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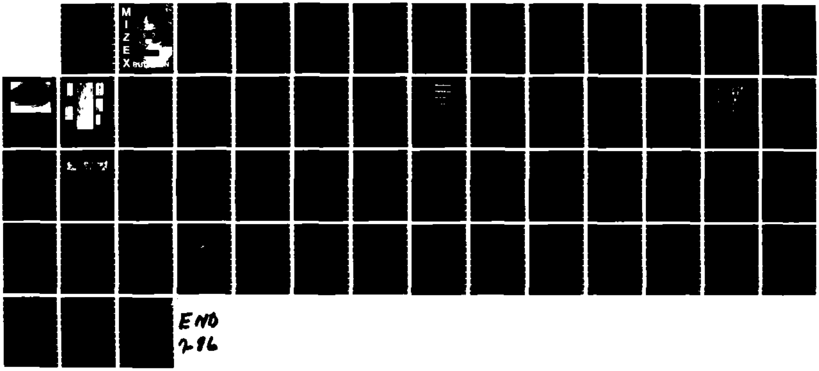

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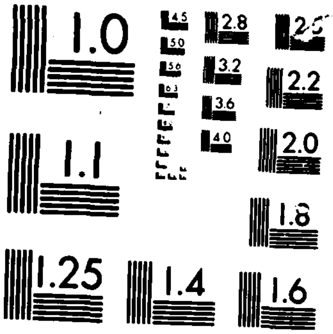

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MIZEX BULLETIN SERIES: INFORMATION FOR CONTRIBUTORS

The main purpose of the MIZEX Bulletin series* is to provide a permanent medium for the interchange of initial results, data summaries, and theoretical ideas relevant to the Marginal Ice Zone Experiment. This series will be unrefereed and should not be considered a substitute for more complete and finalized journal articles.

Because of the similarity of the physics of the marginal ice zone in different regions, contributions relevant to any marginal ice zone are welcome, provided they are relevant to the overall goals of MIZEX.

These overall goals are discussed in Bulletin I (Wadhams et al., CRREL Special Report 81-19), which described the research strategy, and Bulletin II (Johannesen et al., CRREL Special Report 83-12), which outlined the science plan for the main 1984 summer experiment. Copies of earlier or current bulletins may be obtained from the Technical Information Branch, USA CRREL.

Persons interested in contributing articles to the bulletin should send copies to one of the editors listed below with figures reproducible in black and white. Proofs of the retyped manuscripts will not be sent to the author unless specifically requested.

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Cover: Aerial photo of ice margin.

MIZEX
A Program for Mesoscale Air-Ice-Ocean Interaction Experiments in Arctic Marginal Ice Zones

VIII: A Science Plan for a Winter Marginal Ice Zone Experiment in the Fram Strait/Greenland Sea: 1987/89

April 1986

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WINTER MIZEX 87/89 SCIENCE PLAN

1. INTRODUCTION

The present plan is motivated by the need to improve our understanding of the fundamentals of acoustic propagation, noise, and electromagnetic remote sensing in the winter marginal ice zone (MIZ). It is patently clear that a basic understanding of acoustics and remote sensing can best be sought via quantitative description and modeling of the relevant environmental dynamics of the MIZ. Hence the plan strongly emphasizes oceanography, ice dynamics, and meteorology. In fact, the latter disciplines must be deeply enough researched to resolve fundamental questions entailing air/ice/ocean interaction, heat and mass exchanges and balances, growth and decay of ice-edge eddies, and the like. The plan therefore is closely integrated and follows a natural progression encompassing the major physical disciplines.

The plan is to conduct measurements in the Fram Strait-Greenland Sea region of the MIZ in 1987 and 1989, and is put forth in several levels of detail. This first section gives a general overview of the program and a plan for coordination and management. Section 2 expands the scientific objectives and presents a brief of the proposed operations. Section 3 expands the operational details for carrying out the research to achieve the stated scientific objectives. Section 4 introduces the logistic strategies and concepts to support the proposed field operations. This Science Plan will be the basis for a detailed Operations Plan for the proposed field operations in both 1987 and 1989.

Any field research in the Arctic is by its nature difficult and costly, so it is no surprise that others who wish to research the Arctic would ask to be included. The Winter MIZEX plan is happily the focus of such requests—the appendices contain two such requests, for biological oceanography and geochemical oceanography. The possible inclusion of these and other interested disciplines will be dictated by the availability of ship space and other facilities.

1.1 Background

The marginal ice zone (MIZ) is the critical region in which polar air masses, ice, and water masses interact with the temperate ocean and climate systems. The processes that take place there profoundly influence hemispheric climate and have a significant effect on petroleum/mineral exploration and production, naval operations, and commercial fishing. To gain an understanding of these processes sufficient to permit modeling and prediction, a research strategy was developed for summer and winter measurement programs (Wadhams et al., 1981), and a series of field experiments were planned and executed (Johannessen et al., 1983). In 1983 two marginal ice zone experiments were conducted, one during winter in the Bering Sea (*MIZEX Bulletin VI*), often referred to as MIZEX-West, and the second during summer in the Fram Strait and Greenland Sea (Johannessen and Horn, 1984). (Hereinafter we refer to the region of the 1983/84 experiment and the planned 1987/89 one briefly as Fram Strait with the realization that many of our observations have and will be made in the Greenland Sea.) The 1983 Fram Strait experiment was followed in June and July of 1984 by a major multinational experiment, also in Fram Strait (Johannessen and Horn, 1984). The purpose of the 1983 and 1984 programs in Fram Strait was to study the mesoscale physical processes by which ice, ocean, and atmosphere interact in the MIZ in summer. Extensive research programs were conducted in oceanography, meteorology, acoustics, remote sensing, ice studies, and biology. Preliminary results from these experiments, including the Bering Sea 1983 winter experiment, have been factored into the present plan.

