing. A typical mesoscale region in the Arctic Ocean can be expected to contain open water, young ice tens of centimeters thick, perennial ice a few meters thick, and deformed pressure ice up to tens of meters thick. As a result of thermodynamic mass changes at the top and bottom of the ice and dynamic motions that rearrange the existing ice to form leads and pressure ridges, the area covered by any particular thickness category undergoes continual change. Because many properties of sea ice (e.g., surface temperature, tensile strength, growth rate, albedo, ice salinity, desalination rate) are strongly dependent on its thickness, some knowledge of the way in which ice thickness is distributed within a particular area must be available before we can understand the behavior and effects of the ice pack on a regional scale. Of primary concern is the amount of open water and thin ice (<1 m) that not only determines mesoscale mechanical properties of the ice pack but also plays a major role in regional rates of heat exchange between atmosphere and ocean (Badgley, 1966; Maykut, in press).

While little is known regarding spatial or temporal variations in the distribution of ice thickness ($\underline{G}$) in the Arctic Ocean, there is a small amount of submarine sonar data (LeShack *et al.*, 1971; Swithinbank, 1972) from which we can infer the general form of $\underline{G}$ in the region. Unfortunately, the submarine data lack sufficient resolution for reliable estimates of $\underline{G}$ in the 0-1 m range. Aircraft and satellites can provide some information on the amount of open water and thin ice, but these data will, at best, be sporadic because of cloud cover. It is possible, however, given the velocity field of the ice and the energy fluxes at its upper and lower boundaries, to calculate changes in $\underline{G}$ using the theoretical model described by Thorndike and Maykut (1973) and Thorndike *et al.* (1975). Such calculations will be performed with AIDJEX data set to provide detailed information on $\underline{G}$ in the southern part of the Pacific Gyre. Although there are few data presently available from which to draw a firm comparison, we expect that thickness distributions in the Transpolar Drift Stream may be significantly different than in the Pacific Gyre. If, for example, the velocity field of the ice in the Transpolar Drift Stream proves to be more divergent than the flow in the central Arctic, heat exchange between the atmosphere and ocean would be correspondingly more vigorous.

During the polar summer, the regional heat and mass balance is dominated by the interaction of shortwave radiation with the ice cover. At the height of the melt season, the ice pack is composed of three radiatively different components: (i) bare ice with an albedo of 0.55-0.70; (ii) shallow melt ponds with an albedo of 0.20-0.45, which can cover up to 50 percent of the ice; and (iii) leads with an albedo of roughly 0.08. The composite albedo appears to be about 0.45 (Langleben, 1968). Relative changes in the amount of area covered by each of these three categories result in continuous changes in large-scale albedo averages throughout the summer. Theoretical calculations (Maykut and Untersteiner, 1971) indicate that an ice pack with a <u>uniform</u> summer albedo of 0.45 would melt away within a few years under present conditions. The reason for the apparent health of the arctic ice pack is that the pond-covered areas selectively absorb much of the shortwave energy and redistribute it in ways that have only a small effect on overall ice thickness.

During the summer, there is also a drastic increase in the amount of open water occurring within the ice pack--estimates of the area covered by leads range up to 10 percent in the central pack, and somewhat larger percentages can be expected near the margins of the pack. Large amounts of shortwave radiation enter the ocean through these leads, causing significant heating of the upper 20 m of the ocean; the extremely stable stratification of the upper ocean prevents rapid downward mixing of the heat, which, during the subsequent cooling cycle, retards the accretion of new ice.

The thermodynamic equilibrium state of the ice pack is extremely sensitive to the amount of heat reaching the underside of the ice from the ocean. For example, if the oceanic heat flux in the central Arctic were increased by a factor of 4, the ice pack would vanish within a few years (Maykut and Untersteiner, 1971). In the past, the oceanic heat flux was assumed to be the result of heat losses from the Atlantic layer; however, recent evidence suggests that considerable amounts of energy are also available from shortwave radiation absorbed in the ocean. The total amount of energy available from these two sources in the Pacific Gyre appears to be too large to be consistent with the observed thickness of multiyear ice in the region. It appears probable that either estimates of the heat input from the Atlantic layer are too large or that the shortwave energy is being dissipated by mechanisms that have not been carefully examined. One such possibility is that pressure ridge keels act as selective sinks for heat in the mixed layer--preliminary observations during the AIDJEX experiment indicate that large keels can have ablation rates five to eight times as large as on the bottom of undeformed ice. Heat losses from the Atlantic layer in the Eurasian Basin are much larger than in the central Arctic, but again we do not know how significant these losses are relative to absorbed shortwave radiation nor how the overall mass balance responds to these differences.

2. PURPOSE

The primary goal of this part of the program is to determine the heat and mass balance of the ice cover in the Eurasian Basin. Observations would be carried out over a range of ice thicknesses and the results combined with strain data derived from positions of the large-scale data buoy array (see Chapter 13) to make theoretical calculations of the ice thickness distribution within the region throughout the period of the drift. Predicted thickness distributions would be compared with satellite and airborne imagery when available (see Chapter 15). The large-scale response of the ice pack to applied stresses is dependent principally on the amount of open water and thin ice it contains; hence, attempts to model the dynamic behavior of the ice pack in the Eurasian Basin will require information on the lower end of the thickness distribution. Energy flux data taken at the upper surface of the ice, when combined with simple models of heat transport through the ice, can be used to predict rates of energy exchange over <u>any</u> thickness of ice. Integrating these values with the ice thickness distribution then yields regional estimates of heat exchange between the ice and atmospheric boundary layer. Improved knowledge of air-sea interaction in the region will ultimately benefit general circulation and climate models by improved methods of parameterizing the boundary layer over ice-covered seas.

An important part of the program will be to monitor mass changes at the bottom of the ice and heat conduction within the ice, allowing us to estimate the oceanic heat flux as a residual. Occasional direct measurements of the latter may also be possible (see Chapter 8). During the winter and spring, the oceanic heat flux will reflect the rate at which the Atlantic layer is losing heat; during the summer and fall, the oceanic heat flux should contain a large contribution from the absorbed shortwave radiation, and it will be necessary to use information on the thickness distribution to separate the two components. In order to estimate the total amount of heat that the mixed layer supplies to the ice, measurements of ablation on pressure ridge keels will also have to be made. Comparative data on keel ablation and ablation/accretion on the underside of undeformed ice will also provide a basis for estimating the lifetime of pressure ridges, a vital step in achieving an understanding of the total mass balance of the Arctic Basin.

The accretion and energy flux data will allow us to calculate growth rates for all thicknesses of ice, and, since the rate at which salt is initially rejected by sea ice is related to the rate at which it grows, it should then be possible to estimate salt rejection as a function of ice thickness. A few salinity measurements beneath rapidly growing young ice should be made to verify these calculations. Taking the salt rejection values and again integrating over the thickness distribution will yield the total salt input to the mixed layer. During the summer, when first-year ice loses much of its salt through flushing and large amounts of freshwater runoff enter the ocean, the situation becomes complex, and estimates of salinity changes will be extremely crude. The calculations of oceanic heat flux and salt input provide boundary conditions at the ocean surface and would be useful in interpreting results from the physical oceanography program.

The optical properties of sea ice influence not only reflected shortwave radiation but also the amount of energy transmitted to the ocean. In the spring and fall, the interaction between solar radiation and the ice cover is relatively simple, with only snow-free young ice exhibiting significantly different optical properties; in contrast, the rapidly changing amounts of snow, bare ice, melt ponds, and open water during the melt season give rise to large spatial and temporal variations in the shortwave balance. To determine the effect of these variations on the regional heat exchange, periodic surveys of albedos and extinction coefficients in all types of ice should be made throughout the summer. Melt-pond coverage and ice structure should also be monitored. It is hoped that changes in the optical properties of the ice can be related to changes in its structure caused by internal melting. Because spectral albedos and the spectral composition of light transmitted to the ocean beneath bare ice, melt ponds, and leads are significantly different, spectrophotometer data would be used to supplement the bulk radiation measurements. Such data should be particularly useful for productivity calculations in the biology and biochemistry program, where the photosynthetic organisms are sensitive to the wavelength of the available light, and in interpreting data from different wavelength bands in satellite imagery.

3. OBSERVATIONAL PROGRAM

The heat-balance studies need data on radiative, turbulent, and conductive heat fluxes. Radiative and turbulent heat fluxes in the atmosphere would be measured over a smooth floe several hundred meters from the ship as a part of the troposphere program (see Chapter 12). In addition, two portable meteorological stations, capable of unattended observations of radiation, temperature, wind speed, wind direction, and other desired data (e.g., water or ice temperatures) would be used for investigations of heat exchange over different types of ice surfaces such as melt ponds and leads. Radiation measurements would include incoming and reflected solar radiation, as well as net long-wave radiation. Turbulent heat fluxes would be determined by the bulk aerodynamic and the spectral method (see Chapter 12). The instrumentation would be transported by helicopter or sled to nearby sites and would be capable of unattended operation for one to two weeks. Data would be recorded on magnetic tape (cassette), which could be read and initially processed on the minicomputer used for the tropospheric program.

The mass balance program would monitor changes at both the upper and lower boundaries of the ice. An array of about 20 ablation/accumulation stakes would be set out near the ship on level multiyear ice. Snow depth would be measured every two to three days; during the melt season or during periods of snowfall, readings would be taken daily. Two sites would be established in undeformed ice to measure accretion/ablation on the underside of the ice: one site in 1-2 m first-year ice, the second in 3-4 m multiyear ice. At each site, three to five electric thickness gauges would be implanted in the ice and ice thickness measured at two- to three-day intervals. Snow depth or surface ablation must also be measured in conjunction with the ice thickness. Each thickness site would also have a string of approximately 20 thermocouples embedded through the ice to measure temperature gradients--temperatures would be measured at the same time as the ice thickness. If the ice salinity is known, conductive heat fluxes can then be calculated. Six simultaneous salinity profiles would be taken near each site in late fall, midwinter, and late spring to establish baseline salinity values and to define seasonal changes. Since the conductive heat flux is nearly zero during the summer, it is not critical that salinity be measured then. Two similar sites would also be established across multiyear pressure ridge keels--one should be of intermediate size (8-12 m) and the other large (15-20 m). Five to eight thickness gauges would be installed in a line perpendicular to the axis of each ridge, with a spacing that will depend on the geometry of the individual keel. Observation frequency would be on the order of once every three to four weeks; if ablation rates exceed about 30 cm/month, observations would be taken more frequently. During the summer, readings should be taken every two to three weeks.

The extremely large rates of heat loss and ice production that occur in refreezing leads give them a potential importance in the regional heat and mass balance that is out of proportion to the area they cover. Even in the Pacific Gyre, studies in refreezing leads have been infrequent, and the response to different meteorological conditions is imprecisely known. Observations of ice growth, temperature, and albedo in refreezing leads, together with other radiation and meteorological data, can be used to infer turbulent heat losses and thus give a reasonably good picture of the total heat budget. Special lead studies would be carried out by use of the portable observing system under at least three different sets of meteorological conditions that can best be classified by the average air temperature: (i) -5 to -10°C, (ii) -15 to -20°C, and (iii) below -25°C. Ice thickness, albedos, net radiation, air temperatures, wind speeds, and surface temperatures would be observed for a period of two weeks, or until the ice reaches a thickness of 60-80 cm. Some vertical temperature profiles and thickness profiles across leads of different widths would also be taken. Growth rates in young ice are crucial to the thickness distribution calculations, and these measurements would be used to verify and calibrate theoretical models of young ice growth.

Assuming that the thickness sites in undeformed ice will be relatively close to the ship, most of the above program can be carried out by one person. Initial deployment of instrumentation and thickness measurements in the pressure ridges will require the help of an additional person. For reasons of safety, a second person should be available to assist in the early stages of the thin-ice measurements. The additional help required should not total more than about five days per month depending on the location of the thickness sites, and it is expected that the necessary assistance can be recruited from personnel in the troposphere program.

During the summer, a special effort would be made to investigate the optical properties of the ice cover and the temporal changes that occur as a result of the interaction of shortwave radiation with the ice. Observations would be continued throughout the summer and would include: (i) albedos of various surface types, (ii) light transmission through the ice, (iii) vertical profiles of attenuation coefficients within the ice, (iv) brine volume profiles, (v) melt-pond coverage, (vi) ablation in selected melt ponds, (vii) under-ice melt-pond surveys, and (viii) lateral ablation of lead edges. Bulk radiation measurements would be taken with shortwave radiometers above the ice and photodiodes installed beneath and within the ice. Spectral albedos and transmission measurements would be carried out using a submersible spectrophotometer, while measurements within the ice will be made with a profiling spectrophotometer. Two people will be needed to carry out the summer heat and mass balance program.

Because calculations of large-scale totals and averages require both the buoy and environmental data as well as the use of theoretical models of ice growth and thickness distribution, regional values of mass production, heat and salt input to the ocean, and heat exchange in the atmospheric boundary layer cannot be made available in real time. It is expected that data will be processed in month-long blocks and that monthly data reports will be issued with a lag of not more than three to four months. Weather data, incident radiation fluxes, ice growth rates, albedos, and light levels beneath the ice would be made available to personnel from other interested programs.

4. REMOTE SENSING

Although most remote sensing techniques provide relatively crude thickness resolution, it is, nevertheless, desirable to have independent data with which we can periodically compare the theoretical calculations of regional ice thickness distribution. ERTS imagery, together with airborne visual and infrared photography, would provide important information on the area covered by thin ice and open water. Assuming the unavailability of submarine sonar data, the only practical way to obtain estimates on the amount and thickness of deformed ice is from laser altimeter profiles. Personnel and equipment from the heat and mass balance program would be available to provide ground-truth thickness measurements near the ship. Temperature data from the data buoys would also be useful in estimating spatial variations in growth rates within the region.

5. LOGISTICS

Approximately one month after freeze-in of the ship, a senior scientist and field observer would arrive. The senior scientist would remain for two to four weeks to lay out the experiment and assist in instrument deployment. Field personnel would be rotated every four months; a two-week overlap between arriving and departing personnel would be desirable. During the mid-May rotation, two investigators would arrive to carry out the summer program and would remain until mid-September.

The only installations needed will be a small instrument hut on the ice and shop space on the ship. All power can be obtained from batteries or a portable generator. If there are no pressure ridges or leads near the ship, short-range helicopter support will be needed about once a month during the winter and every one to two weeks during the summer. It is expected that these trips will not be more than 10 km from the ship.

6. COST ESTIMATES

6.1.	Personnel	$200,000
6.2.	Equipment	50,000
6.3.	Supplies	50,000
6.4.	Travel and shipping	20,000
6.5.	Computer services	30,000
	TOTAL FOR 2 YEARS	$350,000

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12

TROPOSPHERE

1. BACKGROUND

Transfers of energy and mass within and across the boundaries of the arctic troposphere are of particular importance to the general circulation and thermodynamics of the atmosphere, pack ice, and ocean. Indeed, the Arctic plays an important part in the global atmospheric circulation, acting as a sink for heat transferred northward from the tropics.

The Nansen Drift Station provides a special opportunity to examine, in regions of the Arctic that have been sparsely investigated, the magnitude and variability of surface transfers of heat, momentum, and water vapor and their relation to characteristics of the troposphere. Characteristics to be investigated are the structure of the planetary boundary layer (PBL), the structure of stratus clouds and fog, and the optical properties of haze layers. It will be possible to investigate *temporal variability* for periods ranging from a few hours to a season, as well as variability caused by the changing characteristics of the surface, initially young ice that then ages and deforms as the drift proceeds.

The lower boundary of the arctic troposphere, when viewed on sufficiently small scales, is exceedingly complex, as has been pointed out in Chapter 11 where the emphasis was on investigation of the effects of local features of the boundary, such as leads and r[illegible], on the heat and mass balance of the ice. In this chapter we view the average effects of the lower boundary on the troposphere, i.e., we consider the relation between the statistical characteristics of the surface, such as mean-square slope and distribution function of surface temperature, to processes in the troposphere. The two approaches are intended to be complementary.

1.1. Near-Surface Fluxes

The determination of mean surface transfers of momentum, heat, and water vapor is made easier by the existence of a layer above a homogeneous surface in which the transfers are approximately independent of height. This layer, called the atmospheric surface layer, is typically about 30 m deep. This approximation of height independence is not valid at heights that are of the same order or less than scales characterizing the surface (e.g., heights of roughness elements).

Our understanding of processes within the surface layer is adequate for many applications. Businger (1973) reviews relationships between mean vertical gradients and vertical transfers of momentum and scalar properties for steady flow over homogeneous surfaces. Wyngaard (1973) and Busch (1973) review observations of turbulence spectra and other statistics that are well represented by universal forms when the variables are suitably nondimensionalized. The flux-gradient relations, determined primarily from observations over land, have been used in the Arctic, either directly or in integrated form, to estimate surface stress and heat and mass exchange from observations in the surface layer (see e.g., Badgley, 1966). Eddy-correlation measurements of momentum fluxes have been made in the Arctic by Banke and Smith (1973). It is also possible to estimate fluxes of momentum, heat, and water vapor from measurements of spectra of velocity, temperature, and humidity in the -5/3 range (e.g., Hicks and Dyer, 1972). This approach together with the eddy correlation and flux-gradient methods is used for estimates of wind stress in AIDJEX (Paulson and Bell, 1975).

There are complications due to the lack of horizontal homogeneity of the arctic surface. Arya (1973) suggests that the stress on the ice surface due to form drag on the pressure ridges may be as large as the stress on intervening areas of smooth ice. Because measurements are usually made over relatively smooth floes, momentum fluxes determined from these measurements may be systematically smaller than an areal average. The contribution of form drag on the ridges to the total stress is being investigated during AIDJEX by S. Smith and E. Banke of the Bedford Institute of Oceanography.

There are also complications due to the presence of open leads that have surface temperatures as much as 40°C warmer than the surrounding pack ice and are estimated to have heat fluxes two orders of magnitude larger than over multiyear pack ice in winter (Badgley, 1966). Heat-transfer measurements over floes may not include the entire contributions of open leads, because heat transferred from a lead may be partially transferred through the surface layer in the vicinity of the lead. Measurements of the type proposed in the previous chapter are required to complement measurements over floes.

1.2. Planetary Boundary Layer

The planetary boundary layer (PBL) is defined as the layer adjacent to the earth's surface in which the effects of convection or friction are significant. The depth of the PBL for neutrally and unstably stratified flow is on the order of 1 km but may be much less for stable stratification.

Our general understanding of the entire PBL is less satisfactory than for the surface layer. The PBL has been subjected to scale analyses (reviewed by Tennekes, 1973). However, there is substantial disagreement in the values of the dimensionless constants that must be determined from observations, and there is uncertainty in the scale analysis itself, particularly for stratified flow. Brown (1970) has developed a secondary-flow model of the PBL based on the instability of horizontal vortices aligned parallel to the mean wind. Wyngaard *et al.* (1974) have modeled the neutral and unstably unstratified PBL by a closure scheme in which second-order turbulence moments are retained in the dynamical equations. The second-order moments are related to third-order moments with the introduction of many constants that are assumed universal but many of which are not well determined. Deardorff (1973) has modeled the PBL by a three-dimensional integration of the primitive equations on a grid with the subgrid scale effects approximated by flux-gradient relations. His results are similar to those of

Wyngaard *et al.* (1974).

There is a lack of observations for verification of the models, particularly for stably stratified flow. Perhaps the best observations taken over land are those from Wangara, Australia (Clarke, 1970). Observations of the arctic PBL were begun during AIDJEX Pilot Experiment (Brown, 1974a, 1974b) and have continued during the Main Experiment (Paulson and Bell, 1975). These observations have been primarily directed toward validating models for the determination of surface stress, from observations of the surface pressure gradients, and the height of the PBL. Observations of transfers of heat and water vapor have been of lower priority or have been entirely neglected.

One avenue of determination of surface stress is the evaluation of the momentum integral through the PBL after Brown (1974a). This method supposes that the surface stress is dependent on the boundary-layer heights as measured by an acoustic sounder, the geostrophic wind, and the surface wind. Applications of this method in AIDJEX yield stress values in good agreement with those predicted by Arya (1973), which are about twice the stress obtained over smooth ice via profile analysis. Integral measures of the PBL are desirable in the modeling process because they are measures over a horizontal distance of some 100-300 PBL heights (Shir, 1972; Taylor, 1971). The integral methods need further development and observational verification.

The Arctic has several characteristics that make it a good place for experimental investigations, both to understand the peculiarities of the arctic PBL and to improve our fundamental understanding of the physics of the PBL. The surface of the arctic ice, unlike the Antarctic and most land surfaces, has negligible mean slope, which eliminates gravity-driven mean flows (katabatic winds) as a complication of the dynamics. Diurnal variations due to solar heating are entirely absent during the polar night and are moderated by low sun angles otherwise. The Coriolis force approaches its maximum in the Arctic, and synoptic-scale disturbances are infrequent compared with those at midlatitudes.

The Arctic is a particularly good place to examine the phyics of the stably stratified PBL because of continuous stable stratification induced by radiative cooling during the polar night.

1.3. Stratus Clouds and Fog

A striking feature of the climate of the Arctic is the persistence over the polar oceans, particularly in summer, of extensive layers of stratiform cloud, which include stratus and stratocumulus clouds, and several types of fog. The structure of these clouds is related to the large-scale positive transports of heat and moisture into the Arctic Basin (Oort and Rasmussen, 1971; Newell *et al.*, 1972), to the surface exchanges of heat and water vapor, and to the optical and thermal properties of the liquid water drops or ice crystals. Since the clouds interact with the streams of solar and terrestrial radiation, they affect the thermal and dynamical structure of the PBL and the heat balance at the surface of the pack ice.

Stratus clouds in the arctic boundary layer are tenuous, with an average thickness of about 350-500 m, while surface fogs extend to approximately 150 m. Stratiform clouds in the boundary layer and within the lower troposphere frequently are observed to be laminated, or comprised of separate well-defined cloud strata (Jayaweera and Ohtake, 1973). The frequency of occurence of low clouds is highly seasonal, increasing from April to June to a broad maximum and decreasing again from October to December (Huschke, 1969; Vowinckel and Orvig, 1970).

The macrophysics of fog or a stratus layer can be examined with the aid of a suitable balance equation and appropriate boundary terms. The time rate of change of the moist entropy of an air mass can be represented by the time rate of change of the pseudo-equivalent potential temperature, θ_E, given by

$$\frac{\partial\theta_E}{\partial t} = -V_h \cdot \nabla\theta_E - w\frac{\partial\theta_E}{\partial z} - \frac{\partial}{\partial z}\overline{(w'\theta')}_E - \frac{\theta_E}{C_pT}Q_{rad}$$

Here V_h represents the horizontal wind vector, w is the vertical component of the wind, Q_{rad} is the volume rate of radiative heating, and $(w'\theta'_E)$ is the vertical turbulent flux of pseudo-equivalent potential temperature.

The radiative term Q_{rad} includes the absorption and emission of long-wave radiation and the absorption and scattering of solar radiation by the gaseous absorbers and the cloud particles. The radiative properties of midlatitude stratus clouds have been measured by Neiburger (1949) and Paltridge (1974). Only a single set of measurements of the solar radiative properties of arctic stratus clouds has appeared in the literature (Koptev and Voskresenskii, 1962), although more results will be forthcoming from the recent AIDJEX Arctic Stratus Radiation Experiments. The measurements of Koptev and Voskresenskii indicate mean absorpances of 4-7 percent in typical arctic stratus and stratocumulus clouds. For clouds with thicknesses of up to 500 m, those situated over water had an average albedo of 32-35 percent, while those over ice had a mean albedo of 60-70 percent. It has been suggested (Marshunova, 1961; Herman, 1975) that the emissivity of arctic stratus clouds may deviate from unity because of their low liquid water content and cold temperatures. This feature complicates the treatment of arctic stratus clouds in theoretical radiation calculations.

A method for calculating solar radiation in arctic stratus clouds has been prepared by Wiscombe (1975), and a simplified technique for calculating both shortwave and long-wave radiation in arctic stratus has been presented by Herman (1975). Both methods need to be tested against measurements taken in an arctic atmosphere.

Cloud liquid water contents and several other microphysical properties including drop size distributions, droplet densities, and ice crystal concentrations have been measured in arctic stratus clouds by Dergach *et al.* (1960), Koptev and Voskresenskii (1962), Jayaweera and Ohtake (1973), and Gatham and Larson (1974). These properties are summarized in Table 12.1. Combined measurements of cloud radiative properties and cloud microphysical properties have not been done in the

Arctic.