1.2 The Winter MIZ program objectives

The planned Winter MIZEX in Fram Strait hinges on the need to understand the ice/ocean/atmospheric processes responsible for the advance of the winter ice edge, and their effects on acoustics and electromagnetic remote sensing, under dramatically different conditions than in summer. Atmospheric interactions, ice growth, and surface gravity waves are most intense from December to April. The upper ocean reaches its fully developed winter state in March. For this reason and from logistical considerations the Winter MIZEX in Fram Strait will be conducted in March and April. To project the flavor of scientific challenges during winter, some of the major objectives are summarized briefly here. We plan to measure, understand, and model:

- Changes in acoustic refraction and coherence via winter-related changes in sound speed profiles due to fronts, ice-ocean eddies, and internal waves;
- Intensification of ice cracking noise mechanisms as related to ice-ocean eddies, winds, ice dynamics, gravity waves, and the presence of recently frozen thin ice;
- Microwave electromagnetic reflectivity and emissivity signatures of the winter MIZ and ice and ocean features emphasizing active sensors;
- Growth, propagation, and decay of ice-ocean eddies as affected by ice edge dynamic and thermodynamic processes, and their role in lateral heat transfer across the ice edge;
- Heat, mass, and momentum transfer in the ice/upper ocean system at the ice margin;
- Morphology, rheology, dynamics, and kinematics of the ice field created by forcing of intense incoming gravity waves, winds, and currents;
- Winter ice edge meteorology, including mesoscale cyclogenesis (arctic lows) as influenced by large temperature and water vapor constrasts at the ice edge.

While this list is not complete, it shows that efforts during MIZEX 87/89 will be centered on those attributes of the MIZ most characteristic of the winter season.

Important scientific issues of the MIZ, which are almost unique to it, are the space and time scales of interaction between atmosphere, ice, and ocean. Although much work has been done on identifying appropriate spatial and temporal scales in the atmosphere and ocean, scales for all three media have to be measured for the MIZ, because the sea ice markedly affects the coupling between the media. Given the strong coupling, vertical as well as horizontal spatial scales are important. Sampling costs and technological constraints require that a coordinated program focus on the most important scale. The results of MIZEX 83/84 indicate that the mesoscale is the primary concern. This will be brought out in the following discussions.

Beyond the focus on winter processes, we intend to place special emphasis on ocean eddy phenomena: eddy genesis is a central research element. Electromagnetic sensing via aircraft and satellites will be employed in real time to identify eddy fields and to discern limitations, if any, caused by advection of marker ice fields associated with strong winter winds or waves. Acoustic interactions with eddies are also central to the research. The effects of oceanographic mesoscale phenomena, principally ice-ocean eddies, on acoustic propagation and ambient noise will be investigated. Inverse methods in which acoustics becomes the probe for quantifying the oceanography will be studied. In part, a very strong element in MIZEX 87/89 acoustics is inversion of path time differences (Munk and Wunsch, 1978; Spindel, 1980) or full wave inversion (see Section 2.5) for possible tomographic delineation of ice-ocean eddies and other mesoscale oceanographic features.

The principal scientific research foci for studies in the winter MIZ environment are oceanography, meteorology, ice and wave studies, remote sensing, and acoustics. However, as noted above, an especially large degree of interrelationship among the scientific disciplines during MIZEX 87 and 89 is planned and necessary. Indeed, the success of the program demands that this be achieved: remote sensing researchers require ground truth; acousticians must have water-column sections, ice field dynamics, surface wind stress, and surface gravity wave information; meteorologists need sea surface temperatures and surface roughnesses; and oceanographers must have atmospheric forcing functions and remote sensing for synoptic coverage. While this interdependence is not new, our need is heightened by the especially strong role of acoustics during Winter MIZEX, which is directed toward answering fundamental questions of ice noise generation and the feasibility of MIZ ocean acoustic tomography.

In addition to these specific measurement foci in support of understanding physical phenomena at the ice margin, this program will be particularly helpful in developing and verifying numerical models that simulate the circulation of ice-covere oceans. Analysis of existing coupled models, for example, Hibler and Bryan (1984), has shown that very large amounts of melting occur in winter, primarily due to large oceanic heat fluxes made possible by a relatively neutral density stratification. Consequently it seems likely that the environment in the winter MIZ will be a very delicate balance between growth and melt, with small synoptic events possibly triggering the net balance in either direction. Proper simulation of this balance depends critically on parameterizing both the upper ocean sea/air heat and momentum exchanges, and the ocean eddy structure. Winter MIZEX should be particularly effective in achieving these goals.

1.3 Overall experiment strategy

The field experiments associated with the winter MIZ program will involve three phases. The first phase is already under way. Sonobuoy and AXBT measurement of ambient noise and water column temperature were taken in April 1985 by a Norwegian P3 airplane, and data interpretation is now in process. In additional, NOAA visible and infrared satellite data will be examined for the presence of MIZ eddies. Both these sets will provide invaluable data for planning the later phases of the experimental program. Particular regard will be given to spatial and temporal scales compared to those previously observed in the summer season.

The second phase will consist of a field experiment in the Fram Strait MIZ in March and April of 1987. This experiment will include an icebreaker with helicopter support, an open-ocean ship, fixed wing aircraft for meteorology and remote sensing, and satellite remote sensors. An important part of the 1987 satellite ensemble will be the Shuttle Imaging Radar (SIR-B), which will be orbiting over the MIZ area during this period. The SIR-B L-band (23.5 cm) synthetic aperture radar (SAR) will produce 50 × 100 km images with a resolution of approximately 30 m during its 10-day mission. These data, which will be obtained independently of cloud cover and solar illumination, will provide the first synoptic radar images of the Fram Strait marginal ice zone during winter. The primary goals of the 1987 field program are to:

- Exercise and verify the remote-sensing capabilities for real-time detection and tracking of ice-ocean eddies in winter;
- Provide the first comprehensive data set on the oceanography of the winter MIZ vital for ocean and acoustic modeling;
- Provide the first data on important meteorological questions, including cyclogenesis and surface atmospheric boundary conditions in the winter MIZ;
- Provide a unique data set on ice and surface gravity wave interaction in winter;
- Provide ambient noise data.