The profiles of fluxes of equivalent potential temperature $(\overline{w'\theta'_E})$ and virtual potential temperature $(\overline{w'\theta'_V})$ are not well-known quantities in arctic stratus conditions, although mean sensible heat fluxes have been inferred in a number of investigations (cf. Fletcher, 1965, p. 75). Most of the investigators quoted therein agree that the flux of water vapor is positive (upward) during the summer season but is small and of uncertain sign during the rest of the year. The sensible flux is large and negative (downward) during the late fall, winter, and early spring and becomes positive during the late spring. There is some disagreement as to the magnitude and sign of the sensible heat flux during the summer and early fall, but the results of most investigators suggest that it is upward.

Temperature profiles in the arctic boundary layer have been measured with kites and tethered balloons (Sverdrup, 1933), with radiosondes (Belmont, 1958), and with dropsondes (Poage, 1954). These data indicated that the most frequently occurring structure is a mixed layer 200-250 m in depth capped by an inversion of 2-5°C. They unfortunately did not relate the structure in the temperature profiles to the structure of stratus cloud or fog layers.

The term associated with large-scale subsidence $(w\partial\theta_E/\partial z)$ is important in some stratus cloud problems (Lilly, 1968), but its effect remains to be assessed in the Arctic. California marine stratus frequently forms in regions of intense subsidence associated with the descending branch of the tropical Hadley cell. However, mean vertical velocity fields in the Arctic are so small that even their direction appears to be in doubt, particularly during the summer season (Newell *et al.*, 1972, p. 57).

Herman (1975) treats arctic stratus as a problem in air-mass modification and suggests that stratus clouds form in continental polar air as it flows over the pack ice, with condensation being initiated by long-wave emission to space and the turbulent transfer of heat to the colder ice surface. Herman predicts that condensation should occur in the air mass in about one day and persist because of the absence of effective dissipative mechanisms. Development of a laminated cloud structure is predicted by a greenhouse mechanism, whereby the top and and bottom of the cloudy boundary layer are cooled radiatively while the interior is heated so strongly that the evaporation of cloud particles occurs and a clear interstice is generated.

The presence of a radiatively active cloud cover can substantially alter the turbulent structure of a boundary layer as demonstrated in the models of Lilly (1968) and Herman (1975). Both models suggest that the subcloud regions should be driven by a downward virtual heat flux that is roughly balanced by an upward latent heat flux. These assertions need to be compared with observations.

1.4. Haze

A puzzling and intriguing aspect of arctic climatology is the high incidence of "arctic haze," diffuse bands of tropospheric aerosols that occur northward of about 70° and at altitudes of up to 9000 m. Vertical visibility is negligibly affected by a layer of arctic haze; horizontal and slant visibility, however, may be as little as 3-8 km through such a layer (Mitchell, 1956). Although the existence of arctic haze has been recognized for more than 20 years, it has received only occasional attention.

Recent radiation measurements conducted by the Geophysical Institute of the University of Alaska (Holmgren *et al.*, 1974; Shaw, 1975; Weller *et al.*, 1975) revealed unexpectedly high values of turbidity in the arctic atmosphere, again focusing attention on arctic haze. High turbidities were measured in 1972 during the AIDJEX Pilot Study and in 1974 during the AIDJEX Lead Experiment. Numerous flights over the pack ice north and northwest of Barrow showed that much of the turbidity originated with distinct haze layers at altitudes of a few kilometers. When viewed edge-on, these layers appeared brownish-yellow in color, qualitatively similar to the more familiar urban haze layers. Occasionally the horizontal visibility through these layers was reduced to only a few kilometers. The similarities between these haze layers and Mitchell's observations of arctic haze are striking--there is little doubt that they are the same phenomenon.

The presence of haze layers over the Arctic can cause either a net heating or cooling of the earth-atmosphere system (Chylek and Coakley, 1975). The sign of the temperature change and its magnitude depend on the aerosol properties (size distribution, composition, etc.) and on the albedo of the underlying surface.

The observed haze layers may result from natural processes such as condensation of gases at low temperatures; it is also possible, however, that the arctic haze may originate from industrial sources and thus Man may cause an inadvertent change in arctic climate. The latter possibility may have serious consequences and deserves further study.

The Geophysical Institute of the University of Alaska is planning a small study in the spring of 1976, in conjunction with the University of Rhode Island, to collect samples of the arctic haze aerosols and subject them to chemical analysis. In addition, airborne radiation measurements will be made from Barrow to accumulate data on the optical density and vertical distribution of the haze. Armed with the relevant aerosol parameters, it should then be possible to calculate, by radiative transfer theory, the heating (or cooling) caused by the layers. There are also plans to perform trajectory analysis to attempt to derive the origin of the haze layers (Kellogg, *et al.*, 1975).

The study outlined above is insufficient to delineate all the important parameters bearing on the origin and method of transport of arctic haze. The NDS will provide an excellent opportunity to carry out additional observations, mostly dealing with the radiative properties of the haze layers at a higher latitude than that of Barrow, Alaska.

2. PURPOSE

Based on gaps in our knowledge and the unique opportunity provided by the NDS, the following objectives are suggested:

2.1. Determine the mean vertical transfers of momentum, heat, and water vapor in the surface layer, including their relation to the mean state of the surface and atmosphere and their variation with season, time of day, and geographic location.

2.2. Determine the vertical distribution of temperature, velocity, and humidity in the PBL and its relation to surface transfers, synoptic conditions, and season.

2.3. Determine the macrostructure of fog and low stratus clouds and its relation to surface transfers, PBL structure, the radiation field, and microphysical properties.

2.4. Determine optical properties of arctic haze and estimate the effect of haze on radiative transfer.

Achievement of the above objectives will contribute to our fundamental understanding of PBL dynamics, physics of fogs and stratus clouds, and the nature and effect of haze, as well as elucidating those features that are peculiar to the Arctic. Achievement of the objectives will also lead to improved models and parameterizations of heat, mass, and momentum transfers in the Arctic and will aid the modeling of the arctic climate, e.g., in general circulation models of the atmosphere.

The objectives are closely related to each other: achievement of objective 2.3 requires at least partial achievement of 2.1 and 2.2, and similarly, 2.2 requires 2.1. The proposed objectives also interact with several other research components of NDS. Estimates of the mean near-surface vertical fluxes of radiation and sensible and latent heat are required for the program on heat and mass balance of the ice cover and for estimating the heat balance of the upper ocean. Estimates of the wind stress on the ice are useful in evaluating the deformation of the ice. Meteorological observations are also required for logistical purposes, such as weather advisories for aircraft operations.

Achievement of the proposed objectives will substantially contribute to several national and international programs including CLIMAP, POLEX, and FGGE.

Meteorological observations from the NDS required to achieve the above objectives would provide valuable ground-truth information necessary for the interpretation of satellite observations during the First GARP Global Experiment (FGGE). The observational program during FGGE could be greatly enhanced by taking regular radiosonde observations from the NDS.

3. OBSERVATIONAL PROGRAM

3.1. Near-Surface Fluxes

Estimates of the near-surface exchanges of momentum, sensible and radiative heat, and water vapor are required in approximately hourly intervals throughout the drift. Turbulent transfers may be estimated by use of bulk exchange formulas and the spectral method (e.g., Hicks and Dyer, 1972). The incoming and reflected solar radiative flux can be meaured directly as can the net all-wave radiative flux.

Estimates of the turbulent exchanges will require measurements of mean and fluctuating components of wind speed, temperature, and humidity, together with the mean wind direction. Instruments should include cup anemometers and wind vanes, hot-film anemometers, platinum-resistance thermometers, thermistors, thermocouples, and dew-point hygrometers. Measurements should be made at a minimum of two levels, perhaps 10 and 20 m height, from a mast located on horizontally uniform ice several hundred meters from the ship. Radiometers should be nearby. Measurements at more than one elevation will provide a backup in the event of malfunctions and will give estimates of variations with height of wind speed, temperature, and humidity and fluxes of momentum, heat, and water vapor.

Instrumentation for processing, display, and recording of data will be located on the ship. Data will be transmitted from the tower via electrical cables. The system would include a minicomputer to expedite recording in digital form and to enable much of the analysis to be done in the field.

It would be desirable for several periods during the drift to have simultaneous measurements of the turbulent fluxes by the direct or eddy-correlation method. These measurements provide a calibration for the bulk aerodynamic and spectral methods.

Routine meteorological observations of atmospheric pressure, visibility, and cloud amount, type, and the height should be made as a part of the surface-layer program. These observations would be made on standard synoptic schedules and would be made available, together with other standard surface observations, to national weather services provided radio transmission can be arranged.

3.2. Planetary Boundary Layer

It is feasible to monitor the structure of the PBL continuously throughout the drift with acoustic sounders. A single sounder would give information on the thermal structure, particularly layering and heights of inversions, while a bistatic array would in addition give measurements of vertical velocity. A tristatic array would yield three-component wind vectors in addition to thermal structure. Experience during AIDJEX indicates that operation of a monostatic sounder requires very little manpower.

Pilot balloon observations would be taken twice daily or more often during special observing periods. Pressure would be measured on the ship and at three buoys located at a radius of 200 km from the ship. These pressure measurements would give an estimate of the geostrophic wind. Temperature would also be measured at the buoys. The buoys are also required for additional measurements for the ice-physics and oceanography programs.

It would be highly desirable to have PBL profiles of pressure, temperature, wind speed and direction, and humidity measured for several one-month periods during different seasons of the year. Such measurements of the mean character of the PBL are essential toward fulfilling the GARP and (POLEX) charge to model the PBL for general circulation and atmosphere-ocean interaction modeling. These profiles up to heights of 1 km could be made by one or more instrument packages suspended from a "kitoon" (tethered balloon). The NCAR Boundary Profiler has previously been used in the Arctic, and more sophisticated profilers have been used from ships during GATE. Measurements by the profiler, besides being of interest in themselves, would be a useful aid in developing an improved interpretation of data from the acoustic sounders.

Standard radiosonde observations would be extremely valuable both in support of the NDS boundary layer programs and to contribute crucial high-latitude data to the FGGE data set. (The respective personnel and funding requirements for a radiosonde station are not included below.)

3.3. Stratus Clouds and Fog

Observations of the microphysical, macrophysical, and radiative properties of fogs and low stratus clouds are required. The measurements would be made from instrument packages suspended from the "kitoon." Instrumentation would include radiometers and particle (cloud droplet and ice crystal) samplers.

It would also be desirable to have measurements by an aircraft such as the NCAR Electra, which is equipped for cloud and radiation measurements. Turbulence measurements in the PBL by such an aircraft would also be an extremely valuable supplement to the proposed PBL measurements. Because of the distance of the likely drift track of the ship from suitable airports, such flights are likely to only be possible near the end of the drift when the plane could be based on Spitsbergen.

3.4. Haze

Properties of the aerosols in the arctic haze layers can be derived from measurements of the extinction of light through the layers, made at multiple narrow-wavelength intervals in the visible part of the spectrum. In particular, an estimate of the size distribution of the aerosols can be derived from the wavelength-dependent extinction measurements. In addition, the albedo of single scattering of the aerosols can be derived from monochromatic measurements of the diffuse sky radiance, made at selected pointing direction. Knowledge of the aerosol size distribution and albedo of single scattering, along with the known value of surface albedo, provide sufficient information to calculate the effect of the haze layers on the radiation budget. These specialized radiation measurements would be made during clear, stable conditions from the NDS.

Instrumentation would consist of a multiwavelength sun photometer with a series of narrow-band interference filters to isolate specific wavelength intervals, a diffuse sky photometer, and a sky scanning photometer that provides a map of the sky radiance at specific wavelengths over the entire celestial hemisphere. The instruments and analysis are described by Shaw (1975a, 1975b). Calibration of the instruments is required in the laboratory on a monthly basis. Measurements can be successfully carried out when the elevation of the sun is greater than 5°.

4. REMOTE SENSING

4.1. Aircraft

Periodic surveys of surface elevation and surface temperature are required at different times of the year to determine the statistical characteristics of the surface. A laser profilometer and a single-beam radiation thermometer are suitable instrumentation for these measurements.

4.2. Satellite

Satellite imagery of the surface and cloud tops would be useful for the stratus cloud program. The areal coverage of cloudiness could be observed as well as the temperature of the cloud tops. The location of a satellite receiving station aboard the ship would enhance the usefulness of these data by enabling modifications of the ice-based observation program to complement the satellite observations.

5. LOGISTICS

5.1. Personnel

Four personnel would be required on a continuous basis at the station. During the one-month intensive observing periods of stratus clouds and the PBL, the number of personnel would increase to eight. These personnel would cooperate closely with those responsible for the program on heat and mass balance of the ice cover. Observations of haze would be made by one additional person during periods when the daily sun elevation exceeds 5°.

5.2. Installations

A tower for meteorological observations with a minimum height of 20 m will need to be raised several hundred meters from the ship. Laboratory space on the ship (about 40 m^2) will be required. A prefabricated hut on the ice near the tower may be required to house some of the instrumentation. Electrical cables for data and power will run from the ship to the instruments. The "kitoon" system will require a winch, either mounted on the ship or on the ice, together with suitable protection from the elements.

5.3. Power

Standard 110-V, 60-Hz power will be required with an estimated maximum load of 10 kW.

5.4. Communications

A communications link to transmit standard meteorological observations for use by the national weather services would be desirable.

Care will be required to minimize the effect of radio communications on data acquisition since many instruments malfunction during nearby radio transmissions.

6. COST ESTIMATES

The following estimates are based on a two-year drift followed by one year for completion of data analysis. The amount required for equipment may be less than the estimate, depending on the availability of existing hardware.

6.1	Personnel	$ 900,000
6.2	Equipment	400,000
6.3	Supplies	300,000
6.4	Travel and shipping	100,000
6.5	Computer services	100,000
6.6	NCAR Electra--100 hours	100,000
	TOTAL FOR 3 YEARS	$1,900,000

Table 12.1 Observations of Mean Stratiform Cloud Properties During Summer Conditions

	Liquid water ($g\ m^{-3}$)	Droplet Density(cm^{-3})	Mean Diameter (μm)
Dergach *et al.* (1960) (stratus and stratocumulus, Soviet Arctic)	0.05-0.2 (st) 0. 1-0.3 (sc)		14-20
Gathman and Larson (1974) (surface fogs, Greenland Sea)	0.10	20.7	13.6
Jayaweera and Ohtake (1973) (stratus and stratocumulus, Beaufort Sea)	0.1-0.2	90	13.5
Koptev and Voskresenskii (1962) (stratus and stratocumulus, Soviet Arctic)	0.10-0.15	18-19	9.8-14.2
Kumai (1973) (surface fogs, Barrow)	0.5	15	15.6
Weller *et al.* (1975) (stratus and stratocumulus, Beaufort Sea)	0.2	90	13.5

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13
ICE PHYSICS AND ENGINEERING

1. BACKGROUND

The Nansen Drift Station will provide a unique data-collection center for the broad scale of arctic sea ice force and deformation phenomena. Interest will range from overall regional characteristics and motions (~300 km) to the basic mechanisms that govern these characteristics (~1 km); from local forces and deformations associated with engineering structures (~20 m) to the basic properties from which these occurrences can be predicted (~20 cm); and to other space and time scales associated with a variety of applications. It will be of fundamental importance not only to make and interpret measurements at all of these scales but also to use their spatial and time coincidence to advance our understanding of overall deformation processes and our ability to predict their occurrences.

The following plan consists of three major subprograms associated with different scales of interest.

1.1. Movement, Stresses, and Distribution of Thickness in the Ice Field at Various Scales: Observations and Predictions

A study of the ice motion in the Trans-Polar Drift Stream will include observations at the scale of the overall drift, as well as measurements at smaller, local scales. As a central point for such observations, large-scale and small-scale measurements of ice movements can be made at the same time in the same region. Correlation of measurements at different scales will advance the present understanding of pack ice internal resistance and will improve the existing capability for developing predictive models. The ability to carry out these measurements throughout the drift, in which the ice changes from thin first-year ice to thick multiyear ice, will permit a comparison of the constitutive properties of these different types.

Detailed measurements of ice motions in the Trans-Polar Drift Stream for an extended period of time have yet to be carried out. Such measurements have been made by the AIDJEX program over a region of approximately 800 km in the Pacific Gyre. It will be of great value to have corresponding sets of data on these two main features of the Arctic Basin. A knowledge of pack ice rheology in these two main features will allow for more accurate modeling of the entire Arctic Basin.

In addition to simply observing the motions of the ice field, there will be great interest in improving predictive models for motions, stress states, and the distribution of thickness in various regions of the Arctic Basin. Initial models for ice motion and stress utilized a simple viscosity paramenter for pack ice constitutive behavior (Campbell, 1965). Since then, models have become more refined in response to the predictive inaccuracies of the early models. The AIDJEX program has developed the most detailed model to date. This elastoplastic model is based on local deformation phenomena and is currently being tested with measurements in the Pacific Gyre (Coon and Pritchard, 1974; Coon *et al.*, 1974). Investigators at CRREL have developed a model based on bulk and shear viscosities and have correlated this model with smaller-scale (mesoscale) deformation measurements (Hibler, 1974) in the Beaufort Sea. It will be important to apply these models to the Trans-Polar Drift Stream, both to evaluate their predictive abilities and to determine any modifications that will be required to make them more applicable. One would expect, for example, significant changes in parameters governing the response characteristics of the drift stream ice, such as differences in thickness distribution and in surface characteristics (ridge density). Modifications in the basic AIDJEX formulation might be suggested, for example, by a shift from ridging to shearing and collision as the predominant energy sinks during deformation. Such a major distinction has already been suggested by some Russian investigators (Timokhov, 1970), and this might lend credibility to a phenomenological basis for viscosity-type models.

The AIDJEX model relates strains to the distribution of thickness. The thickness distribution is important not only as a means to compute stress-strain behavior but also as the state variable that determines the heat transfer between the Arctic Ocean and the atmosphere. This is discussed in greater detail in Chapter 11.

The ability to predict large-scale ice-pack deformations rests heavily upon an understanding of the locally observable mechanisms of deformation and an understanding of how these mechanisms combine and manifest themselves in the overall deformation. For these two areas, the NDS can provide a valuable base for observations. The AIDJEX model, for example, is based on some elementary models of the stress levels and deformations associated with lead formation and pressure ridging (Parmerter and Coon, 1972). Although these models are intuitively appealing, and have yielded reasonable results, there is a need for some direct correlation with field measurements of the events in question and for further evaluation of other phenomena such as shearing, rafting, and collisions.

Prediction of the large-scale deformations from these basic deformation mechanisms constitute a broad leap in scale. Consequently, an intermediate-scale, or mesoscale, has been and should continue to be given important consideration. Mesoscale measurements have been made in the Beaufort Sea area by AIDJEX and CRREL investigators and have been qualitatively correlated to lead formation and pressure ridging activity (e.g., Hibler *et al.* 1974). Similar observations should be carried out from the NDS. A model has been developed for the direct computation of stress and strain behavior at the mesoscale level, directly from local mechanisms (Maser, 1975). This model can be used to quantify the contribution of the different deformation mechanisms to the mesoscale motion.

The value of having a stable platform from which to make these measurements cannot be overstated. The recent breakup of the AIDJEX main camp is an illustration of its logistic value.

1.2. Forces and Deformations of Engineering Interest

This area of investigation is primarily concerned with ice forces on structures or the ability of ice sheets to support structures. Consequently, the dimensional scale will be related to that of typical structures of interest.

The NDS can serve as a base for such engineering measurements. The station itself is a structure of interest, and it will be valuable to measure the force levels developed on the hull and how they relate to the deformation in the pack. These types of measurements were considered as a part of the test program associated with the *Polar Star*. Problems associated with timing and resources pre-empted the development of this measurement capability, and hence the program was not carried out. The NDS will provide an excellent opportunity to make such measurements. The duration of the drift will allow more than enough time to investigate alternative measurement systems and ultimately to implement and make continuous measurements with the optimum system.

Another area about which little is known is the influence of the stress field in the pack on the mobility of an icebreaker. It has been found that an icebreaker will become stuck fast in a field of pressured ice, but the mechanisms of this occurrence and the conditions under which it happens have not been explained. Since the drift station will constantly monitor the stress state in the pack as well as on the ship, it will be possible to identify pressure states and to conduct mobility tests and observations. It will also be possible to correlate macroscale and mesoscale strain measurements with ship forces, both from data and through analytic models.

A further area of interest relates to ice forces on fixed structures (offshore platforms, piers, etc.) and the bearing capacity of ice sheets (for aircraft landing, storage, etc.). Both of these depend on the flexural compressive strength as well as the stress-strain behavior of ice sheets. Some investigators have carried out *in situ* beam tests, while others have simply loaded the ice sheet as a whole (Weeks and Assur, 1969), both to determine flexural properties. Other investigations have sought to measure the overall compressive behavior of a sheet by jacking the ice against itself (e.g., the nutcracker test). Many of these results are complicated by changes in the ice temperature distribution resulting from the cutouts made in the ice sheet.

Some recent experiments in the area of *in situ* ice stress and stress-strain measurements have been carried out as a part of the Outer Continental Shelf Project (OCS), funded by the Bureau of Land Management and administered by NOAA. These techniques can be used in conjunction with some of the standard strength and stress-strain tests to obtain a more realistic evaluation of the strength and deformation of floating ice sheets.

1.3. Physical Properties of Sea Ice

A comprehensive description of the mechanical properties of sea ice has yet to arise out of the many investigations that have been carried out over the past 20 years (Weeks and Assur, 1969; Peyton, 1967), but the variability of conditions and testing procedures has made uniform interpretation difficult. Certain principles have been established, such as the dependence of strength and modulus on brine volume (Weeks and Assur, 1969). Other effects, such as dependence of strength on load rate and sample size have yet to be satisfactorily quantified for practical applications. Comprehensive fracture criteria and the influence of stress concentration have yet to be established.

Sea ice is a large-grained polycrystal, each crystal of which has a microstructure of cylindrical holes (brine pockets) and each of which deforms elastically, and viscoplastically along the basal plane. Much of the testing to date, however, has borrowed techniques from other areas that did not take these unique sea ice features into account, and consequently many results have been inconsistent and misleading. Some recent studies have been carried out to explain the load rate (Paige and Kennedy, 1967; Maser, 1972), polycrystalline (Maser, 1972), and brine pocket (Haynes and Nevel, 1975) effects on small sample test procedures. These studies have suggested rejecting certain types of tests and increasing sample sizes.

One other severe obstacle in testing sea ice properties has been difficulty in sample handling. A sample undergoes temperature fluctuation and brine drainage when transported from field to laboratory, and this may produce misleading results. The alternative has been to grow samples in the laboratory. This, however, cannot fully recreate the unique conditions of ice growth on the open water.

Other significant gaps in our existing state of knowledge include the properties and mechanisms by which the salt content varies with time (desalination) and the radiative properties of sea ice in the microwave part of the spectrum. It has been suggested that the unexpected radiative differences in sea ice are related to the age of the ice (Gloersen *et al.*, 1973), which would correlate with physical factors such as salt content and crystal structure.

The NDS will be ideal for an ice testing laboratory for the studies suggested above. Sample transportation and handling will be minimized. This will improve the realism of test results and will allow for many more samples to be tested in the same amount of time. Samples can be taken nearby the ship from different floes of different thickness and age. Since the ship will basically follow the ice for two years, desalination studies can investigate ice throughout its growth cycle, with a complete description of its environmental history available for reference.

2. PURPOSE

2.1. Movement, Stresses, and Distribution of Thickness in the Ice Field at Various Scales: Observations and Predictions

Interest in the measurement and prediction of ice movements, thicknesses, and stress levels throughout the Arctic Basin comes from a variety of sources, some of which are discussed below.

2.1.1. Climatology and Weather Forecasting

The Polar subprogram of GARP represents an extensive and comprehensive effort to investigate high latitude contributions to the global climate systems. Specifically, the extent and thickness distribution of the ice pack will define the heat balance between the ocean and the atmosphere. A program has been outlined to investigate and predict the energy exchange through any thickness of ice (See Chapter 11). The presence of open water will, of course, result in a sharp increase of energy exchange. The ability to predict the thickness distribution and extent of the ice pack through ice dynamic modeling will enable this information to be used to determine the total energy flux throughout the Arctic Basin.