This experiment will also provide valuable experience on ship and helicopter operations in the winter MIZ environment.

Finally, and most importantly, the 1987 experiment will explore in preliminary fashion the ice-edge swath shown in Fig. 1, with the objective of identifying those portions with unusual dynamic behavior. The ice edge, for example, may be relatively fixed in one region due to strong topographic influence, while relatively variable in others where different mechanisms are dominant. It would be important to obtain a preliminary evaluation of this in preparation for MIZEX 89.

The third phase will consist of a field experiment in the Fram Strait marginal ice zone in March and April 1989. This experiment, much broader in scope than its 1987 counterpart, will include an ice camp located approximately 100-150 km from the ice edge in an area tentatively bounded by 79°N, 81°N, 2°W, and 1°E. The location of the ice camp relative to the ice edge will be determined from the ice/wave interaction studies of the 1987 experiment, to ensure that ice integrity will be maintained over the course of the ice camp's approximately 45-day lifetime. The experience gained from previous MIZEX campaigns (e.g. *Polar Queen* in MIZEX 84, *Westwind* in MIZEX-West) indicates that such a deployment requires much planning. Acoustic receiving arrays and a digital acoustic data acquisition system as well as oceanographic and meteorological stations will be located at this camp. The tentative camp location is west of the Yermak Plateau in water of more than 1000 m depth to minimize the effects of bottom interaction for acoustic propagation and tomography. A second, satellite ice camp is planned at a location of approximately 84°N and 10°W. This camp will deploy acoustic projector(s) and shots for propagation through the Fram Strait to the MIZEX array camp. Fig. 1 shows the MIZEX 1987 and 1989 experiment locations in the Fram Strait. The mean ice edge from historical data (1966-1974) is also shown for the end of February and March.

The main reason for the 1989 main ice camp deployment is the high probability that much of the acoustics and ice dynamics at the camp (including atmosphere and ocean boundary layer physics,

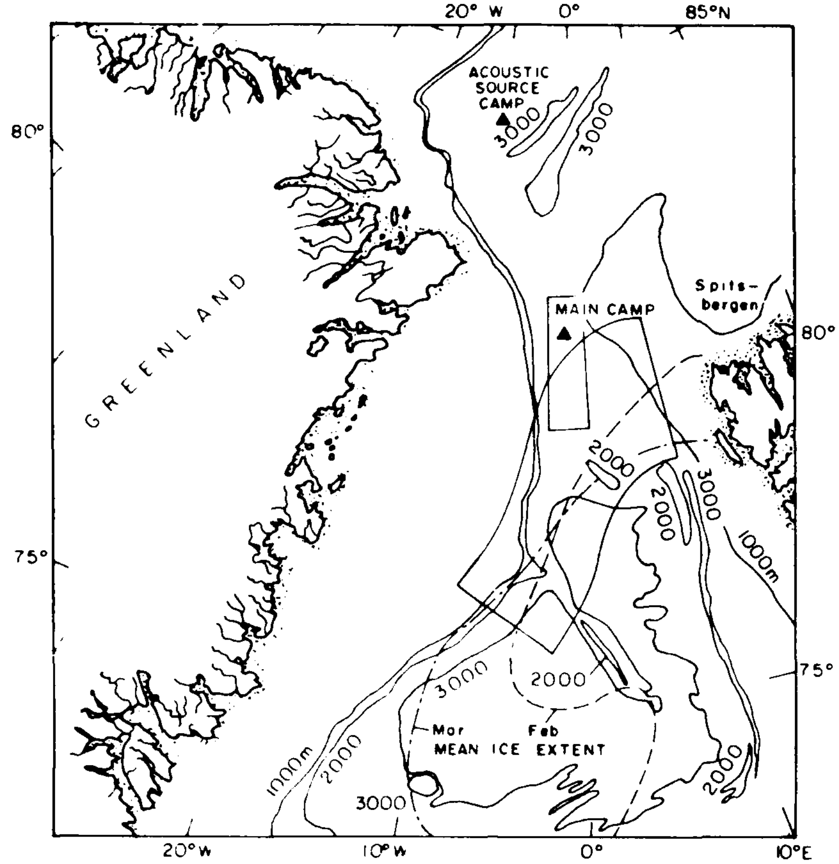


Figure 1. The Fram Strait of the Greenland Sea showing the Winter MIZEX experimental locations.

ambient noise, acoustic scattering from the ice, and spatial and temporal coherence of acoustic signals) will exhibit characteristics initially associated with deep Arctic conditions and changing to conditions common to the marginal ice zone as the camp drifts from its initial location deep in the pack ice through the marginal ice zone. Thus, a connection can be made between the physics of the central Arctic and the MIZ.

Two helicopters will operate from the camp for remote acoustic and oceanographic data collection. In addition, an ice-strengthened ship with helicopters and two open-ocean ships, one towing an array and acoustic projector(s), are planned. The second ship will most likely be an AGOR and will be referred to as such in this plan. Central to the detailed experimental plans (Section 3) is the deployment of autonomous drifting buoys designed for concurrent environmental and acoustic ambient noise data collection. Fixed bottom-moored acoustic sources and receivers, also equipped with current meters, will be deployed in the Greenland Sea and in the Fram Strait area. These sources and receivers will be part of both the Greenland Sea long-term ocean acoustic tomography program as well as the MIZEX 87/89 program. They will be deployed in summer 1988 and recovered in the summer of 1989.

1.4 Coordination

1.4.1 Overall coordination concept

Efficient management of international experiments of this type requires that a project office be established in each of the countries that will be a major logistic support center. In addition, there must be an organization to develop both science and operations plans and to make the necessary corporate management decisions. There must also be a system to permit close collaboration and communication among the participating national groups. Such a system should include a rapid data network (e.g. electronic mail) together with regular correspondence, newsletters, and data bulletins. There is also need in such experiments for a field support office similar to the one established for the NORSEX experiments, in which the Tromsø satellite telemetry station played a vital role in coordinating aircraft operations and in receiving and retransmitting satellite data. Field coordination per se must be clearly delineated and vested in senior scientist(s) through a detailed operations plan.