2.~~1.2~~. Navigation

Navigation and transportation in arctic regions is an area that will be advanced by an ability to predict the stress state, thickness distribution, and percent of open water throughout the Arctic Basin. The Fleet Weather Facility currently provides an ice forecasting service for navigational purposes based on simple wind-driven models. Resource development in the Arctic will, no doubt, see an increase in navigational requirements through the Arctic Basin, including tankers, ore carriers, LNG ships, and submarine tankers. This need must be met by an improved ability to predict navigable paths for surface vessels. Icebreakers will seek routings through areas of unpressured ice and areas where there is a high percentage of thin ice and open water. Submarine transport, as well, will be interested in traveling through regions where a high percentage of thin ice and open water will facilitate surfacing. Air travel will benefit from knowing where minimal pressure ridging and a high percentage of refrozen leads will enhance the chances of finding natural runways. All of these navigational needs will be served by the program that is outlined in the following sections.

2.1.3. Underwater Acoustics

Background noise levels under the ice are related to the type of deformations taking place in the ice itself. It should be possible to associate unique spectra with convergent, divergent, and shearing deformation fields, corresponding to the predominant local deformation modes. It will then be possible to predict the expected background noise spectrum in any given region under the cap, given the predicted state of deformation.

2.2. Forces and Deformation of Engineering Interest

The engineering applications of these investigations are easily identified. Navigability of icebreakers through heavy arctic pack ice is still an area where more needs to be learned. Results from a systematic study of ice breaker forces and icebreaker mobility can influence icebreaker design, and the ability to predict these forces from gross pack behavior will serve to develop guidelines for routing ships through the pack.

Bearing strength studies, in addition to the applications already mentioned, can be used to determine the surfaceability of submarines in thin, refrozen leads. Flexural and compressive strength data can be used to predict ice forces on fixed engineering structures.

2.3. Physical Properties of Sea Ice

An understanding of the physical properties of ice and an ability to make quantitative estimates are important in a number of areas. These include design of instrumentation that is to be supported by or within the ice cover and the modeling and prediction of ice forces on fixed offshore structures. The growth and continuation of investigations and engineering efforts on the ice cover will continually demand an increased understanding of the physical properties of sea ice.

These investigations should also be oriented toward standardization of ice strength measurements. A meaningful standardization would enable comparisons to be made from different sets of data and would help to provide a sound basis for design against ice forces.

Microwave imagery shows every indication of becoming a powerful tool in surveying existing sheets of ice and their changes in time. The establishment of a firm connection between ice radiative properties and age-related physical properties, such as salt content, will greatly enhance the usefulness of this method.

3. OBSERVATIONAL PROGRAMS

The previous section has described a number of important research areas that will be supported and advanced by observational programs from the NDS. These observations, in most cases, are for developing and improving various types of predictions. Since past experience has shown that data collection alone does not advance the state of the art, we propose to include a modeling and data-analysis effort with each proposed data-gathering effort.

3.1. Movement, Stresses, and Thickness Distribution in the Ice Field

Macroscale ice motion will be measured for general observation, for stress prediction, and for thickness distribution prediction. It is believed that an array of buoys surrounding the drifting station in a ring approximately 100 to 200 km in radius would be sufficient for these purposes. These buoys would need to measure position only. The actual buoys, however, can be made to fit in with other data requirements. The basic array would consist of six data buoys at a radius of 200 km and three data buoys at a radius of 100 km. This will provide nine independent strain measurements, plus a number of redundancies that will permit an evaluation of the continuity of the strain field. The measured strain distribution will be used for computing the stress field and thickness distributions around the ship. The experience in the AIDJEX buoy program would indicate that distortion of the buoy array will require that replacement buoys be used periodically to upgrade the array.

Data buoys (*AIDJEX Bulletin* No. 22, 1973) such as those being used in AIDJEX and NOAA-OCS would provide sufficient positioning accuracy for the strain calculations. It now seems that after proper filtering of the data (Thorndike, 1973, 1974), accuracy of the RAMS buoys positioning is 1 km. These filtering and strain-measuring techniques are being developed by the AIDJEX Modeling Group.

The RAMS buoys being used in the AIDJEX ring have, in addition to RAMS positioning, the measurement of barometric pressure and air temperature, and they are equipped with hydrophones. There are two types of RAMS buoys being used in the AIDJEX/NOAA-OCS program. The first of these are marker buoys having only RAMS position-measurement capabilities. However, they can be deployed by dropping from a low-flying aircraft (fixed-wing or helicopter). The other type of buoy being used in this program will measure, in addition to position, air temperature and pressure, and can be equipped with ocean current meters at several depths below the ice. It would seem that some combination of these buoys would satisfy all the requirements for the NDS buoy program. It any event, it appears that the buoy requirements for these strain measurements are minimal by comparison with those for oceanographic and acoustics work, and, therefore, they should be fit into any of the other buoy programs as necessary.

The buoy data will be supported by satellite imagery. Such imagery although available only when satellite trajectory and weather are permitting, can be used to check strain measurements and thickness distribution calculations and hence will be a valuable reference during this program.

Measurements of ice motion on a scale of 5 to 50 km will be made to correlate with and provide a coherent link between macroscale and microscale occurrences. These measurements will be made using a radar transponder system. CRREL investigators have recently purchased such a system and will be using it for measuring nearshore deformation this spring near Prudhoe Bay as part of the Arctic Offshore Program. In addition to strain measurements, interest also exists in monitoring ridge characteristics as a function of time in order to determine, in more detail than presently available, their relationship to deformation on a larger scale.

The basic measuring system consists of an array of remote transponders at a maximum distance of 50 km from the ship, arranged approximately in concentric circles. Two master transponders (connected by a microwave link that obviates wire connection) on a baseline 2 to 5 km in length near the ship will automatically measure distance from the remote devices at regular time intervals. The baseline distance is also measured periodically so that leads through the baseline cause no problem. One of the baseline transponders should be located near the ship to facilitate cable connection (which requires only simple telephone wire). The system is automatically activated with an external digital clock input. Distances are measured (in all weather conditions) with 0.1-m resolution, which, with the proposed baseline, yields an angular resolution of better than ±1 minute of arc. The transponder system is a line-of-sight system, and the actual size of the array depends somewhat on the CRREL experience with various towers and their ease of erection this spring. It is anticipated that 30-m towers will be feasible, allowing up to 50-km distance measurements.

The azimuth of the baseline will be measured periodically by theodolite or, in bad weather, by using a portable remote transponder at two different locations on the ship. Consequently, the ice vorticity data will not be on as dense a temporal scale as the strain-rate data. The data from the array will yield accurate least-squares strain rates on a temporally dense scale (∿3-hour intervals) useful for inputs to drift and deformation models and to ice thickness distribution models. It will also be adequate to examine in detail oscillations in the ice deformation at higher frequencies, such as previously observed at 12-hour wavelengths (Hibler *et al.*, 1974).

With regard to manpower and logistic support, helicopter support will be required for the initial setup of the remote transponder towers and for battery exchange approximately every month. Finding the remote transponder in poor visibility conditions (such as in winter) is facilitated by an extra portable master transponder carried in the helicopter, which gives a continuous distance to the desired remote transponder. Normal manpower would be one person to monitor the system operation and to change batteries. In addition to batteries, each remote system uses a small propane fuel cell, which also requires new propane approximately every month. Initial setup requires about three persons for a short period of time.

Periodic laser profilometry and aerial photography would be required for monitoring lead formation, ridging, and ridge characteristics and statistics and correlating them with the deformation results. Assuming that a laser profiler system is available, implementation of this portion of the program would require fixed-wing aircraft support on an occasional basis (say, every two months).

A local (microscale) measurement program will be directed toward making quantitative measurements of important local deformation phenomena that occur in the pack in the neighborhood of the ship. These phenomena include lead formation, pressure ridging, shearing, and floe collisions. Mesoscale strain measurements will indicate when a particular type of event is likely to occur, and helicopter reconnaissance and shipboard radar will locate the particular features.

A typical observational program of this type will be a pressure-ridge experiment. Pressure ridges can be located at their beginning by observing refrozen leads during a period when a compressive stress state develops in the pack. A particular lead will be identified and surveying equipment and targets placed on either side for distance measurement. Stress transducers will be placed in the ice on the flank of the lead. The nature of the transducer will depend on the time variation of the forces developed in the lead. Flatjack-type devices, similar to those used for *in situ* rock stress, can be used in some cases, while more complex devices, such as those developed by Imperial Oil (Croasdale, 1975), may be required in others. A measurement program of this type is now taking place as part of the Outer Continental Shelf (OCS) project off the coast of Alaska. Some more portable, lightweight stress transducers have been developed as part of this effort, and these can be considered as an alternative to those just mentioned. Coring equipment for obtaining vertical profile information as the ridge develops will also be desirable.

While the ridge develops, the ridging forces will be continuously monitored with the stress transducer, and the relative displacement of the flanks will be recorded using surveying equipment.

The above description is representative of the type of program that is proposed for shearing, shear ridging, floe collisions, and rafting. These are all local phenomena that govern the dynamics of the pack. An understanding of these features will improve stress and thickness distribution predictions at a larger scale.

3.1.1. Modeling and Data Analysis

Models have been developed for the stress-deformation behavior of ice at various scales. Most of these have been tested with limited field data, if any at all. The program described above will seek to use available models to interpret the data that are obtained and will use those data to improve the accuracy of the models themselves.

The AIDJEX model (Coon and Pritchard, 1974) will use the measured strain field around the ship to compute the thickness distribution. This computed thickness distribution can be compared with satellite imagery. It can also be compared to thickness profile measurements made remotely by helicopter.

The AIDJEX constitutive model, as well as that of Hibler (1974), will be used to compute stress in the pack. Attempts can be made to define shear and bulk viscosities in the Hibler model at this scale and perhaps as a function of thickness distribution. Stress computations will ultimately be compared with stress transducer measurements around the ship. The mesoscale model developed by Maser (1975) will use the transponder displacements as boundary conditions. With aerial photography of the region to define the ice geometry, this model will compute stress around the ship, as well as the occurrence of lead formation, pressure ridging, shearing, and other local events. It will also compute mean stresses in the mesoscale region, and these will be compared with those computed at the macroscale.

At the microscale, the AIDJEX model can be checked with a lead experiment. The stress-displacement information can be compared directly to the model predictions. Corings can be used to measure the sail and keel heights versus time, as well as the density of solid material in both sail and keel. Comparison of corings to model predictions will give insight into possible modification of the parameters used in the model or in the model itself.

Acoustic measurements should be carried out in conjunction with the measurement of local deformation mechanisms. These will be the primary source for background noise, and hence a direct correlation of noise spectra to particular events will be extremely valuable in underwater acoustics work. These measurements will be carried out as a part of the marine acoustics program.

3.2. Forces and Deformations of Engineering Interest

3.2.1. Measurement of the Pack Stress on the Ship

It will be important to measure the pack stress at, or immediately surrounding, the ship. On one hand, the ship can act as a large transducer to measure local pack stress and compare with that being predicted by mesoscale and microscale modeling. On the other hand, it is important, from a navigational point of view, to determine how the ship responds to different states of stress in the surrounding pack.

One approach, originally considered for the *Polar Star*, is to instrument structural elements of the ship's frame. Two problems were encountered with the *Polar Star*: the structure was very stiff relative to the pack force level, hence significant measurements would be difficult; and access to the main structural elements was difficult (Buxton, 1975). The icebreaker to be used as the NDS will be a WIND-class icebreaker and, hence, will have a more flexible structure with a higher probability of instrumentation.

Another alternative is to instrument the hull. It is clear that ship instrumentation would have to be investigated further. However, the duration of the drift will permit the evaluation of alternative schemes.

A stress-transducer array immediately surrounding the ship will be valuable, both to calibrate the ship instrumentation and to act as an alternative should ship instrumentation be unsuccessful. Such transducers have been developed and could be easily implemented.

3.2.2. Influence of Pack Stress on Ship Mobility

The influence of ice pressure on icebreaker mobility is not well understood. This program would attempt to investigate the mobility of the icebreaker in various stress states.

The testing assumes that the icebreaker will be mobile. This may not be the case for most of the duration of the drift. However, advantage may be taken during periods following divergence, such as spring breakup, when the icebreaker can move into thinner lead ice. With the development of a compressive component in the pack, the icebreaker can proceed through the ice at different angles to the maximum compressive stress. Velocity versus horsepower measurements will quantify the ease of mobility. Visual observation of the wake, both from the ship as well as by helicopter surveillance, will help to clarify how the wake closes behind the ship in pressured ice.

It will be understandably difficult to make many such measurements. The movement of the icebreaker will be disruptive to the many research programs that are being conducted, particularly in the immediate neighborhood of the ship. However, there will be periods, such as spring breakup, where instability in the ice will force most programs back to the ship. There may be other occasions, such as correction of drift course, when the icebreaker will attempt to travel under power. Since these measurements are quite important to icebreaker navigation, it would be desirable to utilize those periods, plus the incoming data concerning pack and ship stress, to conduct the mobility tests described above.

3.2.3. *In Situ* Beam, Compression, and Bearing Tests

Information regarding ice forces on engineering structures can be obtained by conducting *in situ* beam, compression, and bearing tests. The uniqueness of these measurements here will be the direct correlation of these results with the small sample test results (described in the next section). This will improve predictive capabilities for ice forces.

3.3. Physical Properties of Sea Ice

A systematic study of strength and rheological properties of sea ice can be carried out in a testing facility on board the drift station. Other properties, such as electrical and thermal properties of ice of different brine volumes, will be important to investigate as well.

Studies of strength versus sample size will be important for future standardization of ice sample sizes. Studies of strength measured by different test (e.g., tensile strength through beam bending, Brazil, and uniaxial tests) should be made to develop consistent correlation between these results and to suggest a test method that will become standard for future field investigations. Study of the time-dependent properties will help to improve the *in situ* stress-measuring equipment, particularly that which is being used in other parts of the ice physics program. Other measurements will include correlation of salt content to age of the ice and to its radiative properties and thermal and electrical properties of sea ice.

Test facilities should include a coldroom for sample storage, a universal testing machine, and ice coring and cutting equipment. It has been found that tests are carried out more easily if the testing machine is in a warm room and the sample itself is enclosed in a refrigerated box. Refrigerated sample containers would also have to be supplied. Special sample preparation equipment, such as a lathe for tensile samples, should also be supplied.

It is envisaged that small sample investigations will be carried out over a period lasting one to three months by different groups, and that an overall coordination effort will review proposed research programs so that redundant data are not taken.

3.3.1. Modeling and Data Analysis

Some analyses have been carried out to model phenomena that take place in small samples (Maser, 1972; Haynes and Nevel, 1975). Other work, including the influence of time-dependent and time-independent plastic flow on results for beam, Brazil and other tests and the influence of sample size in general, should precede and accompany each test program. This will ensure that a meaningful set of data will be generated, and that it will be useful for ice-engineering applications.

3.4. Summary of Remote-Measurement Instrumentation Requirements

Figure 13.1 summarizes the permanent instrument array associated with the ice physics and engineering program. Although the ice physics and engineering program simply requires position data buoys, other programs will require hydrophones, barometric pressure sensors, temperature sensors, and other instruments. It is anticipated that the final buoy design will be made to accomodate those other needs as well. The radar transponder array will be required by the marine acoustics program, with perhaps a greater density than that shown. Stress transducers will be unique to the ice physics program. Below is a summary of the program's total instrumentation needs:

9	Active position data buoys and 3 spares for relocation of the array
12	Remote transponders plus main towers and central unit
20	Ice-stress transducers
1	Surveying transit

1 Leveling rod
1 Universal testing machine
1 Coldroom
1 Lathe
1 Ice corer
Strain guages and signal conditioning and recording equipment

3.5. Scheduling, Frequency of Measurements

It is anticipated that data-buoy and radar-transponder measurements will be taken continuously during the entire drift. Interruptions will occur when excess distortion or major course corrections will require repositioning of the arrays. The stress transducer array surrounding the ship as well as stress instrumentation on the ship itself, will also be monitored continuously throughout the drift.

Test programs related to local deformation features in the pack, such as pressure ridging, will be aided by continuous timelapse photography of shipboard radar observations during the periods of interest.

Specific experiments, such as pressure-ridge observations, ice-sheet stress-strain and strength measurements, and studies of the physical properties of sea ice will be carried out during specific two to three month intervals during the drift. It would be desirable to have each program carried out at least twice during the drift--once early in the drift to investigate the young ice and once later in the drift to compare these observations to those for older ice. Measurements that need to be made as a function of the age of the ice, such as salt content, should be made continuously throughout the drift.

Icebreaker mobility tests will be carried out at those special times during the drift when the pack is breaking up and it seems likely that the ship will be capable of moving around. Such measurements should also be made during course-correction maneuvers.

3.6. Field Personnel Requirements

	Man-days
*Deployment and Maintenance of buoy array 2 buoys/day with a 4-man crew x 20 days	80
*Deployment of radar transponder sites and setup of basic system 3 men, 15 days	45
Monitoring and maintenance of radar transponder system 1 man 1/2 time for 2 years	365
Installation and monitoring of stress transducers around the ship and stress measurements of the ship itself 1 man 1/2 time for 2 years	365
Remote sensing from helicopter flights 12 h/month x 24 months	288
Pressure ridge, shear, rafting, and collision experiments 2 men, 5 months	300
Ice-sheet stress-strain and strength measurements 2 men, 5 months	300
Ice physics small sample testing program 2 men, 9 months	540
TOTAL	2283 or 6.25 man-years

*Overlaps with requirements of other programs

3.7. Data Management

Coordination will be carried out between the following data sources:

(a) Buoy position data (transmitted from satellite to a data collection center in the United States)
(b) Satellite imagery (same as above)
(c) Transponder position data (collected on the NDS and sent back periodically)
(d) Helicopter remote-sensing data (same as above)
(e) Stress-transducer data (same as above)
(f) Ship stress and position data (same as above)

It is anticipated that one data-collection center will be responsible for receiving these data and putting them into a form that can be used by the various investigative programs.

For other programs, such as pressure-ridge experiments and measurement of small sample ice properties, data management will be up to the individual investigators. If, however, several different investigators are making studies of the same kind, it will be important to provide uniformity of measurement and correlation of results.

4. REMOTE SENSING

Remote sensing requirements include satellite imagery and aerial photography. Satellite imagery will be used for visual observations of the region being covered by the position data buoys, and aerial photography will serve a similar purpose for the area covered by the transponder array.

At this time, consideration is being given to four different satellite series for coverage of the NDS track. Since the satellite imagery will be used to check the buoy strain measurements, as well as to check out the calculated thickness distribution, it will be important to have at least five to six consecutive days of satellite imagery per month. It appears, at present, that all the imagery systems in current use, as well as those being considered, are capable of providing information related to motion of the ice and are capable of distinguishing thicknesses and the presence of open water.

It is the current understanding (see Chapter 15) that remote sensing flights will be carried out by helicopter. During these flights, aerial photography and laser profilometry should cover the transponder area at least twice per month, with aerial photography requiring a sequence of five days per coverage period. This coverage will be required both to initialize mesoscale ice-dynamic modeling periodically, as well as to follow model predictions for short intervals.

5. LOGISTICS

5.1. Staff Movement

At present it is difficult to estimate precise numbers and dates of staff movements. It is best to estimate that personnel exchange will be approximately four to six persons every three months.

5.2. Shipboard Installations

100-150 ft radar transponder tower

1 Ice testing laboratory with coldroom facilities

No other special logistic requirements are foreseen for this program.

6. COST ESTIMATES

6.1. Personnel (Section 3.6)

		Man-Years
6.1.1.	Field Personnel	
	Experienced Technician	3.5
	Principal Investigators	2.75
6.1.2.	Data Collection and Analysis	
	Data buoys and transponders	
	1. Overall direction Senior Scientist 1/2 time x 2 years	1.0
	2. Continuous strain calculations, Intermediate staff, full time 2 years	2.0

3. Remote sensing interpretation. Intermediate staff, 1/2 time, 2 years	1.0
4. Model analysis--data interpretation:	
Senior Scientist, full time, 2 years	2.0
Senior Programmer, full time, 2 years	2.0
Draftsperson, full time, 2 years	2.0
Junior Programmer, full time, 2 years	2.0

6.1.3. Data Analysis--Other Programs

	Man-Years
1. Small sample ice measurements	
Senior Scientist, 1/2 time, 1 year	0.5
2. Ice-sheet strength and stress-strain measurements	
Senior Scientist, 1/4 time, 1 year	0.25
3. Ice-pack deformation phenomena (pressure ridging, lead formation, etc.)	
Senior Scientist, 1/4 time, 1 year	0.25
4. Ice-stress transducer measurements Ship-stress measurements	
Senior Scientist, 1/4 time, 2 years	0.5
5. Icebreaker mobility measurements	
Senior Scientist, 1/4 time, 1 year	0.25

6.1.4. Summary of Manpower Costs (including overhead, etc.)

1. Senior Scientists--field	
2.75 man-years x $90,000	$247,000
2. Senior technicians--field	
3.5 man-years x $60,000	210,000

3. Senior Scientists--analysis 4.75 man-years x $ 60,000	285,000
4. Intermediate-level staff 5.0 man-years x $45,000	225,000
5. Junior staff 4.0 man-years x $30,000	120,000
ESTIMATED MANPOWER BUDGET	$1,087,000

6.2. Major Material

*12 Dropable RAMS position buoys at $3000	$36,000
+12 Remote transponders at $8000	96,000
20 Stress transducers at $300	6,000
Strain gauges, signal conditioning equipment	18,000
1 Multichannel chart recorder	25,000
1 Universal testing machine	10,000
Data processing and publications costs	200,000
Sample preparation and coldroom equipment	40,000
Miscellaneous equipment	20,000
Travel--6 round trips every 3 months from United States for 24 months = 48 round trips at $1500	72,000
TOTAL MATERIALS COST	$523,000

6.3. Total Projected Cost

Labor	$ 1,087,000
Material	523,000
Total:	$ 1,610,000

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*Minimum buoy requirement. This will most likely be absorbed by a more comprehensive buoy capability.

+Assumes availability of CRREL basic system.

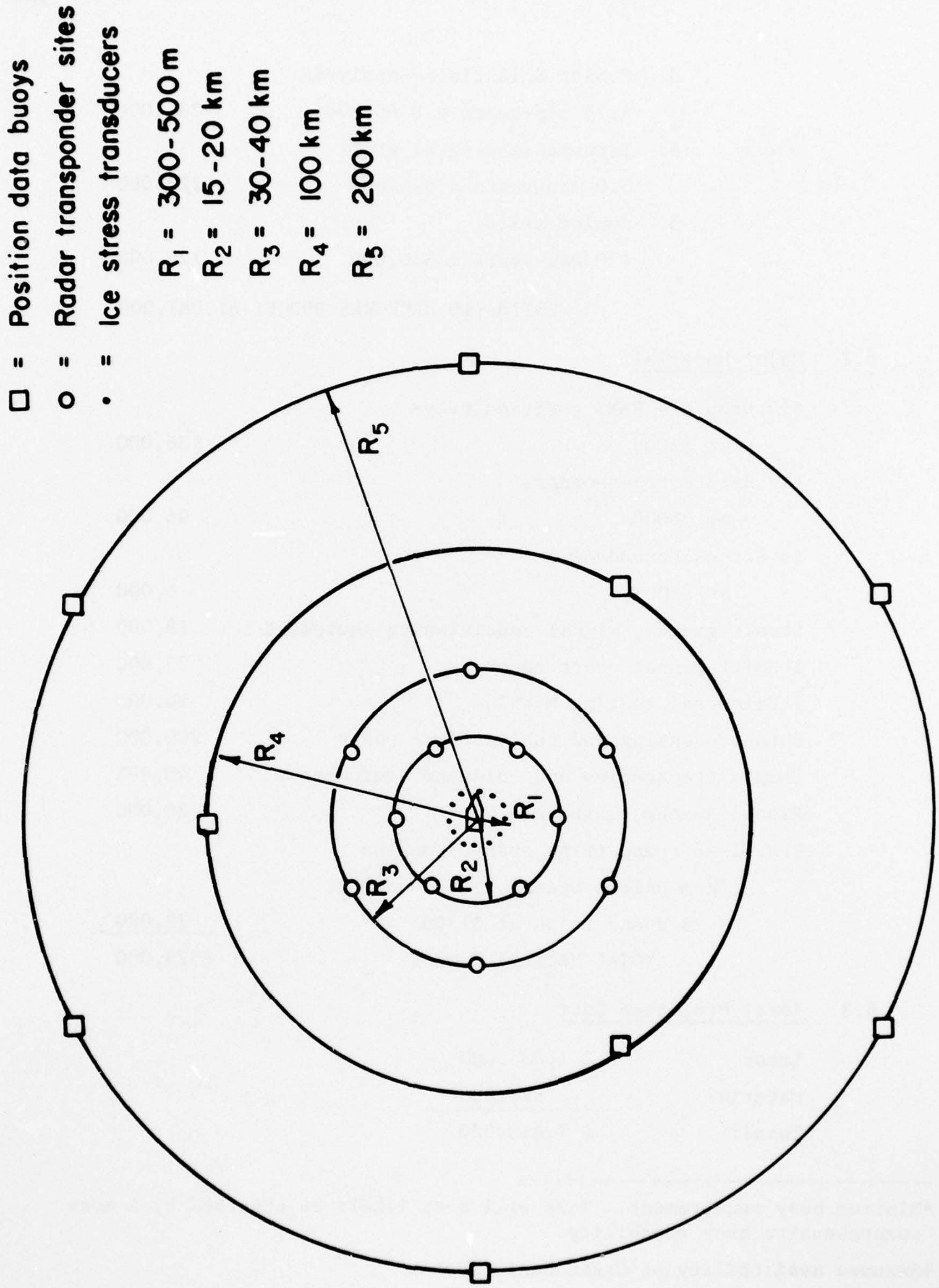

FIGURE 13.1 Preliminary scheme of remote data collection sites with respect to the Nansen Drift Station. At these sites a variety of data will be obtained, serving different programs (see text).