1.4.2 Coordination structure for MIZEX 83/84

To coordinate the MIZEX 1983 and 1984 programs, an international MIZEX Science Group was established. This group consisted of a national coordinator from each of the countries involved plus a chairman for each of the seven science disciplines. The MIZEX Science Group elected their own chairman, vice chairman, and executive committee. The number of national coordinators changed as more countries elected to participate. A coordinating executive office for the MIZEX program was established in the U.S at the Office of Naval Research, Arlington, Virginia, and the European office was located at the Geophysical Institute, University of Bergen, Norway. An electronic mail network, the MIZEX Newsletter, and MIZEX Bulletins were used for coordination and information exchange. The field organization, clearly delineated in each MIZEX Operation Plan, provided effective coordination for the 1983 and 1984 experiments.

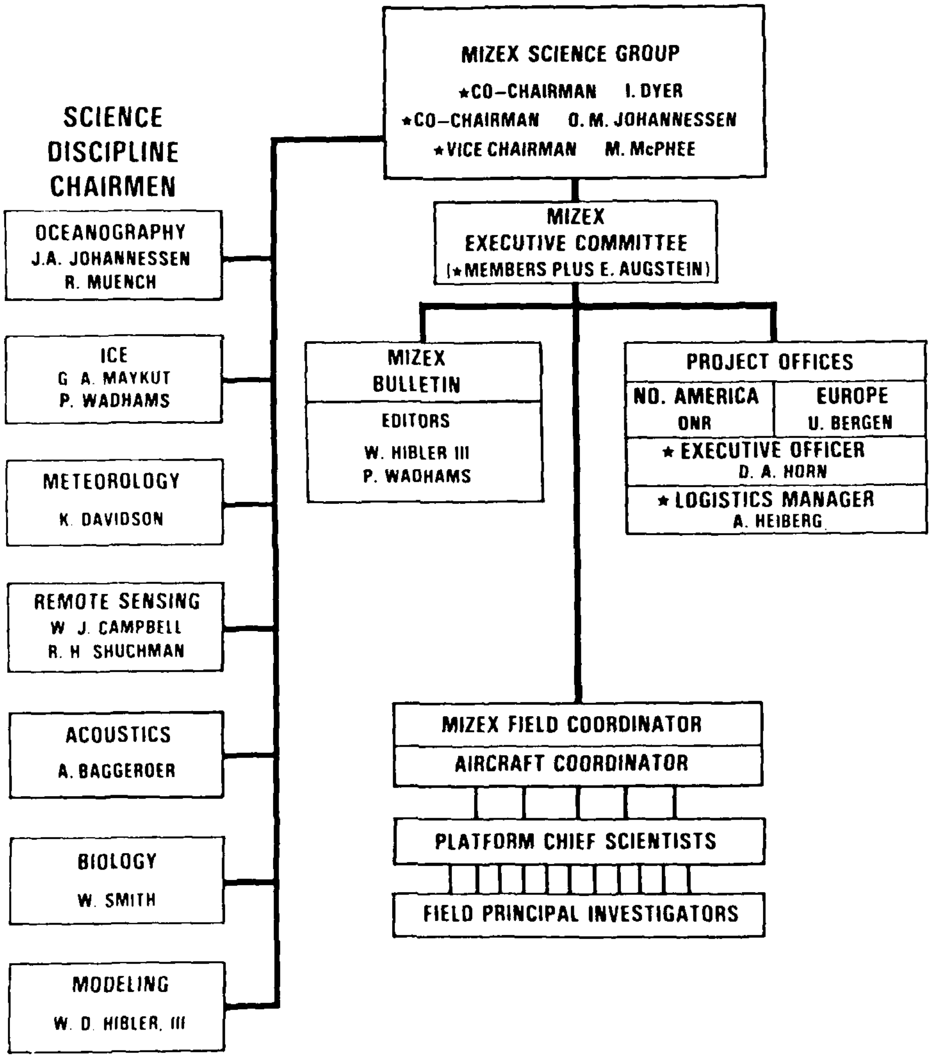


Figure 2. MIZEX Fram Strait organization.

1.4.3 Coordination structure for MIZEX 87/89

Building on the 1983-84 experience and recognizing the reduced scale of the Winter MIZEX program, a modified MIZEX Science Group was established at the 1984 Monterey meeting. This Science Group (Fig. 2) will continue as the basic management organization for MIZEX 87/89. The organization has the desired international character, which is emphasized by the group's action to establish European and U.S. general co-chairmen. The individuals selected to serve as co-chairmen also represent two of the principal foci of Winter MIZEX.

The electronic mail system and the MIZEX Newsletter, initiated in 1983, will be continued as an informal and rapid means of disseminating general information on Winter MIZEX plans and activities to the arctic research community. The MIZEX Bulletin will also be continued as the permanent medium for the rapid interchange of initial results, data reports, and preprints of journal articles on any aspect of MIZ science, including other seasons and localities than winter in Fram Strait. These bulletins, published by CRREL, are under the general supervision of one of their technical editors. (Copies of MIZEX Bulletins may be obtained by writing to CRREL, Attention: Technical Information Branch.)

A data depository and management program, established at NSIDC, Boulder, Colorado, will also be continued for Winter MIZEX (see Section 4.5).

2. DETAILED SCIENTIFIC OBJECTIVES

The physical processes of importance and the scientific objectives of the Winter MIZ program are described in this section. The principal environmental science objectives—organized under oceanography, meteorology, ice kinematics and dynamics, and surface wave studies—are addressed first. These are the core disciplines that provide the physical insight and understanding required for remote sensing ground truth and interpretation, and for tomography, acoustic propagation, and ambient noise modelling. Remote sensing and acoustics objectives follow, reflecting the necessary support of the former disciplines to the acoustics program. Remote sensing and acoustic tomography are also valuable tools that provide vital measurements supporting the environmental science objectives. This reflects the interrelationship and interdependence of the various disciplines characteristic of research in the MIZ.

2.1 Oceanography

Oceanographic conditions in the MIZ are dominated by permanent and transient frontal systems, by ice-ocean eddies, and by upwelling events along the ice edge (Johannessen et al., 1983; Wadhams and Squire, 1983). Various instability mechanisms have been suggested for the presence of these mesoscale (10-100 km) eddies. At present there are five theories on their generation, including baroclinic, barotropic, and topographic instability (Johannessen et al., 1983, 1984, 1985; Wadhams and Squire, 1983). The fourth theory, recently suggested by Hakkinen (1984) in a numerical study, proposes that wind-driven upwelling along a wavy ice edge can generate eddies through differential Ekman pumping. The fifth is simply that eddies are already present in the open ocean and when advected with the northward-flowing Atlantic water they will eventually interact with the ice and polar water. Neither the mechanisms nor the generation of the dynamics of these ice-ocean eddies are fully understood. The primary objectives for the mesoscale Winter MIZEX oceanography program are therefore:

1. Investigation of the characteristics of the ice-ocean eddy field including open ocean eddies with respect to space and time scales, energy, generation, and propagation and structural changes, including eddy/eddy interaction and decay.
2. Investigation of the role the ice-ocean eddy field has in heat and mass exchange across the ice edge in order to parameterize this effect in large-scale models.
3. Investigation of the potential role of the MIZ eddy field in upwelling events, on freezing of new ice, and in deep convection or bottom water formation.
4. Provision of time series, at densely spaced locations, of current shear stress values for correlation with MIZ acoustic properties and signatures, and of the thermohaline structure for determining of sound speed variations.
5. Investigation of the MIZ internal wave field, with emphasis on generation mechanisms associated with the ice field and the interaction between internal waves and ice-ocean eddy fields.
6. Definition of the winter cross-edge velocity

Figure 3. An oblique photograph of a cyclonic eddy observed during the 1984 MIZEX. (Photograph by R. Schuchman of ERIM.)

and thermohaline structure for comparison with summer measurements.

7. Determination of the role of off-ice advection episodes in the heat, salt, and ice budgets.

During the summers of 1983 and 1984, extensive ice-ocean eddy investigations were carried out as part of the MIZEX program. In 1983 synoptic observations, including CTD, XBT, AXBT, and XCP data and remote sensing data, portrayed the ice-ocean eddy frequently located over the Molloy Deep, a depression centered at 79 10'N and 3 E and reaching down to more than 5000 m. Smith et al. (1984) suggest in a numerical model that a stationary eddy located over the Molloy Deep could be explained in terms of topographic generation.

In MIZEX 84 the eddy studies were widened to include transient eddy features north and south of the Molloy Deep. An integrated sampling scheme was utilized including drifting Argos buoys in water and placed on ice, subsurface SOFAR floats, drifting and anchored current meter arrays, shipborne CTD XBT, airborne AXBT, and extensive passive and active remote sensing observations from satellites, aircraft, and helicopters. Real-time analysis of remote sensing observations was used to direct the ships into the eddy field south of the Molloy Deep. Photographic and SAR images revealed surface signatures of cyclonic ice-ocean eddies with scales of 20-40 km and with ice convergence in the eddy center implying that ageostrophic effects must be taken into account (Fig. 3, 4). Vertical CTD sections indicate that the eddy extended to more than 500 m, while drifting Argos buoys and current meters measured orbital speed of the eddies at 30-50 cm s. Speed of sound changes are estimated to be about 15 m s. In studies of the