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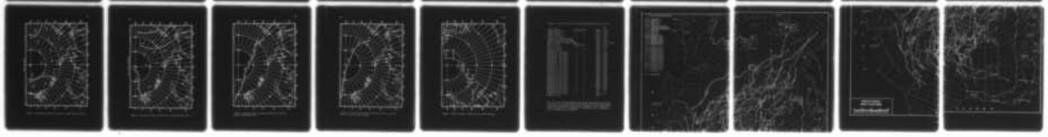

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14

ATMOSPHERE-IONOSPHERE-MAGNETOSPHERE

1. BACKGROUND

1.1. Introduction

The unique location of the Nansen Drift Station will provide an opportunity to make significant measurements directed toward an understanding of the complicated mechanisms that couple energy between the earth's atmosphere, ionosphere, and magnetosphere. The complicated nature of the geomagnetic field as distorted by the solar wind is shown in Figure 14.1 from Heikkila (1973). The principal atmosphere-ionosphere-magnetosphere (AIM) regions that can be studied from the NDS are the polar cap, magnetospheric cusp (or cleft), and auroral zone.

1.2. Polar Cap

The geomagnetic field serves to "funnel" the flow of energy from the interplanetary medium to the earth's polar caps. The amount of energy deposited in these polar processes can be extremely intense and produce drastic physical and chemical changes in the lower atmosphere and ionosphere. For example, intense fluxes of high-energy protons (∿10 MeV) emitted by the sun following certain major flares have access to the polar regions and bombard the atmosphere for several days, providing an energy input equivalent to 10^{12} W (4 times the total power generated by all electric plants in the United States). These particles severely alter the ionosphere to the extent that transpolar VLF and HF radio transmissions (as well as over-the-horizon radar systems) are interrupted for many days (e.g., Zmuda and Potemra, 1972). The chemistry of the neutral atmosphere is severely altered, for example, resulting in an abnormal abundance of nitric oxide (NO), which is believed to have a drastic effect on the important ozone (O_3) shield of the earth (Crutzen, *et al.*, 1975). Ionized particles continuously flow outward along the geomagnetic field lines originating inside the polar cap causing the "polar wind" (Banks and Holzer, 1968).

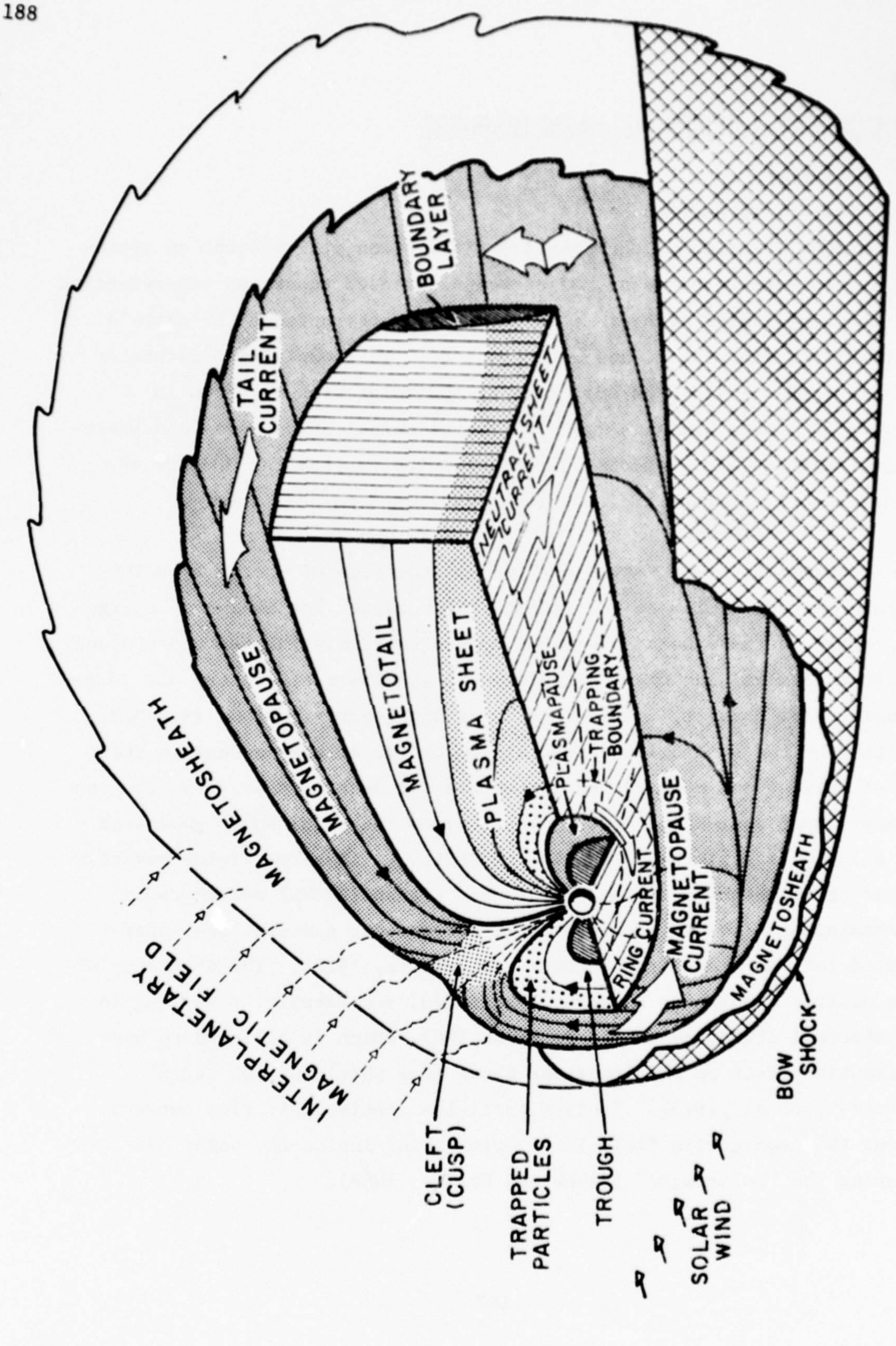

FIGURE 14.1 The magnetosphere (from Heikkila, 1973).

1.3. Magnetospheric Cusp

The cusp (or cleft) shown in Figure 14.1 is a region facing the sun that coincides with the geomagnetic neutral line. Solar-wind and magnetosheath particles are believed to have unrestricted access to the lower ionosphere through this region. The cusp region is particularly important because of its obvious role in connecting solar and AIM phenomena and because of the large variety of wave-particle and plasma phenomena excited there. The precise location of the cusp is not known, possibly because of the high variability of the associated phenomena, but the available observations indicate it to be at fairly high geomagnetic latitudes (approximately between 78° and 82° invariant latitude) and on the dayside of the earth.

1.4. Auroral Zone

Auroral phenomena, by virtue of the associated dramatic optical emissions in the sky (witnessed even by Fridtjof Nansen himself), have been studied since the end of the last century. Energetic particles, primarily electrons with energies between 100 eV and 10 keV, bombard the auroral region, causing a variety of effects including optical emissions (c.f., Akasofu, 1968; Akasofu and Chapman, 1972), and acoustic waves detected on the ground at great distances (Wilson, 1967). Currents flowing along geomagnetic field lines into and away from the auroral ionosphere (originally suggested by Birkeland in 1908 and often referred to as "Birkeland currents") have been recently found to comprise a permanent feature of the auroral zone (Iijima and Potemra, in press) with a total magnitute ranging between 10^6 and 10^7 A, depending on geomagnetic activity.

The auroral zone is a continuous oval-shaped region that expands and contracts in size depending on geomagnetic conditions (Feldstein, 1966). Nighttime aurora (historically observed most often with optical instruments) occur most frequently between 65° and 71° invariant latitude, expanding to lower latitudes during active periods. The dayside auroral zone is a narrower region centered at approximately 75°

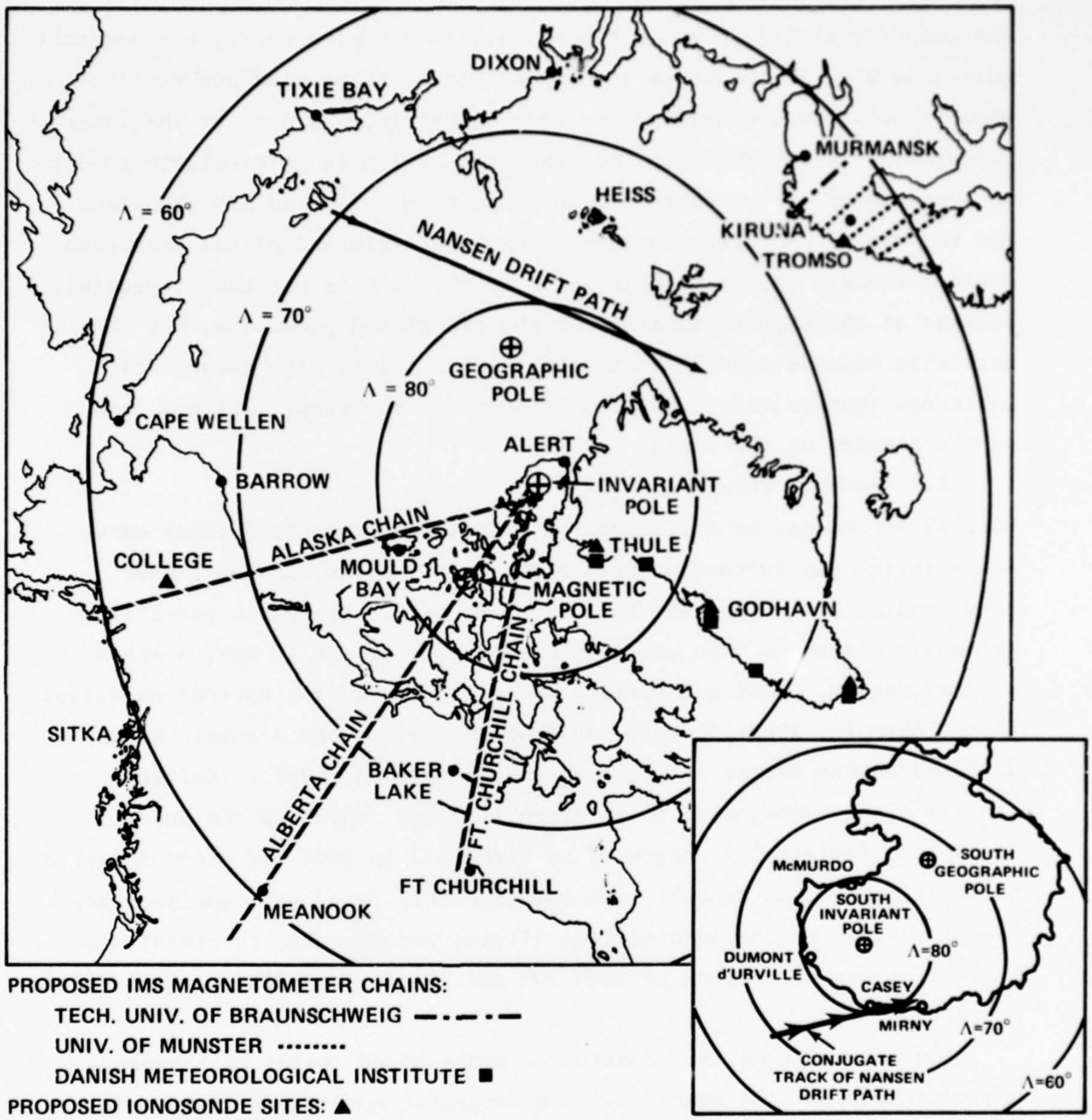

FIGURE 14.2 The estimated drift path of the Nansen Drift Station in the northern hemisphere with ground-level invariant latitudes superimposed. The location of existing and planned experiments for the IMS program are also shown. The inset shows the magnetically conjugate track of the Nansen Drift Station in the southern hemisphere.

invarient latitude (near local noon) and extends only down to 71° during very disturbed periods.

2. PURPOSE

The unique position of the NDS for studies of AIM phenomena is illustrated in Figure 14.2, which is a map of the north polar region with the invariant pole and ground-level invariant latitudes $\Lambda = 60°$, 70°, and 80° superimposed. The estimated drift path of the NDS is shown in this figure, along with the location of existing ground-based magnetometers and ionosondes and those proposed for the International Magetospheric Study (IMS) (IMS Bulletin No. 2, 1975; Wilhjelm and Friis-Christensen, 1974).

The magnetically conjugate track of the estimated NDS drift path is shown in the inset of Figures 14.2. As shown in this inset, stations at Casey and Mirny provide ideal locations for coordinated conjugate studies of magnetospheric phenomena such as VLF wave propagation and micropulsation activity between the north and south hemispheres.

The NDS can be particularly useful as a supplement to the present IMS program, which is an international cooperative enterprise to be conducted in 1976-1978. Its chief objective is to obtain a comprehensive quantitative understanding of the dynamic processes operating on plasmas in the geomagnetic field. The operational basis of the IMS is an international plan of coordinated observations from spacecraft, ground-based facilities, aircraft, balloons, and research rockets.

Evident from Figure 14.2 is the fact that almost the entire U.S.S.R. mainland and all of Scandinavia are below 70° invariant latitude. Consequently, with the exception of isolated locations such as Heiss Island, there are no land areas in the eastern hemisphere from which high-latitude ($\Lambda \geq 70°$) AIM observations can be made of, for example, dayside aurora, magnetospheric cusp, and polar-cap phenomena. Further, baseline studies of the same phenomena with simultaneous observations at widely spaced stations are virtually impossible. Satellite observations, which have produced the bulk of the knowledge of these regions, can only provide samples at intervals of approximately 100 minutes and at high altitudes (greater than approximately 500 km). The path of the NDS shown in Figure 14.2 will extend from 70° to 80° invariant latitude and be directly across the invariant pole from a good selection of established observatóries in northern Canada and Greenland (such as Fort Churchill and Godhavn).

For these reasons, the location of the NDS offers a singularly unique opportunity as a platform for important observations of AIM phenomena. Furthermore, the background signal levels are, in many cases, reduced from those encountered at lower latitudes (e.g., city light interference with optical measurements or pollution layer effects on electric-field observations). Also, processes normally dependent on the diurnal variation of solar radiation (such as ionization mechanisms and aeronomy processes) can be studied during extended periods of darkness or daylight.

2.1. Significant Problems

The most significant problem concerns the mechanisms that convey energy from the sun through the magnetosphere to the lower ionosphere and atmosphere. Specific aspects of this enormously complex problem include the following:

2.1.1. Substorm phenomena: What is the spatial distribution of energy deposited by energetic particles (and the associated visual auroral emissions and geomagnetic disturbances) during various phases of substorms?

2.1.2. Particle entry throught the magnetospheric cusp: Where is the cusp; what particle flux variations occur within it; how far in local time does it extend in local time; and what are the variations with geomagnetic activity?

2.1.3. Convective electric fields across the polar cap and their connection to the global ionospheric potential: Can separated ground-based static electric field measurement be used to monitor transpolar electric fields and be related to interplanetary phenomena such as the direction and intensity of the interplanetary magnetic field?

2.1.4. Maintenance of the polar nighttime ionosphere: In the absence of solar radiation during long polar nights, what are the important ionization sources?

2.1.5. Minor species in the polar-cap atmosphere: What is the effect of prolonged periods of sunlight or darkness on the abundances of O_3 NO, or O_2 ($^1\Delta g$), for example?

2.1.6. Effects of solar activity on surface weather: Are particle bombardment of the polar cap, field-aligned current systems in the auroral region, or polar-cap convective electric fields associated with major meteorological patterns?

2.1.7. Upper atmospheric dynamics: What plasma motions and wind velocity patterns prevail over the polar cap?

2.1.8. Plasma instabilities: What is the geographic extent of intense plasma irregularities that develop with the ionosphere because of electric fields?

2.1.9. Survey of electromagnetic disturbances in the polar cap region: How effective are various ground-based and satellite communication and navigation systems from ELF to VHF frequencies in the polar-cap region; how do a variety of AIM phenomena affect these systems; and does the vastly different conductivity of deep ice (in comparison to seawater) significantly affect the reliability and accuracy of these systems?

2.2. Collaborative Experiments

Data obtained from the AIM program of experiments can be used in a variety of collaborative experiments planned for the International Magnetospheric Study (IMS) during 1976-1978. Included are the observations from the ground-based magnetometer networks of many international groups: in Greenland by the Danish Meteorological Institute, in Europe by the University of Münster and the Technical University of Braunschweig, in Norway by the Norwegian Institute of Cosmic Physics, and in North America by several U.S. and Canadian groups.

3. OBSERVATIONAL PROGRAM

Active and passive measurements of various AIM phenomena are recommended as part of the NDS program. A few remote sensors may be placed on the ice at some distance from the ship (to reduce background interference caused by onboard equipment) with data returned over cables or by a short-range telemetry system. Some measurements will require periodic changes of photographic film or magnetic tapes but otherwise will function continuously and automatically. It is expected that there will be "planned campaigns" conducted by principal investigators onboard the NDS, in which case some experiments will be operated in special modes.

The data from all AIM experiments can be returned in digital form to a central data-handling facility for preliminary processing and eventual storage on magnetic tape. The details of the experiment interfaces are discussed in a later section. The variety of AIM instruments should be similar to those used in various Antarctic research activities (Report on U.S. Antarctic Research Activities, 1975).

3.1. Specific Observations and Instruments

3.1.1. Vector magnetometers for continuous measurement of geomagnetic fields: on board requiring special interference canceling techniques and remote with telemetry link to ship. These instruments should be similar to those used in various Antarctic programs, for example, normal low-sensitivity magnetograph (Ruska) for recording H, D, and Z, proton precession magnetometer for determination of total field.

3.1.2. VLF receiver for continuous monitoring of phase and amplitude of active VLF transmissions from Omega, U.S. Navy, and U.S.S.R. stations (for example, NLK near Seattle, Washington, NAA in Cutler, Maine) as a monitor of ionization enhancements in the ionospheric D-region. These transmissions are also useful for radio-propagation studies over vast expanses of ice.

3.1.3. Broadband VLF receivers for observations of whistlers and VLF emissions associated with wave-particle interactions associated with cusp and polar-cap phenomena.

3.1.4. Riometer to measure ionospheric absorption at 30 and 50 MHz on a continuous basis as an indicator of widespread particle precipitation.

3.1.5. Multifrequency digital ionosonde to observe ionospheric structure, motions, and temporal variations between 60 and 300 km altitude. Plasma motions and associated electric fields in the ionosphere will also be studied with this instrument. The system should be similar to the NOAA Dynasonde (Wright, 1975), which includes minicomputer programmable flexibility in data acquisition and on board analysis.

3.1.6. Static electric-field sensor to monitor continuously geopotential field during all local times and during various geophysical conditions. Coordinated measurements should be made with another station (for example, in Greenland).

By means of portable electric-field sensors (see Chapter 6, Section 3.1.4) observe field strengths and their secular changes in the lower 2 m of atmosphere and within the sea ice. Attempts should be made to detect electrical fields in the water beneath the ice-water boundary, although the instrumentation is not obvious. Coordinate at least a systematic portion of these measurements with measurements at other stations recording electric and magnetic field perturbations. Test for correlations of electric field strength changes with aging of sea ice (i.e., electrical potential generated by the freezing process and migrations of ions in water films within the ice) and with changes in atmospheric concentrations of ions such as $SO_{\underline{x}}$. Ice nuclei in the atmosphere (some of which may originate through bursting bubbles at the open sea surface, see Blanchard, 1975; Blanchard and Syzdek, 1974; Schnell and Vali, 1972) should be investigated with regard to seeding frazil ice in open leads (cf. Michel, 1967; Katsaros, 1973).

3.1.7. All-sky cameras for 35-mm black-and-white and color time-lapse photography of aurora.

3.1.8. Photometers for continuous monitoring (when weather conditions are favorable) of certain individual spectral lines, for example, 3914 Å, 4278 Å of N_2^+ for monitor of particle bombardment, 1.27-μm for estimate of $O_2(^1\Delta g)$ and O_3 abundances, 4861 Å (Hβ) for proton aurora, and the red oxygen line at 6300 Å.

3.1.9. Scanning spectrometer for detailed structure of optical and IR emissions to identify atmospheric species and processes during a variety of conditions.

3.1.10. Infrasonic microphones in the range 0.001-1 Hz to observe acoustic-gravity waves associated with auroral activity.

3.2. Frequency of Observations

Continuous observations should be made with the magnetometers, VLF receivers (active transmissions and broadband emissions), static electric field sensors, and HF riometers.

The multifrequency ionosonde should be programmed for "background observations" every 5 minutes to determine electron densities, locations of lateral structure (e.g., cusp positions, electron precipitation activity), and plasma velocity. More intensive observations should be conducted during active periods.

The all-sky camera observations depend on favorable weather conditions during which time exposures will be automatically made at 15-minute intervals. During auroral displays, one to ten exposures per minute should be made.

The photometer and scanning spectrometer measurements can be made during "clear-sky" conditions when continuous observations can be made.

In addition to the continuous and automatic recordings, special intensive campaigns will be conducted, when for short periods of time (two to four months) the principal investigator will operate the respective instrument in special modes.

3.3. Personnel

Virtually all AIM instruments provide automatic data accumlation with a minimum of personnel support required for periodic maintenance and replacement of film and magnetic tape. It is suggested that three electronic technicians provide onboard support for the AIM experiments for the duration of the NDS project. Provision should be made for periodic visits by principal investigators who will conduct more intensive observations, for example, coordinated measurement with observatories located in Greenland, Alaska, Canada, and Scandinavia, or with rocket and satellite experiments.

3.4. Data Management

Figure 14.3 shows the experiment interfaces for the AIM sensors. The outputs of all sensors (both analog and digital) will be connected to a data multiplexer that will establish the data format and combine with time and position data. The outputs of remote experiments (e.g., magnetometer observations on the ice at some distance from the ship) and other automatic geophysical sensors (e.g., acoustic microphones and temperature sensors) would be fed to the multiplexer.

The digital ionosonde is the only "active" AIM experiment (in the sense that the ionosphere is probed with radar pulses) and is a sufficiently complex system that it requires a minicomputer and peripheral equipment (tape recorder, disk files, and terminals). The option exists to accomodate the other AIM sensors within the ionosonde computer.

The raw data, in a "standard" format (i.e., similar to a satellite telemetry frame) will be processed by a redundant minicomputer system that will convert all analog data to a digital format and provide other low-level processing such as editing and position transformations (i.e., geographic to geomagnetic).

All data including reference times and geographic position will be stored in digital form on magnetic tape for storage and periodic transference to the mainland for further analysis.