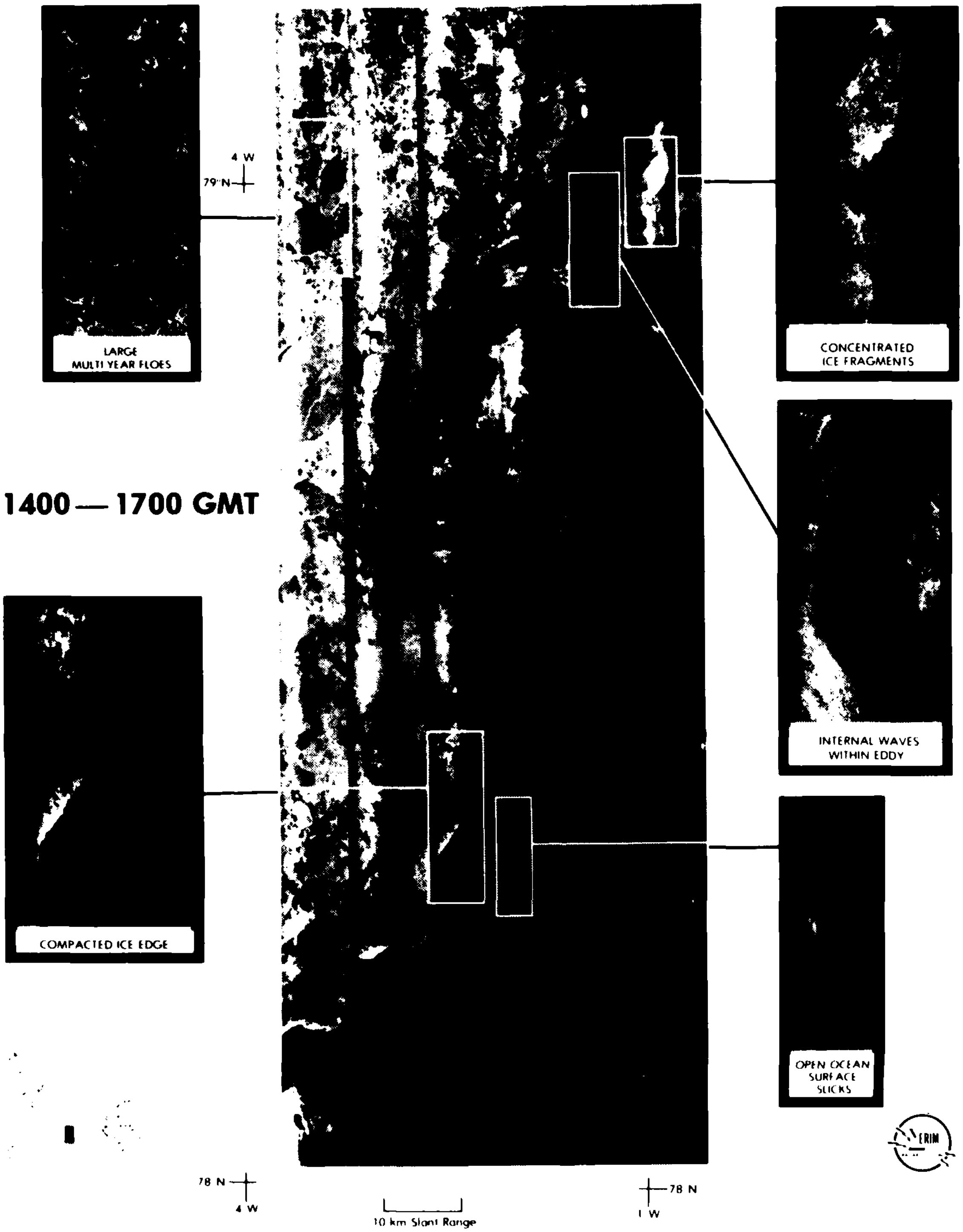


Figure 4. SAR mosaic [ERIM/CCRS CV-580, L-Band (HH)] for 5 July 1984. Note the eddy clearly visible in the center of the image.

MIZEX 84 eddy data there are strong indications that the smaller eddies located south of the Molloy Deep might be spun off from the Molloy Deep region. The Molloy Deep may therefore be an important area for generation of both the large (50-100 km) stationary eddy as well as smaller (20-40 km), transient eddies.

From consecutive remote sensing images, eddy propagation is estimated to be on the order of 10-15 km day^{-1} in a southward direction, while the observed track of an Argos drifting buoy apparently trapped in an eddy suggests that the lifetime was more than 20 days. One eddy feature north the Molloy Deep was also tracked from R/V *Hakon Mosby* for about 15 days while it propagated slowly (less than 5 cm s^{-1} or 4 km day^{-1}) in an eastward direction.

The importance of the eddies for ice edge retreat has been estimated quantitatively for summer conditions. On the assumption that the bottom ablation is 10-20 cm day^{-1}, as reported by Josberger (1984), the warm (3 °C) Atlantic water that is advected 10-20 km under the ice associated with eddy motion can melt 1.5-m-thick ice in 10 days. Then, on the assumption that the mean distance between eddies along the ice edge is 50 km, the ice edge will retreat 0.4 km day^{-1}. In the absence of these eddies the retreat due to bottom ablation is reduced by a factor of 10.

Inspection of a large number of NOAA satellite images from winter tells us that ice-ocean eddies are frequently present. Prevailing strong winds in winter may often destroy the surface signatures of the eddies, so that in situ measurements during winter are needed to address the importance of eddies in ice edge exchanges. Recently a pilot winter ice-ocean experiment was performed using a Norwegian Air Force P3 with the objective of studying the structure of the eddies and making some preliminary measurements of acoustic ambient noise they induced. After a 10-day period of strong northerly wind, many eddies were observed along the ice edge.

Passive microwave satellite observations from Nimbus-7 SMMR have also indicated that transient freezing of new ice over large areas occurs in the region where we will be operating. Salt is rejected during freezing so the upper layer may become denser, potentially setting up convection. *Fine structure studies in the upper few meters* should be made to investigate this.

Another ice-mass loss mechanism in the MIZ occurs during episodes when wind rapidly advects ice over warm water, where the ice diverges and rapidly disintegrates. During the summer MIZEX 84, two such episodes accounted for perhaps 100-120 km of pack ice melt in the region south of the *Polar Queen*, despite much smaller changes in the ice edge position. (The edge was at about 80 °N and between 2° to 6 °E.) The divergence creates a broad swath of diffuse ice farther north.

Boundary layer measurements of turbulent stress and oceanic heat flux, combined with ice ablation data from near the *Polar Queen*, suggest that buoyancy flux associated with ice melt is instrumental in causing the divergence. Figure 5 shows relative mean velocity and horizontal turbulent stress at 7 m below the ice floe adjacent to the *Polar Queen* during a period of rapid southward drift. (The velocity is relative to the southward ice drift, and hence shows northward components.) Late on day 190, the floe drifted into water about 1 °C above freezing and began melting rapidly. Turbulent stress in the last three 6-hr periods is significantly reduced by surface buoyancy, showing how turbulence and momentum are trapped closer to the surface.

During summer, divergence near the ice edge both increases contact between ice and warm water and enhances insolation in the vicinity of ice floes by lowering albedo. The combined effect probably enhances overall ice melting. In winter, similar divergence presumably cools sea water over a much broader area and increases overall ice production.

Internal wave investigations in the MIZ are scarce. Muench et al. (1983) hypothesized interactions between sea ice and internal waves in the MIZ, but they were not able to test their hypotheses due to lack of suitable data sets. During

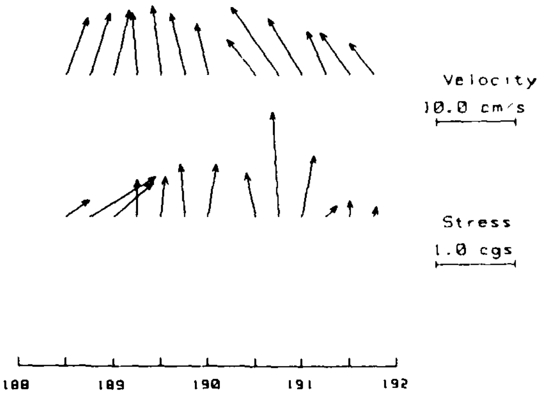


Figure 5. Mean velocity (top) and Reynolds stress at 7 m below ice, from 6-hour composite averages. Up is north.

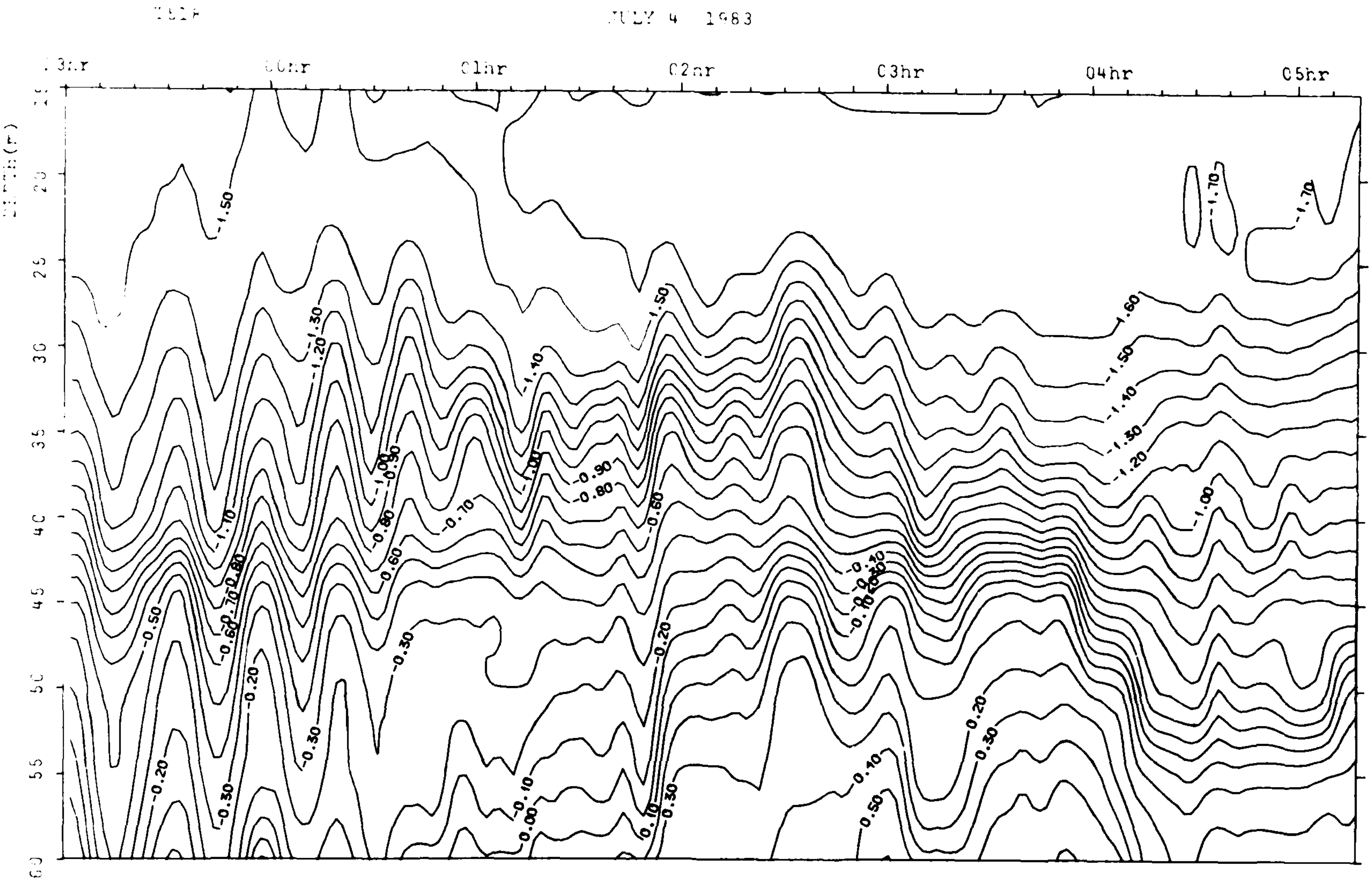


Figure 6. Contour plot of isotherms.

MIZEX 83 in the Fram Strait-Greenland Sea however, internal wave studies were conducted over a 10-day period using three thermistor chains with 2-min sampling intervals located in a triangle 500 m across and 10 km in from the edge of the ice field (Johannessen et al., 1985). This study was complemented by hourly CTD observations and current meter arrays suspended from ice floes. Fig. 6 shows an example of a 6-hr record from the original data interpolated to depth variations of the isotherms. At the beginning of this series, internal waves with 20-min period and with a vertical displacement of 10 m dominated the record. The frequency spectrum in general showed that the energy level was somewhat lower than indicated by the 'universal' Munk and Garrett theory. It should, however, be noted that these data were obtained during calm wind conditions.

In MIZEX 84, the internal wave study was expanded to include acoustic and remote sensing observations, and internal wave trains with wavelengths of 2 m were clearly seen in the ice edge region in SLAR imagery obtained under calm conditions (Ross and Tomchay, 1984). The 1984 data set should yield new and interesting results on the internal wave field under both calm and windy conditions. Impact of internal waves on acoustic ambient noise caused by convergence and thus bumping of the ice floes, and on acoustic propagation through focusing and defocusing effects, should be elucidated by this data set. Results are also expected on the interaction of the internal wave field with ice-ocean eddies.

During winter, wind forcing is expected to be much stronger than during summer. Therefore the thrust of the Winter MIZEX internal wave investigation will be to study generation of internal waves through wind/ice coupling, as well as to study the interaction of internal waves with ice-ocean eddies and fronts.