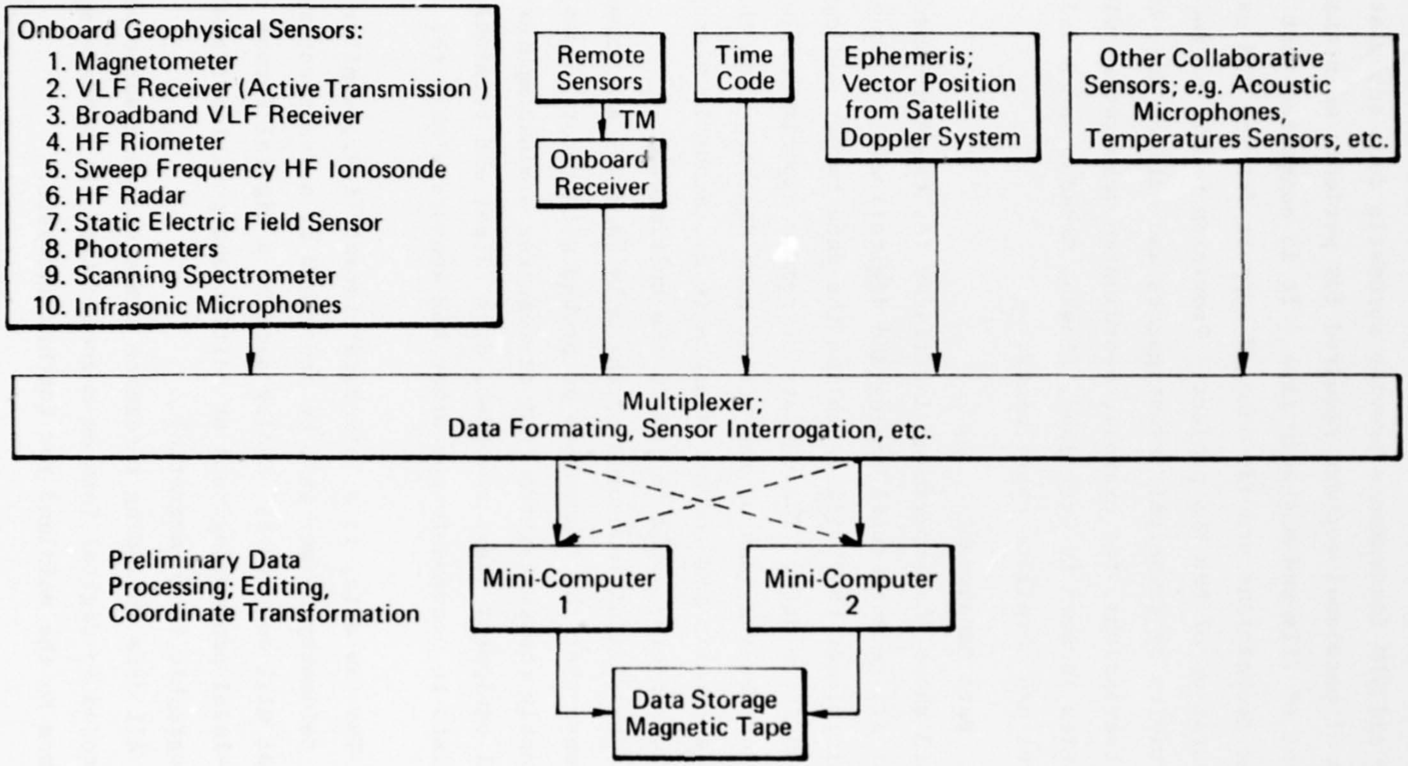

FIGURE 14.3 Experiment interfaces for AIM on Nansen Drift Station.

The option will be open to use this system as a satellite tracking station to record both TM signals and other signals for possible collaborative experiments, for example, observations of ionospheric scintillations to satellite transmissions in the auroral and polar region correlated with the AIM observations on board the NDS.

4. LOGISTICS

4.1. Movement of Staff

Three electronic technicians, who will be relieved during the regular crew changes, will be required to maintain the AIM experiment for the duration of the NDS project. Periodic visits of principal investigators are expected to last for periods of two to four months.

4.2. Needed Installations

The AIM experiments will require two or three environmentally controlled areas for electronic equipment and maintenance facilities (i.e., in size comparable with a "standard" laboratory, 20 ft x 30 ft). Deck space will be required for antenna systems and sensors. One or two antenna towers exceeding 100-feet height will be required, preferably at the bow and stern of the ship. An optical port (for example, located in the roof of a deck house) will be required for the optical measurements. Storage space will be required for data tapes and electronic equipment.

4.3. Power

Standard three-phase 220-V 60-Hz or 400-Hz primary electrical power will be required with a maximum load estimated to be 30 kVA.

4.4. Communications

Periodic communications will be required to keep the AIM experimental team informed of global geophysical conditions and of the schedules of other experimental programs. It is expected that a daily report to the mainland to exchange this information will be sufficient.

4.5. Flight Support

The three-man AIM experimental team can accomplish all routine activities on board the ship and will require transportation only during the scheduled crew changes (estimated to be four to six months). When possible, principal investigators will visit the station for shorter time periods (two to four months). Data tapes should be shipped on a monthly basis (consisting of approximately 30 tapes--less than 100 lbs.) by air. Provisions should be made for emergency air shipment of equipment and supplies.

4.6. Surface Transportation

It is expected that automatic remote sensors (e.g., magnetometers) will be transported some distance (<10 miles) from the ship and left unattended for large periods of time to collect data in a "quiet" location. No surface transportation from the ship will be required except for emergency maintenance of a remote sensor.

5. COST ESTIMATES

It is expected that the AIM experiment will extend for four years, divided into the following three major phases: (1) system design, test and integration lasting one year; (2) data acquisition on board the NDS lasting for the duration of the drift (estimated to be two years); and (3) data reduction and analysis lasting two years past the completion of the data acquisition.

It should be emphasized that the total estimate cost below includes the entire AIM project with the exception of travel for regular crew transfers. No capital shipboard equipment such as large platforms or hoists are needed, nor are special large-scale expeditions on the ice with helicopter support required.

An estimate of the costs of these phases is as follows:

5.1. System Design, Test, and Integration

<u>Personnel</u>

Project scientists (physicists, technicians, draftsmen, machinists, etc.) approximately 9 man-years	$ 550,000

Hardware	
(all instruments and equipment to be purchased from commercial sources) magnetometers, riometer, ionosonde, etc.	$ 500,000
Minicomputer system for sensor interrogation, analog-to-digital data conversion, and data formating and processing, includes shipboard and "severe climate" quality equipment with peripheral terminals, line printers, disk storage, and tape recorders	350,000
5.2. Data Acquisition	
Three full-time technicians, expendable supplies, test equipment, transportation ($300,000 per year)	600,000
5.3. Data Reduction and Analysis	
Senior Scientists, data technicians, computer programmers, computer time for two years	500,000
TOTAL COST OF 5-YEAR AIM PROJECT	$2,500,000

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REMOTE SENSING

1. BACKGROUND

The remote sensing problems encountered by the scientists involved in the Nansen Drift Station (NDS) are primarily associated with determining the characteristics of the different varieties of sea ice. The reason for this is simple--the vast majority of the area of the Arctic Ocean that will be traversed by the NDS is covered by a drifting ice cover that is nearly continuous even during the summer. This ice cover effectively acts as a filter in that it greatly limits our "view" of the ocean from remote sensing platforms that operate above the ice as well as our "view" of the atmosphere from platforms operating below the ice. The formation of leads, of course, provides "windows" through the ice cover. The views through these windows are, however, restricted by the limited areal extent of most leads, which in many cases are smaller than the footprint size of many sensors. Also, leads commonly remain open for only short periods, being closed either mechanically or via the formation of thin skins of new ice. In fact, purely oceanographic remote sensing will undoubtedly be primarily limited to observations of the thermal and optical characteristics of the waters of the continental shelves north of Siberia and of Svalbard and Greenland during the summertime periods when the NDS is entering or leaving the pack.

The remote sensing of sea ice is a young field, if the occasional hand-held aerial photograph taken for illustrative purposes is excluded. The first sonar records of the roughness of the underside of pack ice date from the late 1950's; preliminary attempts to obtain and interpret thermal infrared (IR) and side-looking airborne radar (SLAR) imagery were made in the early 1960's; research in the interpretation of multispectral sea ice imagery in the visual and near-IR frequency ranges dates from the late 1960's and was primarily initiated to provide background for the launch of the LANDSAT series of satellites; the first laser profilometer observations of the surface roughness of sea ice were made at about the same time; and the first high-quality passive microwave data from sea ice was obtained in the spring of 1970 from north of Point Barrow. Details about, and references to this "early" work can be found in the papers of Campbell *et al.* (1975), Hibler (1975), Page and Ramseier (1975), Pouiin (1975), and Williams *et al.* (1975). The great majority of these studies were concerned with verifying the interpretation of the resulting imagery. Good on-the-ice ground-truth studies were, and still are, quite rare, and verification usually consisted of comparisons with simultaneous visual photography. Also, remote sensing observations were commonly sufficiently isolated in time that they provided little insight into sequential changes in the nature of the ice cover. In summary, most of the early remote sensing could be characterized as being primarily remote sensing for its own sake, in that it was not as yet focused on important problems and did not contribute significantly to our understanding of the physical nature and behavior of sea ice.

However, once these preliminary studies had demonstrated the capabilities of presently available remote sensing technology as applied to sea ice, it became possible to utilize these techniques as essential parts of larger integrated studies of the subject. These possibilities were explored during both the 1971/1972 AIDJEX Pilot Studies and the BESEX program, where passive microwave techniques were used to classify ice types (Gloersen *et al.*, 1973, 1974a; Campbell *et al.*, in press); detailed ground-truth observations were made in an attempt to formulate physical models for interpreting the microwave results (Meeks *et al.*, 1974); methods were developed for estimating ice thickness distributions from both IR observations (Gloersen *et al.*, 1974b) and from surface-roughness measurements (Ackley *et al.*, 1974); and remote sensing imagery was used extensively in the study of ice dynamics (Hibler *et al.*, 1973, 1974a; Campbell *et al.*, 1974). Although the above studies were primarily based on imagery collected by aircraftborne sensors, the application of satellite-based systems to similar types of problems also progressed rapidly during the same time period. Of particular interest here are the studies that have utilized satellite imagery in quantitative investigations of ice drift and deformation both near to and far from shore (Hibler *et al.*, 1974b, in press; Nye, 1975; Shapiro and Burns, 1975; Rothrock and Hall, 1975).

In the main AIDJEX program, which has recently been completed, an attempt has been made to utilize this experience in designing a program that couples remote sensing with surface measurements to expand our knowledge of ice dynamics within the Beaufort Gyre (Weeks *et al.*, 1974; Weeks and Campbell, 1975).

The remote sensing program developed here is in some ways similar to the AIDJEX remote-sensing program. This is hardly surprising in that the general ice-related problems being investigated are similar in both projects. There are, however, striking differences in that the NDS research program is much broader in scope than the AIDJEX program. In addition, much of the NDS drift track is out of effective range of large aircraft such as the NASA Convair 990, which was a main element in the AIDJEX program. Therefore, the NDS program must rely heavily on data collected from satellite platforms and from small aircraft and helicopters that can be based either from the drifting platform itself or from the surrounding ice.

2. PURPOSE

The NDS will be frozen into the pack ice of the Arctic Ocean north of the Lena Delta and will then drift past the North Pole and exit from the pack via the East Greenland Drift Stream. During this drift, the NDS will transit the complete length of the Trans Polar Drift Stream, which is the major ice dynamics feature in the Arctic Basin. During the time that it takes for this transit, the young, saline, lightly deformed ice of the Siberian Shelf will be gradually transformed into the thick, low-salinity, highly deformed ice that is observed exiting the Arctic Basin east of Greenland. Inasmuch as the NDS will move with the ice, it will serve as an excellent platform from which both the dynamics and the metamorphism of the ice can be studied.

As described in the ice physics and engineering program, (Chapter 13), it is proposed to deploy data buoys around the NDS in two rings with radii of 100 and 200 km. Within these buoy rings there will be a more detailed deformation array utilizing radar transponders and sonar buoys located up to 40 km from the ship. The principal task of the NDS remote sensing program is to provide quantitative information on the state of the ice pack within the ring of data buoys and particualarly within the area covered by the radar transponders. The specific data that are required are those necessary for modeling the behavior of the ice and allowing detailed comparisons to be made between the estimated ice behavior and the actual observed behavior. In accomplishing this, four different types of remote-sensing information are required:

2.1. Sequential Imagery That Can be Used in Conjunction with the Movement of the Data Buoys and Radar Transponders to Define the Ice Drift and Deformation Field in Considerable Detail

This is important in advancing our understanding of the geometry of the large-scale deformation processes that occur within the ice pack. Of particular interest here are the changing patterns of leads and of recently deformed ice as well as the homogeneity of the deformation as viewed on different scales. Also of interest will be contrasts between the tectonic style of the ice deformation within the Trans Polar Drift Stream as examined by the NDS program as compared with the ice behavior within the Pacific Gyre as investigated by AIDJEX.

2.2. Direct Measurements of the Ice Thickness Distribution G

To estimate G, one must be able to obtain accurate estimates of the areal percentage of ice of different thicknesses within the study area. Of particular interest are estimates of the amount of thin ice and open water present at any given time. It is currently believed (Thorndike *et al.*, 1975) that the ice thickness distribution is the most important single parameter controlling the rheological response of the ice pack to the external forces that are imposed upon it. However, if G is known at one instant in time, the changes in the thickness distribution caused by mechanical and thermodynamic effects can be calculated. Therefore, one needs to measure G only occasionally in order to initialize and verify such calculations. This is fortunate because good estimates of G are difficult to obtain for the wide expanses of ice that are of interest here. A considerable portion of this difficulty is caused by the fact that there currently is no simple direct method for determining the thickness of sea ice via remote sensing techniques.

2.3. Direct Distribution of Ice Types within the Study Area as well as the Physical State of Each of These Types

Valuable information on the nature of the ice in any given area is provided by knowing its thickness (i.e., the G function). In addition, it is useful to have independent methods for estimating ice age and properties. Of particular importance in fixing the ice properties are information on its age, salinity, and temperature.

2.4. Top and Bottom Roughness of the Ice Pack

Accurate estimates of the pertinent roughness parameters are required if one wishes to calculate the wind and water stresses that are transmitted to the ice pack. It is to be expected that significant changes in the top and bottom roughness of the ice pack will occur from the time that the ice first forms over the Siberian Shelf to the time when it exits from the Arctic Basin via the Greenland Sea. Also of interest is the modification of existing roughness elements during the summer melt season.

2.5. Contributions to Other NDS Projects

The NDS remote sensing program will clearly contribute directly to the use of remote sensing techniques via aircraft and satellite platforms to study sea ice. It will be particularly helpful in bridging the gap between present research-oriented programs and future operational ice forecasting operations. The program will provide data that are needed to characterize the ice within the buoy and the radar transponder deformation arrays and, as such, will serve as input to various numerical models for the ice behavior. The development and verification of such models is, of course, an essential part of improving both short- and long-term meteorological models for the polar ocean areas and for developing formal schemes for optimal ice forecasting and ship routing through regions of heavy pack ice. The data will also contribute to the transfer of our knowledge of large-scale geophysical forces within the ice to the prediction of the small-scale forces that the ice exerts on man-made structures such as ships and offshore platforms. This information is badly needed by engineering groups designing structures for arctic operations.

The remote sensing program also contributes directly to a variety of programs other than the ice program. For instance, the attenuation of underwater sound as a function of range is believed to be strongly dependent on the roughness of the underside of the ice along the sound track. This bottom roughness is a parameter that can be estimated from laser profiles of the upper ice suface. Also, ice deformation (cracking and ridge formation) is generally believed to be the major source of ambient underwater noise in the Arctic. To forecast these noise levels, the development of an operational ice deformation model is required. In operating an ice-deformation model, remote sensing data on the ice thickness distribution will be required. This same information will be needed by the biologists in their attempts to model primary production, inasmuch as submarine illumination is largely controlled by the ice thickness distribution. Good ice information is also needed by the oceanographers and the meteorologists as the mixing processes in the near surface layers of the ocean are to a considerable extent caused by the pronounced convection produced by rapid ice growth and salt rejection in newly formed leads and by the mixing that is caused by the motion of pressure ridge keels through the near-surface waters. Coupled with these oceanographic processes are the fluxes of heat and moisture into the atmospheric boundary layer from the warm water that is exposed in leads. Again, to develop any adequate model for the modification of air masses moving over ice covered waters, a good ice model is required. The remote sensing program will provide necessary input into such an effort. Even the estimation of the wind and water stresses exerted on the drifting ice cover requires remote sensing information, inasmuch as the form drag associated with the presence of ridges is currently believed to be more important than the stress exerted on the more extensive areas of relatively undeformed ice. Finally, the proposed DMSP station (see below) for the NDS will not only provide invaluable information on ice dynamics but will also contribute data on the heights (and temperatures) of the stratus cloud systems that are common over the Arctic Ocean. Valuable information (aurora photographs, particle precipitation data) of use to the upper-atmosphere program can also be obtained. The real-time DMSP imagery would also be available on board ship to assist in making the weather forecasts that will be required by aircraft operations.

3. OBSERVATIONAL PROGRAM

3.1. Constraints

There are two types of constraints that must be kept in mind in designing a remote sensing program for the NDS. First, it is important to utilize instruments that are effective under the extremes of lighting and weather that can be expected in the Arctic. At the high latitudes along the NDS track (commonly ⩾80° N), continuous sunlight occurs during the summer, continuous darkness during the winter, and transition periods in between (for instance, at 80° N the sun is continuously above the horizon between April 13 and August 30 and continuously below it between October 17 and February 22). Also, during the summer and fall, low stratus clouds and fog are commonly present over the pack. Therefore, sensors requiring natural illumination such as standard photography cannot be utilized during the arctic night and should be replaced by IR imagery. In addition, both visual and IR systems are ineffective in the summer. It would, of course, be desirable to be able to utilize only all-weather systems such as passive microwave and SLAR. However, the imagery that can be obtained by the all-weather systems does not fully substitute for the results that can be obtained by the weather-limited systems. In most cases a compromise must be struck in matching required resolution, lighting, and weather.

The second constraint is caused by the extremely remote location of the drift track. Unless arrangments can be made for refueling at locations in northern Siberia, much of the drift track will be beyond the range of all but very long-range aircraft. Also, even if an aircraft can reach the drift station, it would have only a very limited time available for data collection over the station. Therefore, in designing a program, we will assume that most of the airborne remote sensing will have to be carried out from either the two helicopters that will be based on the ship or from a STOL aircraft based on the ice near the ship. The remoteness of the drift track also affects data collection from satellite-borne sensors, inasmuch as while the satellites are over the target areas, they will be out of range of existing readout stations. This means that the data will commonly have to be recorded for later playback to a ground station. While this is certainly possible, it does require considerable planning, effort and cooperation by the agency that collects and processes the satellite data. Also, many satellite orbits are such that high-latitude locations are not covered.

3.2. Satellite-based Program

Considering the large tracts of ice that will lie within the outer buoy ring, the development of an adequate satellite program is essential. Inasmuch as we do not know the exact deployment dates of NDS at the present time, or the exact satellites that will be operational during this period, we can only discuss a satellite program in a general way.

It currently appears that there will be five satellite series that could be useful to the NDS program: LANDSAT, SEASAT, the Defense Meteorological Satellite Program (DMSP), and the NOAA and Nimbus satellites.

The multispectral imagery collected by LANDSAT provides an excellent base for studying lead and floe geometry and the distribution of strain within the pack. It can also be used to assist one in estimating the ice thickness distribution if supplementary surface observations are systematically made. The scale of the imagery is nearly ideal ($1:10^6$), the resolution is quite high (80 m), and the image is cartographically correct. LANDSAT does, however, have two major drawbacks in its application to NDS. First, no sea ice data can be obtained during dark or cloudy periods. This means that we can expect good LANDSAT imagery only during the late winter to early summer, with limited data also being obtained during the fall. Second, the LANDSAT orbit is such that imagery is not obtained from latitudes higher than 81° N. This is a major restriction because much of the proposed drift track is north of this latitude. Nevertheless, LANDSAT can provide valuable imagery during both the initial and the final segments of the drift. This imagery should be most useful in providing information on the behavior of the ice in the marginal seas of the Arctic Ocean. After all, it is the ice conditions in the marginal seas and the interaction of this ice with the main polar pack that are of principal importance in most applied problems at present. Even in these marginal seas there are potential problems because some of the areas of interest are out of range of existing ground stations making direct readout impossible. Therefore, extensive use will have to be made of the satellite's tape-recording capability with a data dump when the satellite is over a ground station. It should also be noted that in the past the LANDSAT tape recorder systems have been plagued with a number of problems, and their failure rate has been high.

These requirements for tape recorder time should be formulated as soon as possible and steps made to include the NDS program in current NASA planning. Fortunately, there is a strong possibility that a Scandinavian LANDSAT receiving station will become operational sometime in 1977. The proposed site of this station is ideal (Tromsö, Norway), in that it would allow direct readout of imagery during the final segment of the NDS drift and remove the hazard of relying on an operational tape recorder on board the satellite. A request should also be made recommending that NASA include a very-high-resolution IR sensor on future LANDSAT vehicles. This would allow imagery to be obtained during the dark periods.

SEASAT-A, which is scheduled to be launched in 1978, also carries sensors of interest to NDS. Of particular importance is the Synthetic Aperture Radar (SAR), which is expected to have a surface resolution of 25 m and is not limited by light conditions or by clouds. The magnitudes of SAR returns are a function of the dielectric properties of the ice and the roughness of the ice-air interface. Therefore, SAR can be used to show lead and crack patterns, areas of deformed ice, and floe shapes during all periods of the year. SEASAT will also carry a Scanning Multichannel Microwave Radiometer (SMMR). This system will also provide all-time information on lead patterns; ice type identification; and percentages of open-water, first-year, and multiyear ice. There are, however, two major problems associated with SEASAT's possible contribution to the NDS program. First, its planned orbit will allow only the acquisition of data at latitudes lower than 75° N. If this orbit is not modified, the NDS track and SEASAT coverage will be mutually exclusive. Recently, it has been suggested to NASA that the SEASAT orbit be modified so that data could be collected up to 80° N. If this orbit change is made, SEASAT will, as will LANDSAT, be able to contribute valuable information on the state of the ice in the marginal seas of the Arctic Ocean and over the initial and final regions of the NDS drift track.

The second problem relates only to SEASAT's SAR system. The data production rate of the L-band SAR system that will be flown on SEASAT is so large that it is beyond the capability of the on-board tape recorders. Therefore, SAR imagery can only be obtained when the satellite is within range of a ground receiving station. At these high latitudes, present receiving stations will allow SAR imagery to be collected only north of eastern Siberia and the Alaskan Northslope. When the planned LANDSAT receiving station for Tromsö, Norway, becomes operational in 1977, it is possible that its capabilities may be expanded so that it would also receive SAR data from SEASAT. This would then make SAR imagery collection possible for large areas of the Greenland, Barents, and Kara Seas. Of particular importance would be the possible coverage of the complete East Greenland Drift Stream in the region where the NDS is expected to exit from the ice.

To summarize the above, both SEASAT and LANDSAT should, if proper arrangements are made, be able to provide valuable imagery of the ice conditions along the initial and final portions of the NDS track, as well as of the ice in the marginal seas of the Arctic Ocean. This will be useful, and arrangements to make this possible should be initiated as soon as possible.

However, what the NDS program actually needs is real-time, all-weather imagery over the complete drift track. There are two satellite series that can partially provide this type of coverage: DMSP and NOAA. The imagery produced by these satellites is somewhat similar (both visual and thermal IR), with DMSP being preferable because of higher resolution (0.5 km versus 1.0 km) and an appreciably less distorted projection. Also, the DMSP system has a wide variety of special image processing options that are particularly useful in the study of sea ice in that they can reveal subtle changes in the lead systems with great definition (Dickenson *et al.*, 1974). For both DMSP and NOAA, the satellite data-receiving systems are such that they could be installed directly on board the NDS. This is particularly true of DMSP, which comes in a portable van. In fact, the effective operation of such a shipboard satellite receiving station during the NDS drift would be the most important single component of the remote sensing program in that it would provide a real-time capability of examining the ice and meteorology in the central Arctic Basin during both the light and dark periods.

During most of the high-latitude (>80° N) portions of the drift track, there would be a potential of over 40 satellite passes overhead per day. This would allow the station operators to select only the best tracks. Also, the ability to have the original imagery immediately available on the drifting platform would greatly enhance its usefulness, particularly as related to a variety of operational problems.

Unfortunately, the ice observations possible via either the DMSP or NOAA systems are limited by the presence of clouds. This drawback can, to some extent, be obviated by utilization of the imagery that will be collected by the Scanning Multichannel Microwave Radiometer (SMMR) that is scheduled to be flown on Nimbus G. This system, which is similar to the SMMR on SEASAT, will take measurements in five spectral bands with ten channels (because of dual polarization) in the wavelength region between 0.8 to 6 cm. The spatial resolution of the elliptical footprint varies between 26 and 144 km depending on the frequency. The important advantage of the Nimbus G system over that of SEASAT will be caused by the fact that Nimbus G will be launched into a polar orbit, thereby permitting its SMMR to image the complete NDS track. These data will not be required on a real-time basis. However, if interesting features appear on the imagery that could be investigated by the staff on the drift station, the processed imagery could be flown to the ship on the next resupply flight. Again, arrangements should be initiated to assure rapid transmittal of the SMMR imagery to the NDS project office and then to individual investigators.

3.3. Land-Based Aircraft Program

Because of aircraft range limitations, the development of an effective land-based remote sensing effort during the first part of the NDS program would undoubtedly require aircraft to refuel in Siberia. For instance, the operational range of the NASA 990 on its arctic flights is approximately 4600 km (5 1/2 hours at 832 km/hour). Assuming that a minimum useful mission would require one hour over the drift station, the maximum distance between the NDS site and the 990's base reduces to 1872 km (assuming the aircraft returns to the same base). The distance between Fairbanks and the start of the drift is, however, 2880 km; between Fairbanks and Tromsö, Norway, 4995 km; and between Fairbanks and Svalbard, 4100 km. Although such refueling arrangements are unlikely, they should be explored. For instance, it might be possible to arrange a joint U.S./U.S.S.R. remote sensing program, such as the highly successful BESEX program, that would permit the U.S. and Canadian planes to refuel. Assuming a refueling capability, a variety of large research planes such as the NASA 990, the NCAR Electra, and the Canadian Department of the Environment C-130 might participate.

Even if a land-based aircraft program cannot be arranged for the first part of the drift track, it can definitely be arranged for the latter part, inasmuch as the last two thirds of the track are within easy aircraft range if the aircraft is based out of Svalbard. A land-based aircraft program would allow the collection of very-high-resolution SLAR, microwave, IR, and visual imagery and allow an effective link to be made between shipboard ground-truth observations and the satellite imagery. However, it should be remembered that even at best, such flights would only be available during selected short periods. The flights should, if at all possible, be scheduled to examine the state of the ice cover during different representative times of the year (late winter, freeze-up, melt season). The flight paths should be arranged so that the data can make a maximum contribution to the satellite program and couple with the work in ice physics, which can readily provide ground truth on a variety of problems.

In addition to these pure remote sensing flights, valuable data can be collected by mounting selected instruments on the C-130 resupply aircraft. The principal problem here would be to modify the aircraft so that suitable instrument parts are available. This clearly will take considerable lead time. One useful experiment that could be carried out on the resupply flights would be the collection of long ice-roughness profiles (via laser) along possible sonar propagation paths between

NDS and land-based receiving stations. Other useful information would be the collection of simultaneous microwave and IR profiles along long tracks in the Arctic Ocean. Such flights should concentrate on providing information on ice that is beyond the range of NDS-based helicopters. Utilization of these resupply flights is advantageous in that they will be made on a reasonably regular basis (every one to two months, excluding the summer) and will assist in bridging the long temporal gaps that might occur between land-based pure remote sensing flights.

3.4. NDS-Based Helicopter Program

At present, the only aircraft that are scheduled to participate in the NDS remote sensing program are the two helicopters that will be based on the drift station. Helicopters are hardly ideal platforms for such work because of vibration problems and limited space. Useful compact instrument packages would include camera systems, which could be mounted completely external to the cabin, a laser profilometer, an IR profiler, a pulsed radar for measuring ice thickness, and a multispectral microwave profiler. Because of space limitations, all of these systems could not be operated simultaneously. The systems would also have to be removed from the aircraft so that freight loads and equipment for other projects could be handled. Therefore, considerable thought should be given to the packaging of the sensing systems so that they can be rapidly installed in (and removed from) the helicopters. Because of their limited range, helicopters are only useful within a radius of approximately 160 km of the base station; i.e., they would be effective only within the inner ring of data buoys. Sets of remote sensing flights should be completed at least once a month. It should also prove possible to obtain much of the needed remote sensing data during flights that are made for other projects, for example, during aeromagnetic surveys, gravity traverses, or buoy maintenance and repair flights. Again, to do this the instrumentation must be as compact and as portable as possible. This is not necessarily difficult, but it does take time. Also, lead time is required to install instrument ports in the helicopters. The principal drawback in the helicopter program is that the data collected will, with the exception of the photography, all be profile as opposed to areal coverage. Because of the larger space requirements of scanning systems, it appears unlikely that they could be accommodated in the helicopters.

There is some possibility that a STOL aircraft such as a Twin Otter would be based on an ice runway near the drift station during part of the field season. Such an aircraft provides a much more desirable remote sensing platform than does a helicopter. If this occurs, plans should be modified to use it as much as possible in the remote sensing program. Its longer range would also permit remote sensing flights to be extended to the outer array of data buoys.

3.5. NDS-Based Ground-Truth Program

It should be easy to develop an excellent ground-truth program for remote sensing. This would primarily be carried out by the investigators running the ice physics studies, inasmuch as much of the needed information is required by both groups. For instance, a knowledge of the temperatures, compositions, internal structure, electrical properties, and surface topography of the various identifiable ice types that occur within the buoy array would be highly desirable. Also, calibrated sites and tracks can be laid out to verify the results of the pulsed-radar ice thicknesses determinations and to act as controls in the estimation of ice thicknesses via IR measurements and in developing methods for predicting bottom topography from surface topography. In addition, a series of time-lapse photographs should be taken of the Plan Position Indicator (PPI) display of the ship's radar. This will provide a continuous record of the formation of leads in the near vicinity of the ship and will contribute to the interpretation of the radar transponder and sono-buoy ice-deformation array located within 30 km of the ship.

3.5. Frequency, Times, Schedules

Satellite imagery should be obtained as often as possible. The exception to this is the DMSP program with its large number of possible satellite passes per day. In this case, the best combinations of orbit and sensor should be selected so that two images per day are obtained. Additional images could be acquired as needed.

In the land-based aircraft program, the flights should be spaced so that interesting and representative conditions are sampled. For example, flights should be scheduled during the peak of the melt season, the freeze-up and the winter or early spring. If observations are made from the resupply flights, these will occur at either one- or two-month intervals, which is certainly adequate for sampling changes that occur with season.

The helicopter observations should be made monthly, with the scheduling arranged so that a maximum amount of remote sensing information is collected on flights that are required for other purposes. Special flights could, of course, easily be arranged as needed.

The remote sensing program would continue during the complete lifetime of the NDS experiment.

3.7. Personnel Required

It will take a minimum of four people to operate the DMSP station if it is placed on the NDS. These people should be extremely capable electronics technicians, who could also assist with instrument problems that are encountered during the operation of the helicopter-based remote sensing program. The main responsibility of the helicopter program would be handled by an investigator, who would also assist with the ice physics program.

Data analysis would require roughly four additional people full time, both during the period of ice drift and for one year after the completion of the field program.

3.8. Data Management

The main problem in this area is the difficulty in reproducing a large number of duplicate copies of the map-type imagery. This should probably be handled by a large processing laboratory as soon as the original copies of the imagery are returned to the United States via the resupply flight. Copies of the images and duplicates of the data tapes would then be sent to principal investigators as required.

4. LOGISTICS

4.1. Movement of Staff

Personnel will have to be rotated on a schedule arranged so that continuity of staffing is maintained. The details of the scheduling would, of course, depend on the spacing of the resupply flights. Three months is probably a useful residence time on the station (efficiency usually declines after three months).

4.2. Needed Installations

The DMSP ground station comes in a portable trailer that can be installed directly on the ship's deck. It may prove advantageous to "devan" the equipment and place it in two rooms on the ship. This would not be difficult, but it would take a month or two of work to complete. It will also be necessary to install a DMSP tracking antenna on the ship. In addition, a small (4 m x 4 m) refrigerated structure should be placed on the deck for use as a coldroom by the ground-truth group.

4.3. Power

The DMSP van has its own power unit, but it would be advantageous to operate off the ship's power. The exact power requirements are presently unknown.

4.4. Communications

No special communications problems are anticipated other than to note that good radios that would allow contact between the ground-truth parties, the helicopters, and the ship would be necessary.

4.5. Flight Support (Helicopter)

Extensive helicopter support will be required for shipboard remote sensing. For planning purposes, we will assume that six each 125-km-long flight lines arranged in a hexagonal pattern that radiates out from the ship will comprise the remote sensing flight pattern. Assuming that a given helicopter flight can travel 400 km, each mission would consist of a 125 km leg out, a 125 km outer segment of the hexagon, and 125 km leg home, which would complete a 60° triangular portion of the hexagon. Three such triangular flights would comprise the monthly remote sensing series with an estimated total of ten flight hours. If two hours of helicopter support are added for ground-truth studies, this gives a minimum total of 12 hours of helicopter flight time per month.

4.6. Surface Transportation

A small, tracked vehicle will be required by the ground-truth party. At least two small snowmobiles would also be desirable.

4.7. Volume of Equipment

The major item will be the DMSP van, which is the size of a small house-trailer. Additional equipment needed for the helicopter and ground-truth programs is estimated to have a cube of 20 m^3.

5. COST ESTIMATES

The cost of deploying the DMSP unit aboard the NDS is unknown. There are operational DMSP groups in both the Navy and the Air Force. It is possible that the DMSP support can be arranged at little cost to the NSD program with the exception of salaries (a value of $50,000/man year will be assumed).

DMSP station (4 man-years)	$200,000
Helicopter remote sensing (1 man-year)	50,000
Ground truth (3 persons for 2 months/year)	25,000
Travel and freight	30,000
Data analysis (4 man-years)	200,000
TOTAL COST PER YEAR	$505,000
Cost assuming 2 years of operation plus 1 additional year of data analysis	$1,210,000

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III
LOGISTICS AND OPERATIONS

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III

LOGISTICS AND OPERATIONS

1. Introduction

The NDS project is expected to be based on a WIND-class icebreaker.

The ship will depart from the United States west coast and, under its own power, proceed to the beginning of the drift track. At this point, the propulsion plant will be shut down and the ship will drift with the ice.

The ship will keep its life-support systems running and thus provide a safe platform for scientific activities on board. Also, it will provide support for scientific activities for permanent and temporary field camps on the ice at some distance from the ship.

Logistics support will be required for research in a number of scientific disciplines. A preliminary statement on support requirements is given in Chapter 6-15.

2. Significant Problems

A WIND-class icebreaker cannot be used for this project in its present operating configuration. The ship's fuel capacity is not sufficient for remaining passive in the ice, even if the propulsion system is inactive. Also, the capacity for carrying aviation fuel for ship-based support aircraft is not sufficient because the standard rotary-wing aircraft that are commonly used for supporting icebreaking activities are smaller aircraft that require significantly less fuel than the aircraft to be used for supporting the NDS project.

The standard icebreaker has only limited space for supporting oceanographic activities and thus does not have sufficient space for most of the proposed scientific activities.

The icebreaker, however, can be modified to accommodate the NDS program. A feasibility study for the conversion of the ship was initiated in mid-February 1976. The study will yield cost estimates for the necessary modifications and also a basis for specifying detailed design changes and shipyard work.

A significant problem is timing. The submission of engineering change orders for the ship work must precede the scheduled departure of the ship from the United States west coast port by about 14 months. Assuming normal ice conditions, the only time of year that the ship can commence its passive drift in the northern Laptev Sea is September or early October (see time table, Chapter 4).

3. Logistics Planning

A detailed planning process for the NDS project should commence as soon as a decision has been made to provide basic operations funding for the project. Individual proposals for the various science disciplines should be submitted soon thereafter.

A preliminary field operations plan, along with cost estimates for the operations and field support, should be prepared when the individual proposals are submitted. Certain changes of the operations plan will become necessary as the scientific program develops.

4. Operations

4.1. Deployment

The *Burton Island* is the icebreaker that will probably be assigned to the NDS project. She is presently homeported in Long Beach, California. It is assumed that the modifications to the ship will be made on the west coast. The shipboard scientific equipment should be installed at the yard, and the rest of the scientific and support equipment should be loaded on the ship at the departure point. The first scientific crew should embark at the same point, since the ship will not make port calls along the coast, with the exception of Dutch Harbor in the Aleutian Islands, where fuel will be taken on. The ship will continue to the Laptev Sea before freeze-up and program GP-1 of the marine geophysics and tectonics program (see Chapter 6). Upon completion of these activities, it would be desirable to have all fuel tanks topped off by another icebreaker before the ship is inserted in the ice at approximately 78.5° N and 137° E.

4.2. Field Operations

Once the ship has gone into a passive status in the ice, the operations away from the ship can commence. Small field camps will be constructed on the ice pack as required. The permanent camp structures should be modular, prefabricated, collapsible, and transportable by helicopter. The temporary camp structures should be of any suitable frame-and-canvas type. The outlying camps will be supported by ship-based rotary-wing aircraft. It is assumed that a fixed-wing STOL aircraft will be based near the ship. These aircraft will support activities that are farther away from the ship and outside the helicopter's range limits.

The fixed-wing aircraft cannot follow the ship continuously during the drift. Ice and runway conditions will dictate the fixed-wing aircraft availability. From previous experience one can assume that fixed-wing support can be obtained before darkness in the fall and after sunrise until surface melt begins in the spring. Limited fixed-wing support may be possible by small aircraft during the summer seasons.

4.3. Support Personnel

It is anticipated that a greatly reduced U.S. Coast Guard complement will operate the ship, and a contractor will operate the support aircraft.

A chief scientist and a manager of field operation will be on board the ship at all times. A number of experienced support personnel to construct and maintain remote camps and assist the various research groups in specific tasks will be provided.

4.4. Crew Rotation

Since the ship will be some distance from any point in the United States or Canada during the first year of the drift, it will be difficult to maintain a regular flight schedule between the ship and the shore. Approximate distances to feasible departure points in Canada and Svalbard are shown in Table III.1. The first crew change could occur in February, the second in mid-April, and the third in mid-September.

Since one complete crew rotation would cost approximately $100,000 in 1976 money, only three such rotations should be planned per year.

It is desirable to use C-130 Hercules aircraft to rotate crews. However, it may be difficult to find a runway long enough (1500 m) and near the ship. The artificial construction of a runway by leveling and flooding is possible only under special circumstances. An alternate aircraft is the C-117 (Super DC-3). The Naval Arctic Research Laboratory has recently acquired two of these. The C-117 is considerably smaller than the C-130 but does not require more than approximately 900 m of runway, a length much easier to find on the ice.

One would possibly have to use a C-117 aircraft for the crew rotations that will occur in the fall. At that time, the ice is not strong enough to support C-130 landings.

Initially, Barrow (Alaska) and Alert (Ellesmere Island) are about equally far from the ship. After the first winter and throughout the year, the projected drift track approaches both Longyear Byen (Svalbard) and Alert. The choice of logistic support bases will depend on a number of circumstances that will be evaluated as planning progresses.

4.5. Ship Support

4.5.1. Ship Conversion

1. A design study is presently under way at the Puget Sound Naval Shipyard. It takes into account some of the major modifications required to accommodate the scientific program. A special problem is fuel. The ship's existing tanks are insufficient to hold the diesel and aircraft fuel needed for the duration of the drift. Efforts are being concentrated on finding an economic and safe method of carrying additional fuel in a secondary ship or barge. A fuel resupply by air will be both costly and difficult.

2. A general layout will show where and in what manner existing gear, such as cargo-handling cranes and life-saving appliances, must be rearranged.

3. The interior of the ship has to be modified to some extent also. The existing icebreaker normally carries a crew of approximately 200. The proposed total crew, scientific personnel included, totals no more than 110. Excess sleeping and living areas will be converted into science work areas and storage space.

4.6. Accommodations

The ship will provide electrical power, heated working space for science laboratories, a large oceanographic winch, navigations systems, living areas for the entire crew, storage space for scientific gear, communications, hanger space, and fuel for two helicopters, and fuel for a fixed-wing aircraft based near the ship.

4.7. Ship Mobility

The actual drift of the station may be quite different from the one projected on the basis of average flow patterns. If the deviation is not acceptable to some of the scientific programs, the ship will, during the summer, attempt to use its power plant to return to the desired drift track. Before this occurs, all the permanent and temporary installations have to be brought back to the ship. They will be redeployed after the ship has reached its new position.

4.8. Air Support

In order to support scientific work at considerable distance from the ship several aircraft have to be based on the ship or near it.

Based on previous operational experience on the pack ice, it is recommended that one or two fixed-wing aircraft be used when daylight is available and ice conditions permit.

Rotary-wing aircraft based on the ship are considered necessary, and it is recommended that two helicopters be deployed throughout the entire drift of the ship.

Several suitable types of aircraft are described below.

Twin Otter. This aircraft should be equipped with complete instrumentation for instrument flying: a VLF navigation system, astrocompass for celestial navigation, VHF and HF communications systems, fuel transfer system for refueling the tanks from fuel drums carried internally, and ski landing gear.

The following performance data are typical for a Twin Otter aircraft and can be used for planning purposes.

Speed: 122 knots (225 km/hour)
Payload: for 175 nm (320 km) 3200 lb (1452 kg)
350 nm (640 km) 3000 lb (1362 kg)
525 nm (960 km) 2400 lb (1090 kg)
Endurance: 4-1/2 hours with normal tanks

These performance data include fuel reserves for 100 nm diversion and 45 minutes in holding.

Also, these data change somewhat from aircraft to aircraft depending on the actual empty weight of each individual aircraft.

The current cost for such an aircraft is $400 per hour.

Helicopter Bell 205A-1. This aircraft should be equipped with complete instrumentation for instrument flying: a VLF navigation system astrocompass for celestial navigation, VHF and HF communications system, long-range tanks, ski-skid landing gear with portable wheel gear, and sling gear for external loads.

The following performance data are typical and can be used for planning purposes:

Speed: 90 knots (167 km/hour)
Maximum external load for moving gear locally: 5000 lb
Maximum internal load for moving gear locally: 4000 lb
Payload: for 90 nm (167 km) 3400 lb (1590 kg)
180 nm (335 km) 3800 lb (1270 kg)
270 nm (500 km) 1800 lb (817 kg)
Endurance: 4 hours

The current cost for such an aircraft is approximately $590,000 per year.

Helicopter Alouette 11. This aircraft should be equipped for instrument flying: a VLF navigation system, astrocompass for celestial navigation, VHF and HF communications system, ski-skid landing gear with portable wheel gear.

The following perfomance data are typical and can be used for planning purposes.

Speed: 90 knots (167 km/hour)
Payload: for 90 nm (167 km) 1000 lb (450 kg)
Endurance: 4 hours

The current cost for this aircraft is $270,000 per year.

C-117, Super DC-3. This aircraft can be used for crew rotation and resupply, if the C-130 "Hercules" cannot be used. It requires less runway length than the C-130. The required runway length is approximately 3000 ft (914 m).

The C-117 is considerably smaller than the C-130; however it has payload range characteristics that will be sufficient to fly safely between the ship and the shore.

The following performance data are typical for a C-117 aircraft and can be used for planning purposes.

Speed: 168 knots (311 km/hour)
Payload: for 860 nm (1592 km) 9000 lb (4086 kg)
1200 nm (2222 km) 6400 lb (2361 kg)
1670 nm (3093 km) 5200 lb (2361 kg)
1840 nm (3408 km) 4000 lb (1816 kg)
2200 nm (4074 km) 2000 lb (908 kg)

These performance data include 3 hours of fuel reserve for diversion and holding. The current cost for such an aircraft is $400 per hour.

C-130, Hercules. This aircraft can be used for crew rotation and resupply. It requires a minimum runway length of 5000 ft (1524m).

The following performance data can be used for planning purposes.

Speed: 270 knots (500 km/hour)

Payload: for 1500 nm (2778 km) 40,000 lb (18,160 kg)
2000 nm (3704 km) 35,000 lb (15,890 kg)

These performance data include fuel reserve for 300 nm (556 km) diversion and holding.

The current cost for such an aircraft is $7.00/nm.

Summary of Twin Otter and Helicopter Flying and Fuel Requirements

	Twin Otter	Bell 205A-1	Alouette 11
1. Marine Geophysics and Tectonics	300	400	100
2. Marine Geology and Paleoclimatology	480	-	200
3. Physical Oceanography	543	-	50
4. Biology and Biochemistry	-	-	-
5. Marine Acoustics	454	43	186
6. Heat and Mass Balance of the Ice Cover	-	-	40
7. Troposphere	-	-	-
8. Ice Physics and Engineering	183	-	101
9. Atmosphere-Ionosphere-Magnetosphere	-	-	-
10. Remote Sensing	150	150	-
11. Logistics and Support	250	125	65
TOTAL	2360 hours	718 hours	742 hours

The Otter requires 75 gallon/hour; 177,000 gallons of JP-5 is required.

The Bell 205A-1 requires 100 gallon/hour.

The Alouette requires 25 gallons/hour.

Both helicopters use JP-4 fuel; 92,850 gallons of JP-4 is required.

Table III.1 Great Circle Distances from Estimated Drift Track To Shore Stations

Date	Drift Track		Alert, N.W.T.	Nord, Greenland	Longyear byen, Svalbard
	Position		82°30' N	81°50' N	78°15' N
			62° W	18° W	12°30' W
Year 1					
October	78.5° N	137° E	1125 nm	1152	1345
December	80.3	134	1022	1040	1232
Year 2					
February	82.1	128	920	922	1112
April	83.7	119	828	808	996
June	84.9	99	746	685	865
August	85.3	84	701	614	788
October	85.6	68	625	540	710
December	85.5	36	556	396	563
Year 3					
February	84	01	429	190	364
April	81.1	10° W		84	173

The distance from Barrow, Alaska, for the first three drift track positions: 1046, 1060, and 1089 nm respectively.

Tentative Operations Cost Summary

	Cost in $ Thousand
Modification of icebreaker	4,000
Operations of ship, including crew and fuel	7,900
Bell 205A-1 helicopter	2,263
DeHavilland Twin Otter support	944
C-130 aviation fuel resupply	1,120
Aviation fuel	145
Crew rotation, 6 times	700
Field support equipment (wanigans, vehicles, communications, miscellaneous field equipment)	600
TOTAL	17,672

APPENDIX A: EXPLANATION OF FIGURES

PROJECTED DRIFT TRACK OF THE PROPOSED NANSEN DRIFT STATION (PREPARED BY FLEET WEATHER FACILITY, SUITLAND, MD., OCTOBER 1975)

FIGURES 1-4

Theoretical direction and distance of 30-day drift from selected points throughout the Eurasian Basin based on average geostrophic winds for a 24-year period 1946-1969. Resultant drift is a speed approximating 1.4 percent of the geostrophic wind speed north of the New Siberian Islands increasing to 2 percent in the diverging ice field nearing the exit west of Spitsbergen. These percentages are based on those reported by Nansen on the *Fram* expedition. Percentages are not adjusted seasonally, although it is likely that summer drift will be at a slightly higher rate than shown because of an increased number of water openings and winter drift conversely slightly less. Note: Permanent currents are not represented in Figures 1-4.

FIGURE 5

Anticipated track of the Nansen Drift Station based on actual tracks of (a) previous drift stations, (b) a comparison of these tracks with concurrent pressure charts, (c) permanent currents, (d) and Figures 1-4. An observation from review of previous stations transiting the Eurasian Basin is that few stations follow a "normal" drift path and there may therefore be little reason to expect the Nansen Drift Station to do so. The period of drift is expected to be 1-2 months shorter than that of the *Georgiy Sedov* (primarily because of the abnormally rapid easterly drift during the initial 3 months of the *Sedov's* voyage, Figure 1.1) and 4-6 months shorter than that of the *Fram*. Average monthly surface winds would not suggest a northwesterly drift as early in the mission as occured with the *Fram* (Figure 1.1), and a duplication of that drift is considered one of the lesser possibilities. Summer course reversals for extended periods, responsible in part for the longer drift of the *Fram*, although not rare, are less likely northward of the *Fram* track.

FIGURE 6

The predicted Nansen Drift track crosses or passes within 50 nautical miles of the tracks of a significant minority of previous drift stations, which subsequently followed a more northerly path. Figure 6 presents a generalized composite of these tracks. The track of NP-19, in particular, represents an interesting variation of this "secondary" track, drifting from north of the New Siberian Islands to within a few miles of the Pole and eventually reaching 87° N 56° W (very nearly into the Pacific Gyre) before turning southeastward into the East Greenland Drift Stream. Interestingly, this is the path favored by Figures 1-4, neglecting all other input.

FIGURE 7

Graphical expression of the remote possibility that a drift station could exit the Trans-Polar Drift Stream and enter the Pacific Gyre. Periods of abnormal drift will almost certainly be imposed upon the drift station during its life span. When, where, the magnitude, and nature of those anomalies as dictated by surface winds are almost totally unpredictable. Figure 7 is presented, as was Figure 6, only to emphasize that the projected track in Figure 5 is the most probable rather than certain track.

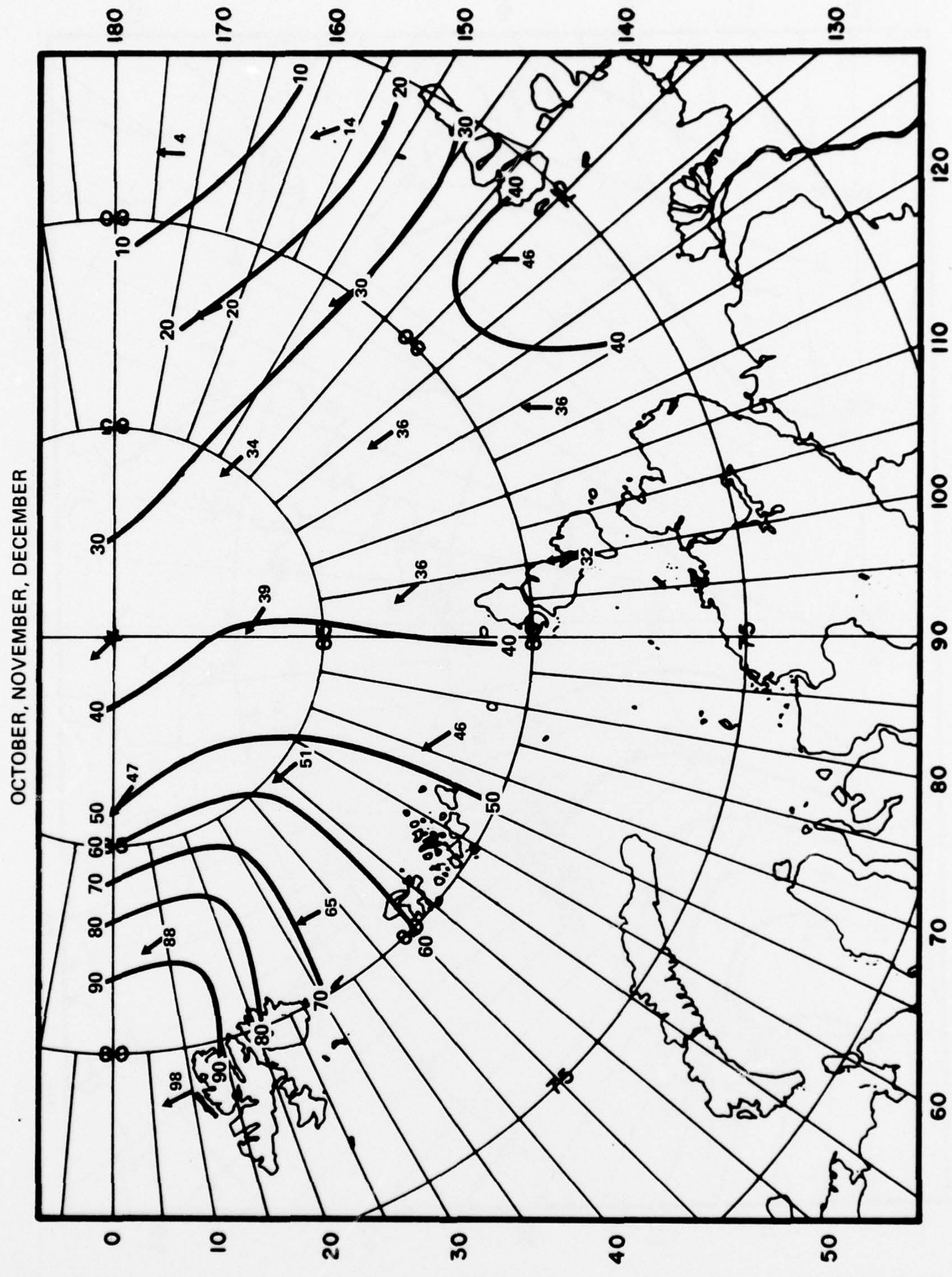
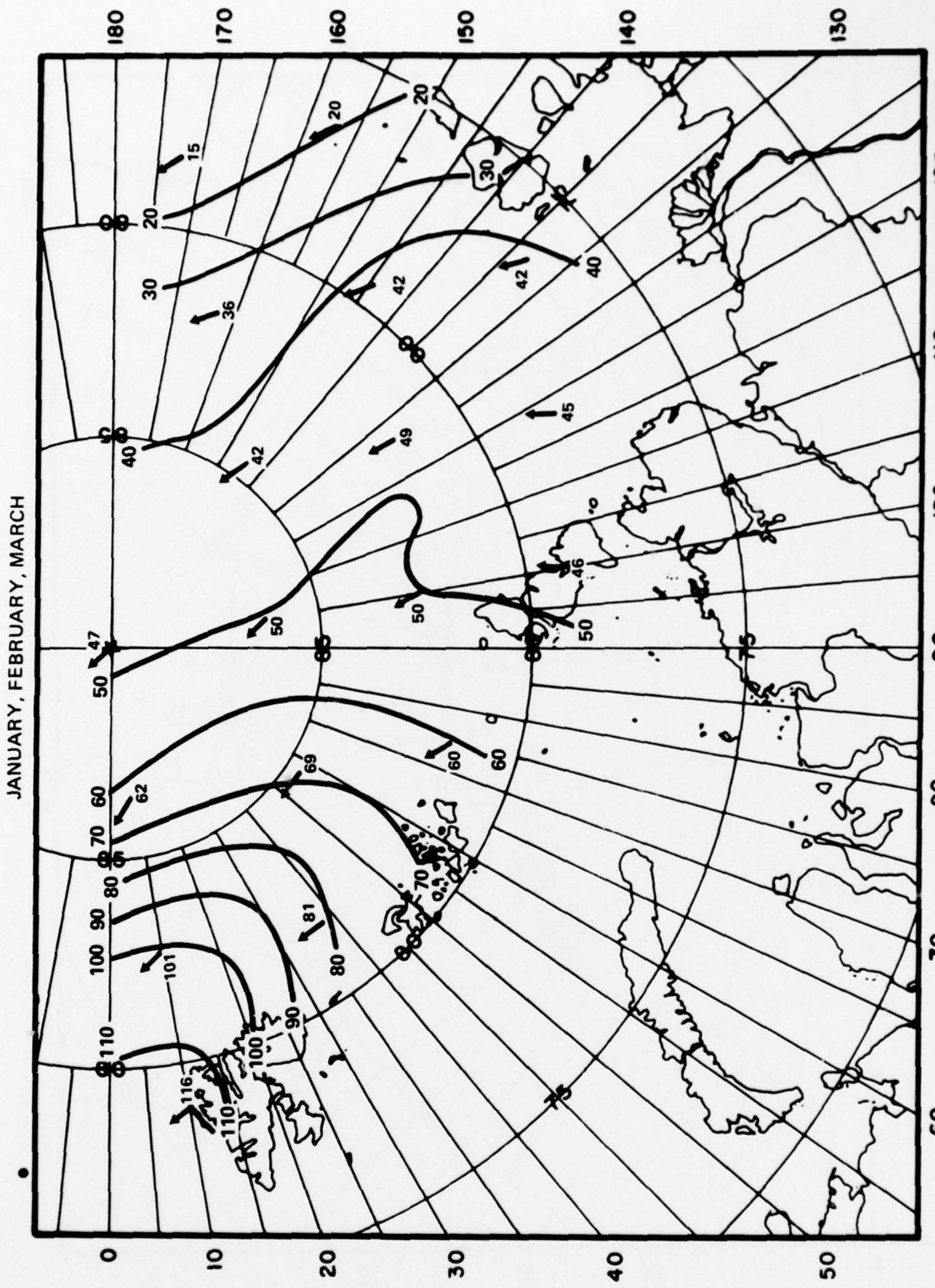


FIGURE 1 Theoretical 30-day ice drift due to wind (nautical miles).



JANUARY, FEBRUARY, MARCH

FIGURE 2 Theoretical 30-day ice drift due to wind (nautical miles).

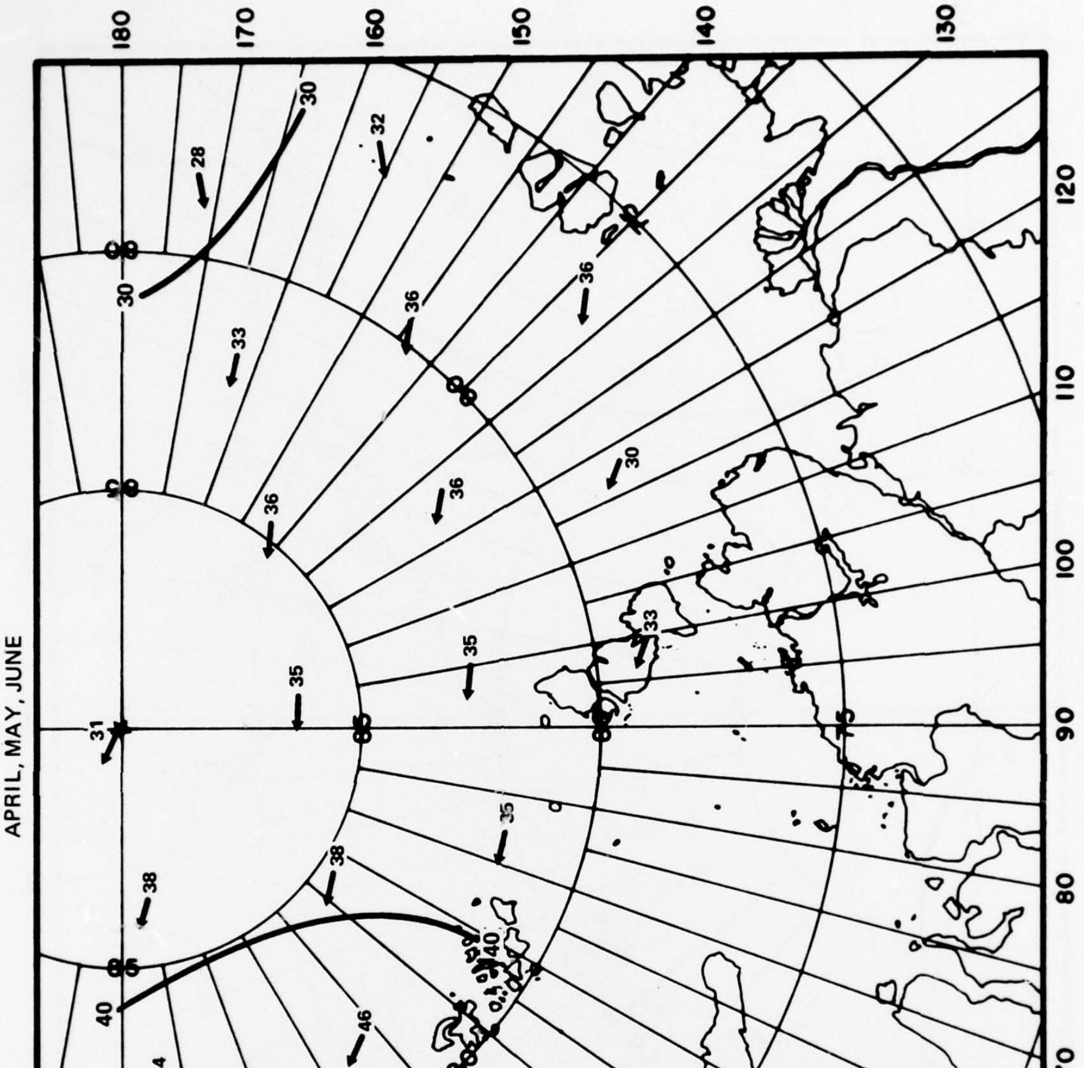


FIGURE 3 Theoretical 30-day ice drift due to wind (nautical miles).

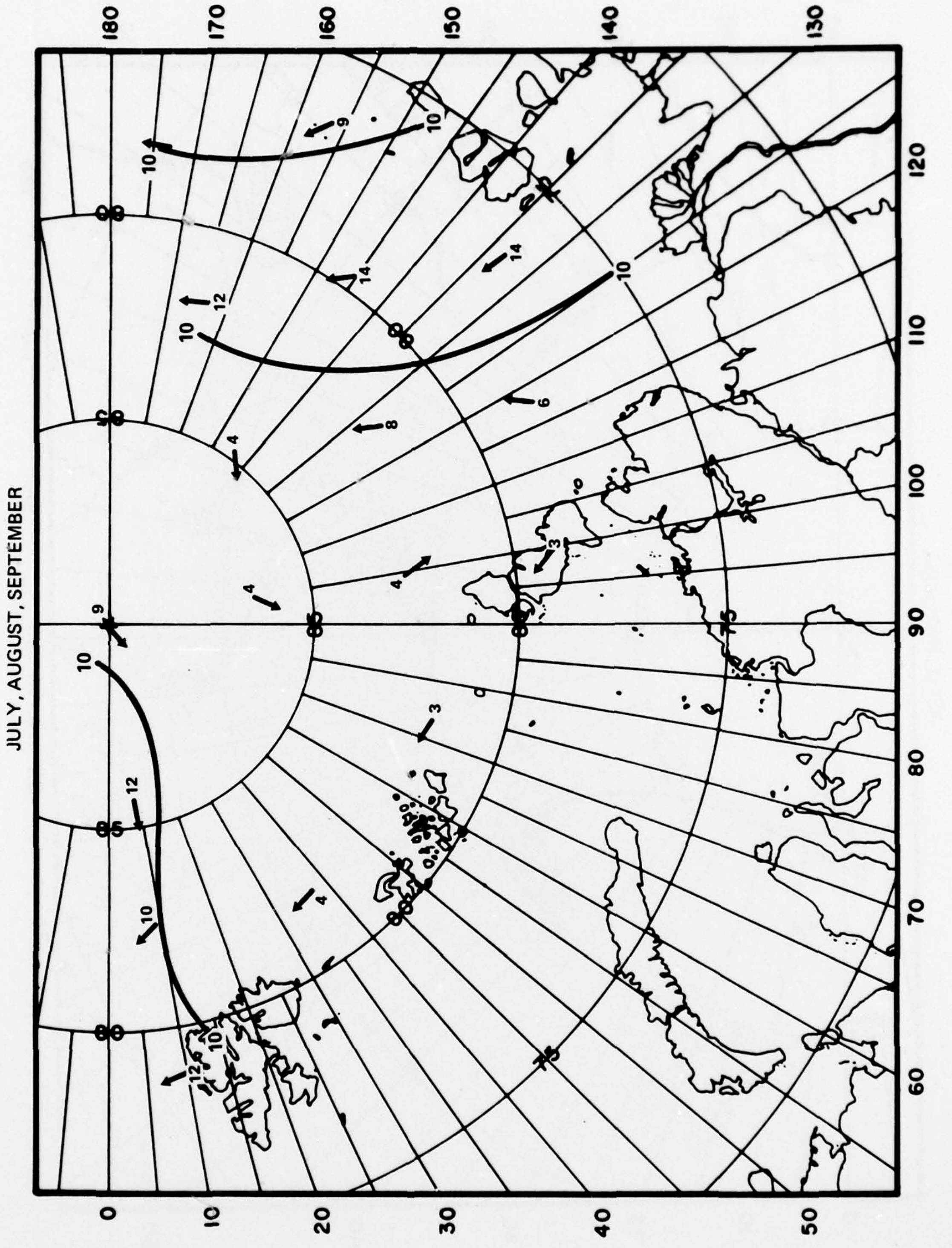


FIGURE 4 Theoretical 30-day ice drift due to wind (nautical miles).

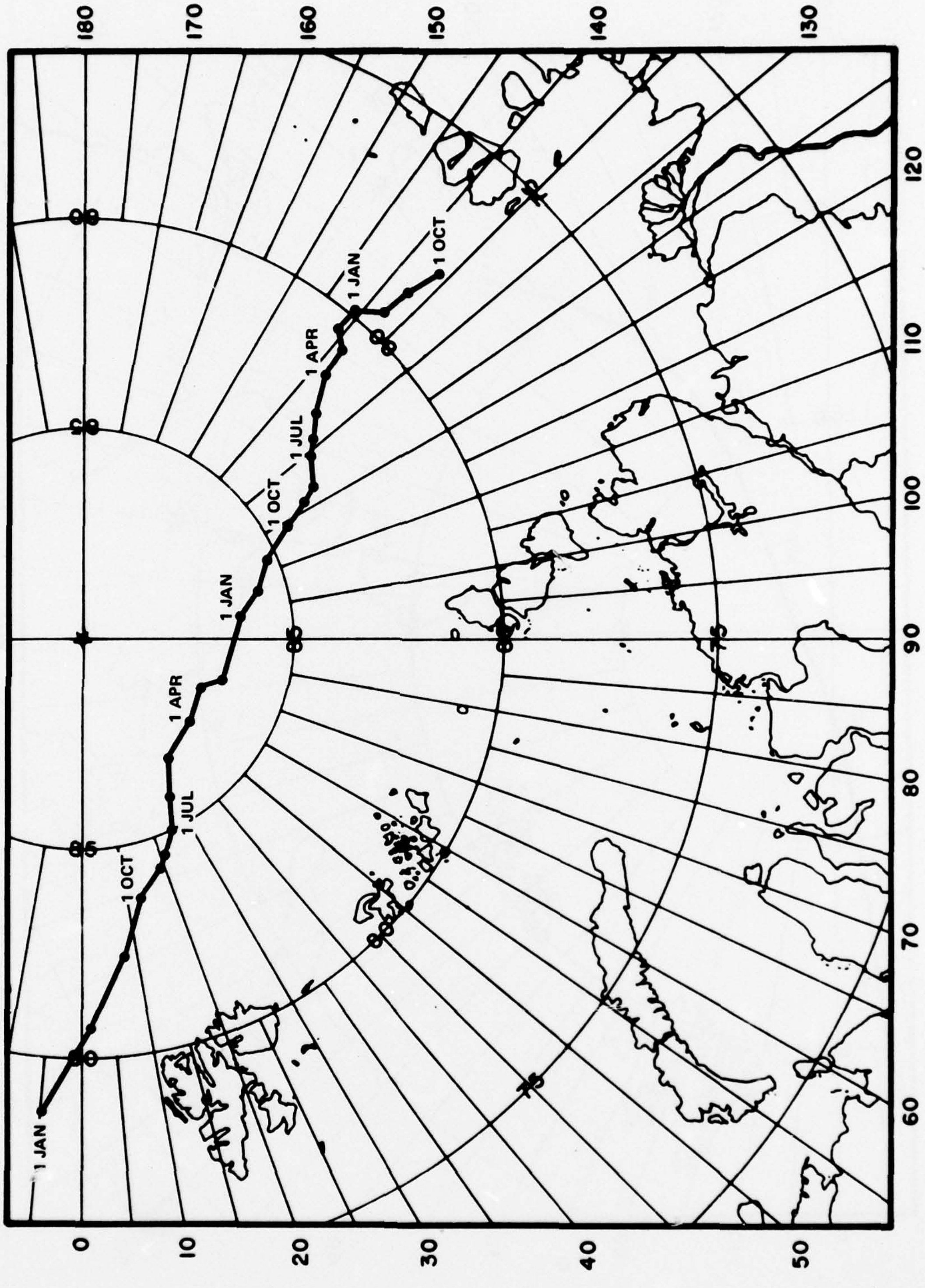


FIGURE 5 Predicted track of proposed drifting ice station, October 1976-January 1979.

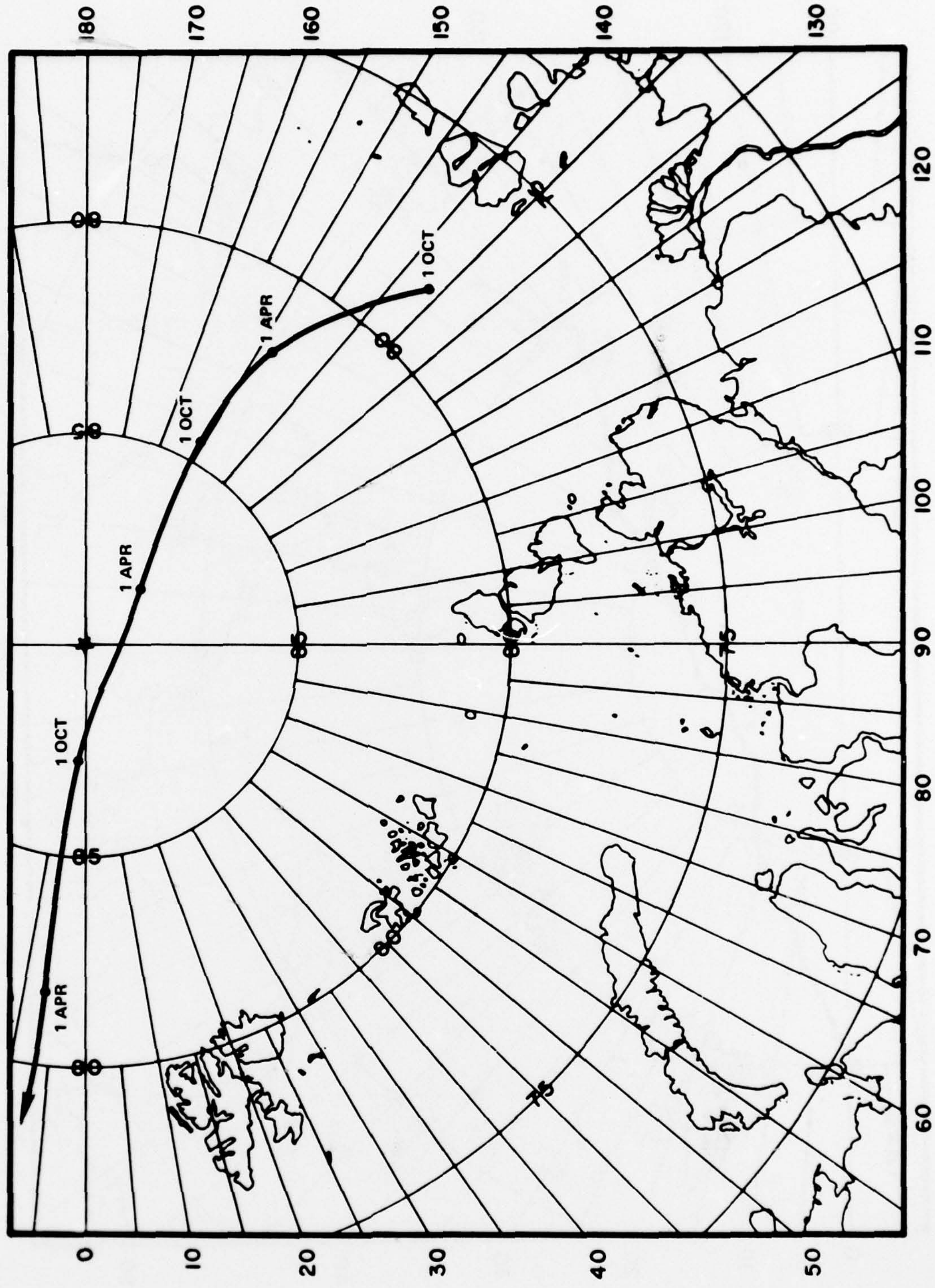


FIGURE 6 Alternate track based on composite drift of sizeable minority of prior drift stations.

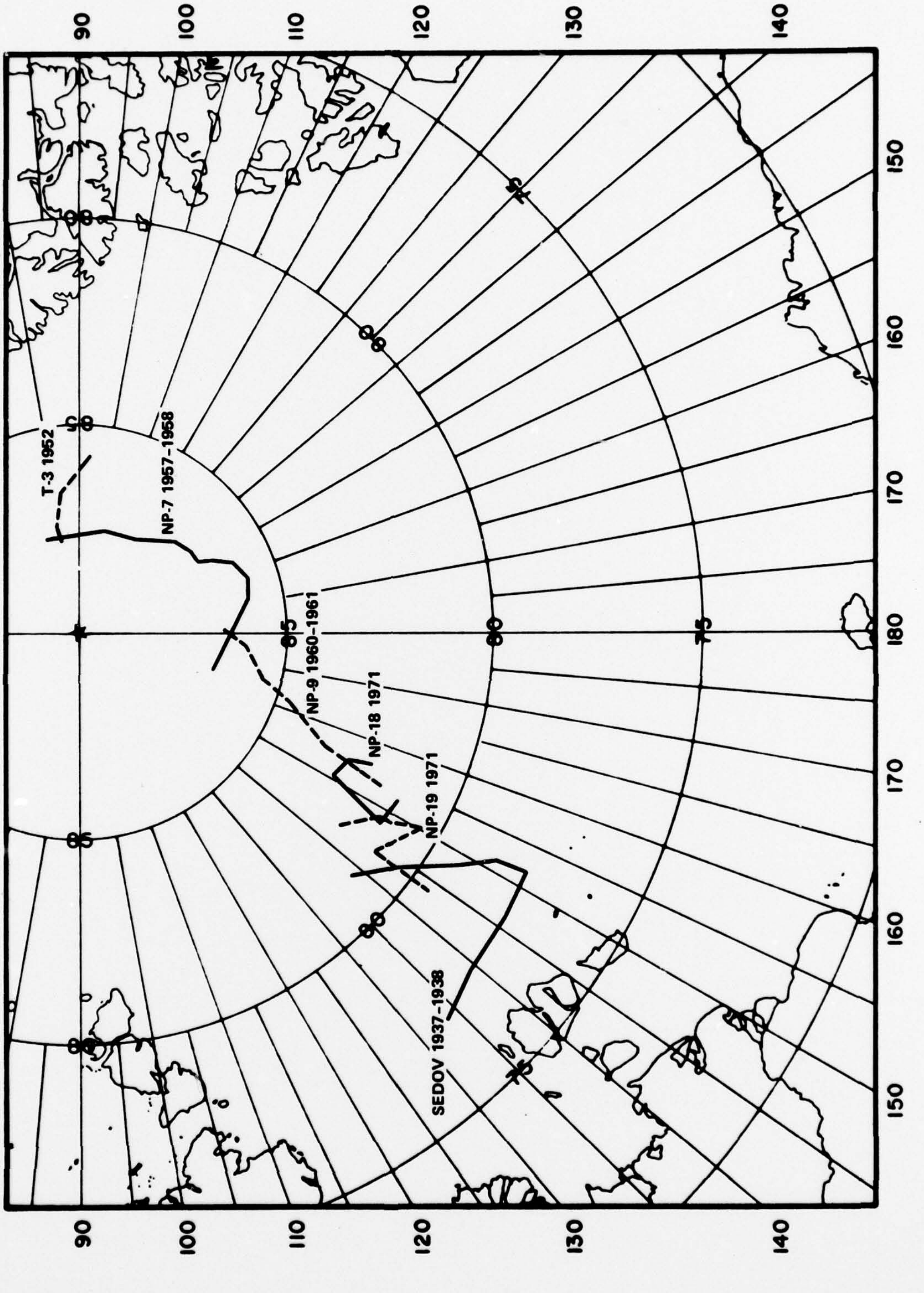
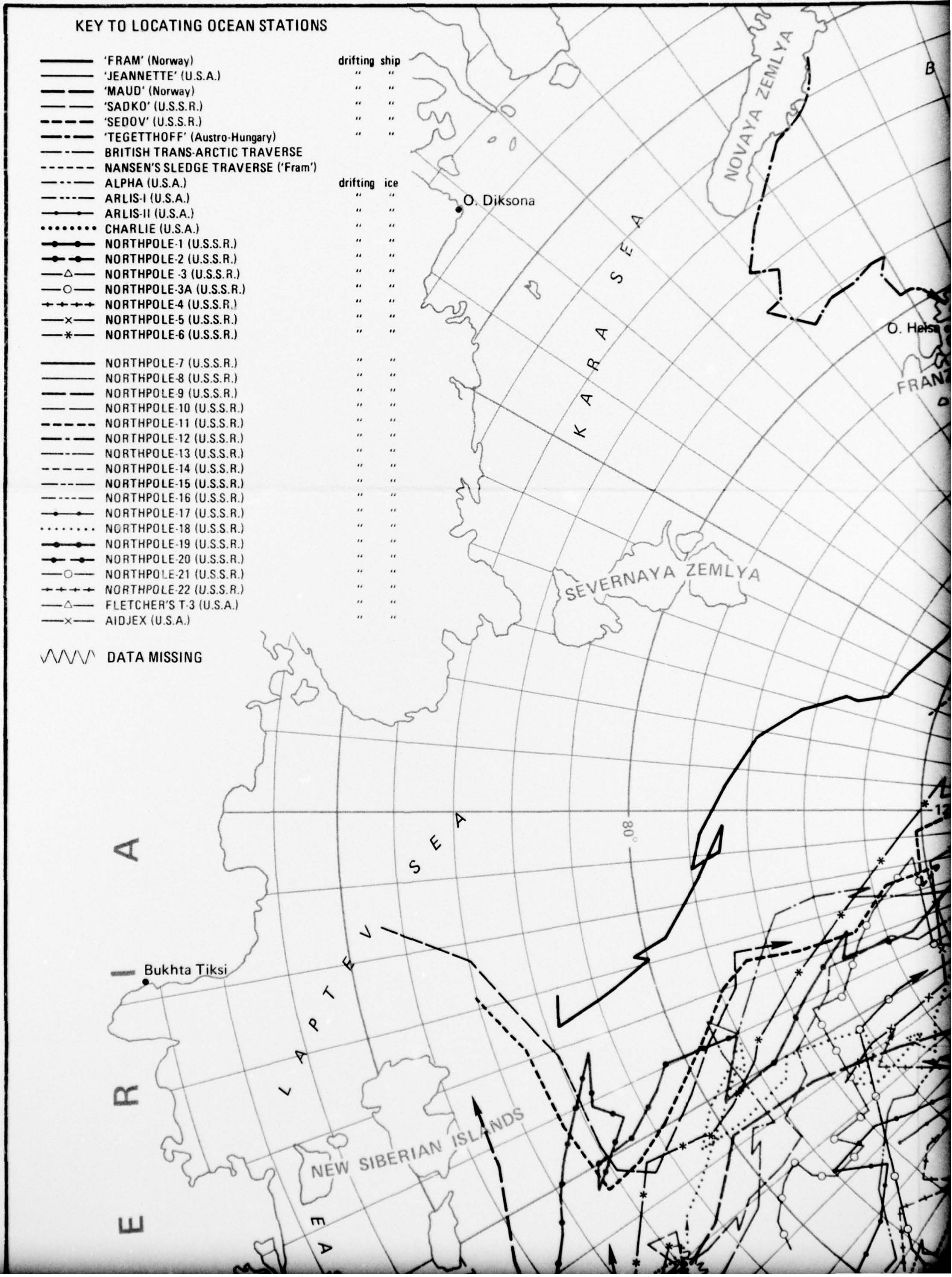


FIGURE 7 Partial tracks of selected arctic drift stations.

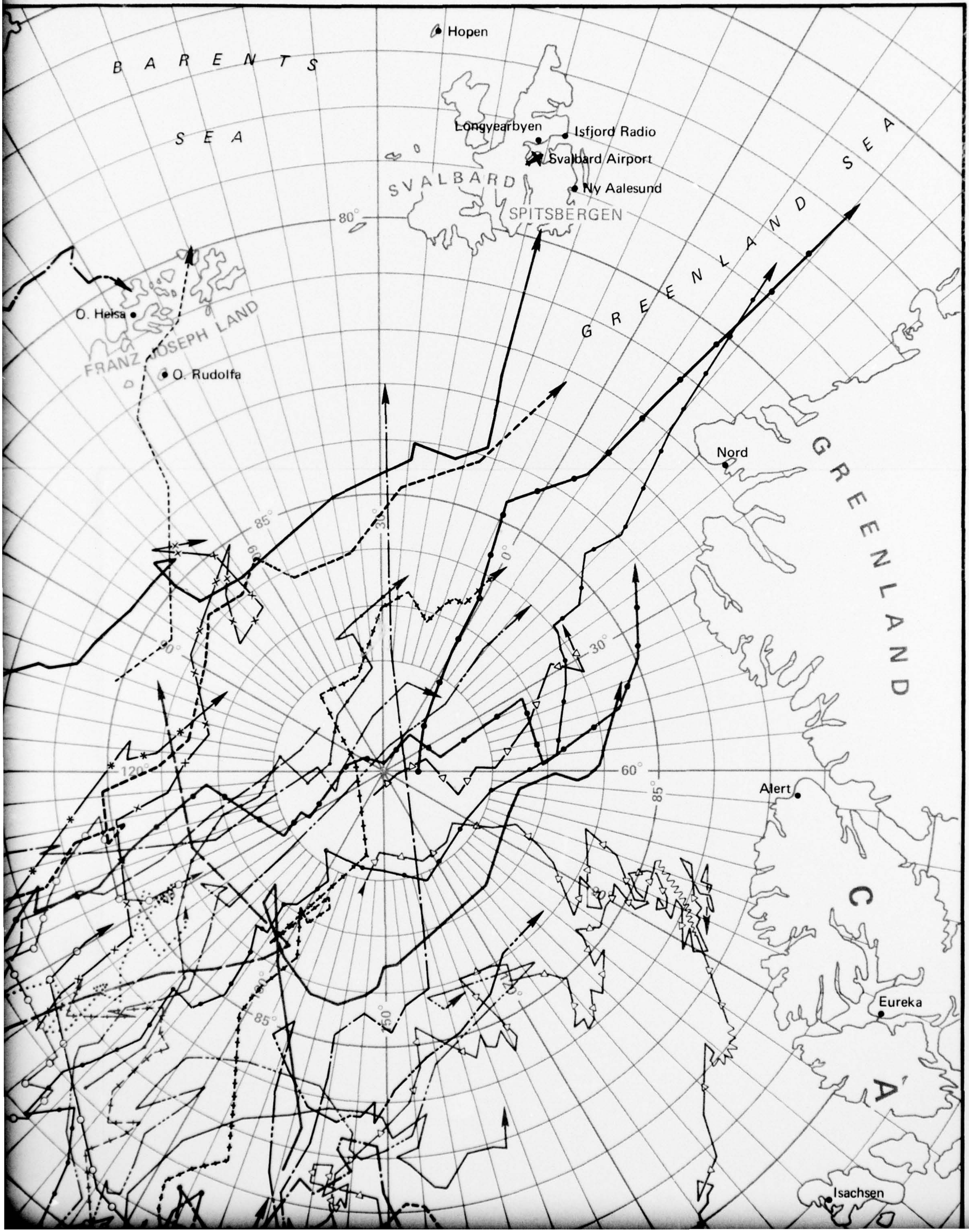
Summary of the Paths of Arctic Ocean Drifting Ships and Ice Stations

		Date
'Fram' (Norway)	Drifting Ship	10/93 - 1/96
'Jeannette' (U.S.A.)	" "	9/79 - 5/81
'Maud' (Norway)	" "	9/22 - 1/24
'Sadko' (U.S.S.R.)	" "	10/37 - 1/38
'Sedov' (U.S.S.R.)	" "	11/37 - 1/39
'Tegetthoff' (Austro-Hungary)	" "	8/72 - 1/73
British Trans-Arctic Traverse		3/68 - 1/69
Nansen's Sledge Traverse ('Fram')		3/95 - 9/95 - 4/96
Alpha (U.S.A.)	Drifting Ice	4/57 - 1/58
Arlis-1 (U.S.A.)	" "	9/60 - 1/61
Arlis-11 (U.S.A.)	" "	7/61 - 1/65
Charlie (U.S.A.)	" "	6/59 -
Northpole-1 (U.S.S.R.)	" "	5/37 - 1/38
Northpole-2 (U.S.S.R.)	" "	4/50 - 1/51
Northpole-3 (U.S.S.R.)	" "	7/54 - 1/55
Northpole-3A (U.S.S.R.)	" "	8/54 - 1/55
Northpole-4 (U.S.S.R.)	" "	11/54 - 1/57
Northpole-5 (U.S.S.R.)	" "	4/55 - 1/56
Northpole-6 (U.S.S.R.)	" "	5/56 - 1/58
Northpole-7 (U.S.S.R.)	" "	5/57 - 1/59
Northpole-8 (U.S.S.R.)	" "	5/59 - 1/62
Northpole-9 (U.S.S.R.)	" "	5/60 - 1/61
Northpole-10 (U.S.S.R.)	" "	11/61 - 1/64
Northpole-11 (U.S.S.R.)	" "	5/62 - 1/63
Northpole-12 (U.S.S.R.)	" "	5/63 - 1/65
Northpole-13 (U.S.S.R.)	" "	5/64 - 1/67
Northpole-14 (U.S.S.R.)	" "	5/65 - 1/66
Northpole-15 (U.S.S.R.)	" "	4/66 - 1/68
Northpole-16 (U.S.S.R.)	" "	5/68 - 1/70
Northpole-17 (U.S.S.R.)	" "	6/68 - 1/69
Northpole-18 (U.S.S.R.)	" "	11/68 - 1/70
Northpole-19 (U.S.S.R.)	" "	11/69 - 1/70
Northpole-20 (U.S.S.R.)	" "	5/70 - 5/72
Northpole-21 (U.S.S.R.)	" "	5/72 - 5/74
Northpole-22 (U.S.S.R.)	" "	9/73 -
Fletcher's T-3 (U.S.A.)	" "	4/52 - 1/70
AIDJEX (U.S.A.)	" "	3/74 -

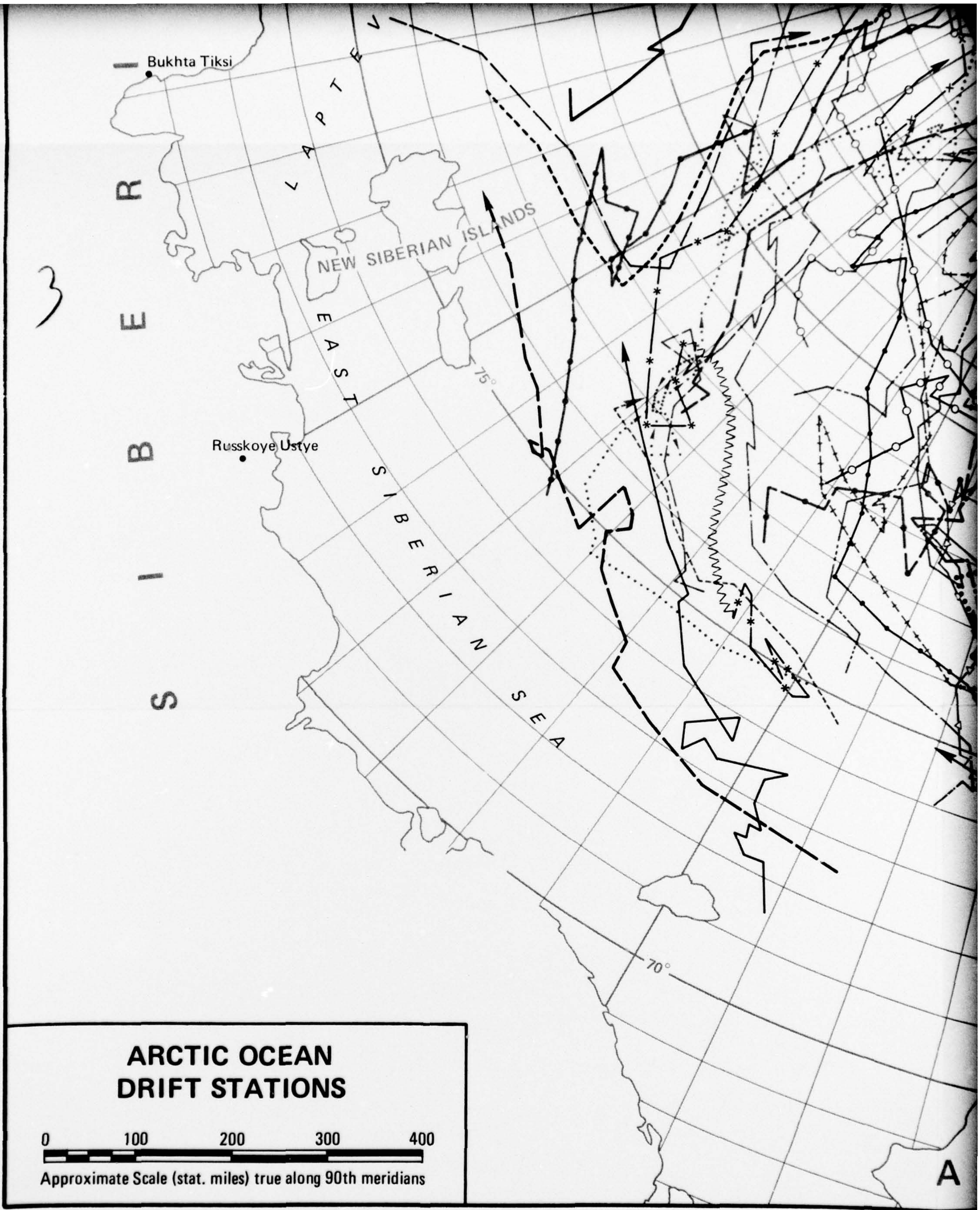
This list does not include short-term station and automatic data buoys. It is based on "Surface Climate of the Arctic Basin" U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia. Report number ETL-TR-71-5, December 1971 (prepared by A. D. Hastings, Jr.), augmented by recent information up to mid-1975.


KEY TO LOCATING OCEAN STATIONS
'FRAM' (Norway) drifting ship
'JEANNETTE' (U.S.A.) " "
'MAUD' (Norway) " "
'SADKO' (U.S.S.R.) " "
'SEDOV' (U.S.S.R.) " "
'TEGETTHOFF' (Austro-Hungary) " "
BRITISH TRANS-ARCTIC TRAVERSE
NANSEN'S SLEDGE TRAVERSE ('Fram')
ALPHA (U.S.A.) drifting ice
ARLIS-I (U.S.A.) " "
ARLIS-II (U.S.A.) " "
CHARLIE (U.S.A.) " "
NORTHPOLE-1 (U.S.S.R.) " "
NORTHPOLE-2 (U.S.S.R.) " "
NORTHPOLE-3 (U.S.S.R.) " "
NORTHPOLE-3A (U.S.S.R.) " "
NORTHPOLE-4 (U.S.S.R.) " "
NORTHPOLE-5 (U.S.S.R.) " "
NORTHPOLE-6 (U.S.S.R.) " "
NORTHPOLE-7 (U.S.S.R.) " "
NORTHPOLE-8 (U.S.S.R.) " "
NORTHPOLE-9 (U.S.S.R.) " "
NORTHPOLE-10 (U.S.S.R.) " "
NORTHPOLE-11 (U.S.S.R.) " "
NORTHPOLE-12 (U.S.S.R.) " "
NORTHPOLE-13 (U.S.S.R.) " "
NORTHPOLE-14 (U.S.S.R.) " "
NORTHPOLE-15 (U.S.S.R.) " "
NORTHPOLE-16 (U.S.S.R.) " "
NORTHPOLE-17 (U.S.S.R.) " "
NORTHPOLE-18 (U.S.S.R.) " "
NORTHPOLE-19 (U.S.S.R.) " "
NORTHPOLE-20 (U.S.S.R.) " "
NORTHPOLE-21 (U.S.S.R.) " "
NORTHPOLE-22 (U.S.S.R.) " "
FLETCHER'S T-3 (U.S.A.) " "
AIDJEX (U.S.A.) " "
DATA MISSING
NOVAYA ZEMLYA
B
O. Diksona
KARA SEA
O. Helsi
FRANZ
SEVERNAYA ZEMLYA
80°
LAPTEV SEA
Bukhta Tiksi
E R I A
NEW SIBERIAN ISLANDS
E A

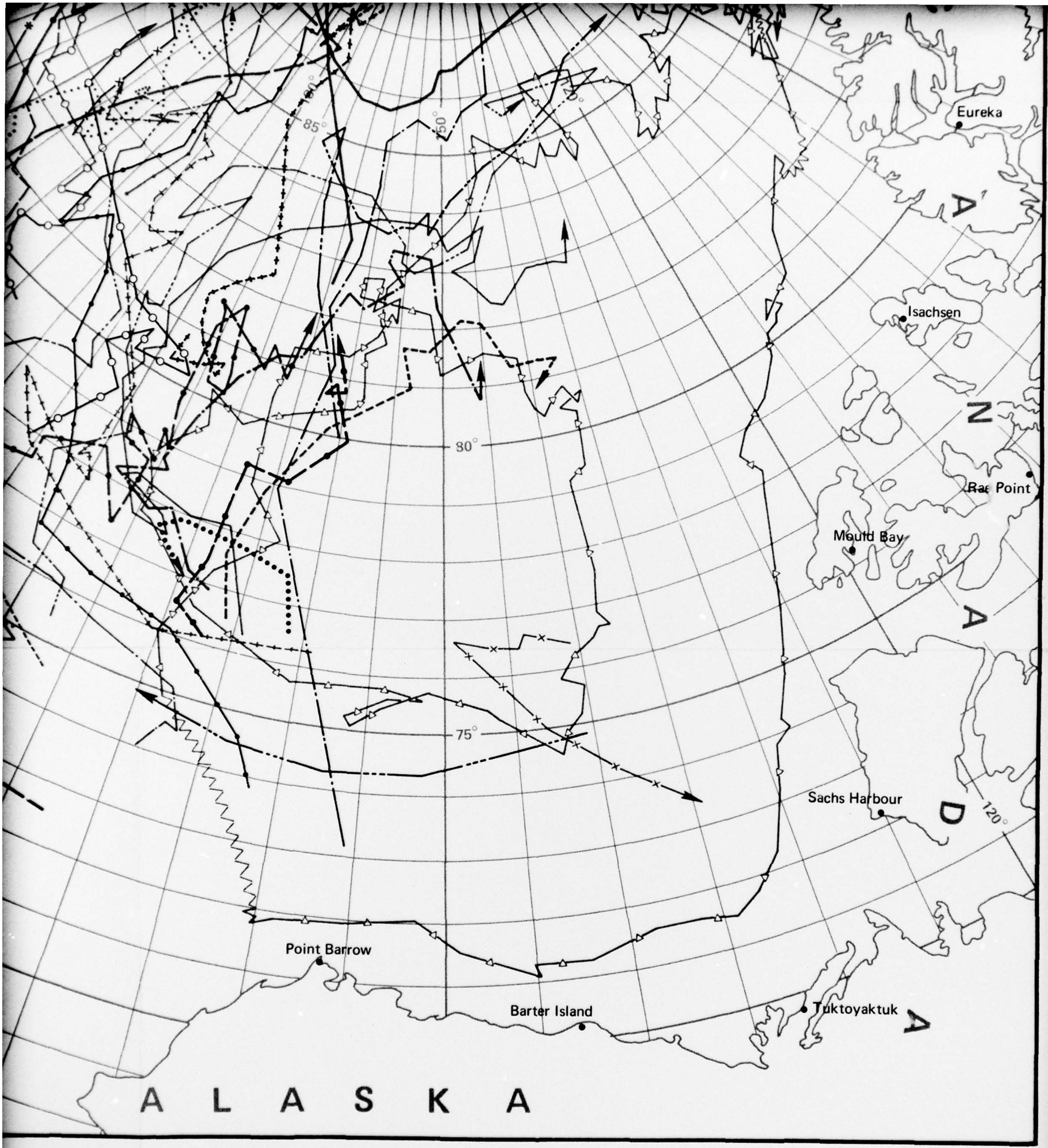
2



Hopen
BARENTS SEA
Longyearbyen
Isfjord Radio
Svalbard Airport
SVALBARD
Ny Aalesund
SPITSBERGEN
80°
GREENLAND SEA
O. Heisa
FRANZ JOSEPH LAND
O. Rudolfa
Nord
GREENLAND
85°
30°
60°
0°
30°
120°
60°
85°
Alert
90°
120°
85°
150°
CA
Eureka
Isachsen



ARCTIC OCEAN DRIFT STATIONS



Eureka
Isachsen
Rae Point
Mould Bay
Sachs Harbour
Tuktoyaktuk
Barter Island
Point Barrow
ALASKA
CANADA
85°
80°
75°
150°
120°