2.2 Meteorology

Atmospheric forcing is a primary concern in oceanographic, ice dynamics, and acoustic studies of the MIZ. The forcing contributes to acoustic background, to changing the upper part of the ocean, and hence to sound velocity profiles, to ocean eddy formation and dissipation, and to ice movement. A number of factors can change the wind and atmospheric forcing in the vicinity of the MIZ. The transition from pack ice to ocean is characterized by extreme changes in the surface roughness and temperature. It is also characterized by sizeable changes in the relation between pressure gradient and surface wind velocity, either through a change in the boundary layer height or through baroclinic effects caused by horizontal temperature gradients or a sloping inversion.

The winter MIZ environment, in contrast to that of summer, provides a far more dynamic set of conditions in which to study the atmospheric processes at the ice/ocean interface. There are stronger temperature gradients and higher winds and sea states, coupled with the most active ice growth of the yearly cycle. The scientific plan for the winter MIZ atmospheric measurements and analysis is based on the need to obtain microscale, mesoscale, and synoptic scale descriptions. Of the three, the mesoscale is believed to be the most important, as we will discuss in Section 3.2. The synoptic scale atmospheric feature of primary interest is the geostrophic flow (on/off and parallel to the ice edge) over the region and general air mass properties that are modified by the MIZ processes. The mesoscale feature of primary interest is the genesis, rapid intensification, and movement of low pressure systems (vortices) near the winter MIZ. These intense arctic lows are of particular interest for the winter MIZ meteorological program, for their role in ice and ocean dynamics, for their causal relationship to sea spray icing on ships and structures, and for their impact on acoustic ambient noise. The microscale features of primary interest are the surface flux of momentum and heat over adjacent ice and open water regions, and the resulting structure of the adjacent atmospheric and oceanic boundary layers and ice movement. Surface properties as affected by whitecaps are also a concern.

The objectives of the meteorological program are:

1. To characterize surface layer fluxes (momentum, i.e. wind stress, sensible and latent heat) that are responsible for forcing of the ice and the upper ocean and contribute to mesoscale atmospheric cyclogenesis (arctic lows) adjacent to the MIZ.
2. To provide time series, at several locations, of surface stress values for correlation with MIZ acoustic properties and signatures.
3. To understand how the vertical and horizontal structures of mesoscale atmospheric features are related to the surface boundary condition imposed by the MIZ and synoptic scale forcing.
4. To improve the ability to relate atmospheric features to changing ice and ocean conditions remotely sensed from surface (rough-

ness) and tropospheric (cloud) properties.

5. To characterize the sea surface whitecap cover and the resulting effect on surface production of aerosol and on emissivity of the sea surface.

Characterizations achieved in objectives 1 and 2 from direct measurements will be oriented toward the formulation of procedures to estimate the forcing of ice and ocean and modification of the overlying air on the basis of bulk surface and atmospheric properties. These will require the application of exchange (drag) coefficients that are dependent on surface layer stability, ice conditions, and atmospheric boundary layer depth.

Insights achieved in objective 3 as to the role of the MIZ on horizontal and vertical variations of atmospheric dynamic and thermodynamic properties are necessary if we are to relate significant atmospheric forcing to unique properties of the MIZ. The generation and maintenance of mesoscale lows are influenced by horizontal and vertical structures of momentum, temperature, and moisture fields. The mesoscale features influenced by surface flux can change the responsible surface boundary motion near the edge and in floe breakup throughout the MIZ.

Improvements gained in objective 4 in interpreting present and near-term satellite remote sensing data are necessary if qualitative and quantitative descriptions of relevant features are to be available. The present multi-faceted explanation of intense cyclogenesis in the MIZ vicinity requires knowledge of both surface (ice, surface temperature, and vector wind) and tropospheric features. Analysis, as well as prediction, of these features will require satellite data.

Knowledge gained in objective 5 will support the development of physical models of the MIZ that can be sensed remotely. Objective 5 also supports acoustic modeling of ambient noise in open water adjacent to the ice edge.

2.3 Ice physics

Ice characteristics in the MIZ are dominated by dynamic and thermodynamic changes, with wave action playing an important role in both ice motion near the edge and floe breakup throughout the MIZ.

2.3.1 Ice dynamics and thermodynamics

Objectives in observing the dynamic and thermodynamic characteristics of the winter MIZ are to:

1. Determine typical deformation rates and ice kinematics in the winter MIZ for comparison with model predictions.
2. Provide time series of ice drift, concentration, and shear for correlation with MIZ acoustic properties and signatures.
3. Deduce ice rheological behavior and its role in ice edge advance by examining ice kinematics in conjunction with wind and water stress measurements.
4. Determine mass balance of the ice field in terms of growth rates for different thicknesses and the effects of ice deformation on growth rates.

Due to its almost constant motion, air/sea exchanges in the MIZ are much different from those for a static ice cover. Openings of the ice pack increase the open water and hence support rapid ice growth, even while thicker ice may be melting. As a consequence, the dynamics of the ice cover itself may play a critical role in determining how rapidly ice is frozen or melted. Analysis of the momentum balance of this system shows ice kinematics to be a balance between surface currents, winds, and ice interaction, with surface gravity waves also playing a very major role as the edge is approached. As discussed in Section 2.1, Oceanography, the kinematics are also critically affected by the boundary layer drag in the ocean, which in turn can be affected by melting or freezing. Under compacting conditions the rheology of the ice field can significantly affect the dynamic behavior and probably also the acoustic signatures. Present models of ice dynamics make use of plastic rheologies (for example, Hibler, 1979), which provide a consistent way of describing a strong nonlinear resistance to convergence while at the same time having little resistance to divergence. Under compacting ice winds such a rheology also leads to a relatively solid plug flow phenomenon when analyzed in conjunction with a fine-scale ice edge model (Lepparanta and Hibler, 1985) that tends to be in agreement with summer MIZ observations from 1983. However, the nature of the plastic yield curve and the role of floe bumping may alter this traditional view of ice rheology near an ice edge. It should also be noted that such a nonlinear rheology also plays a critical role in seasonal simulation by keeping ice from building up near the coast and still allowing it to drift relatively freely parallel to the coast.

Based on studies of granular flow in other media, we expect a plastic-like rheology to be applicable to the marginal ice zone under relatively

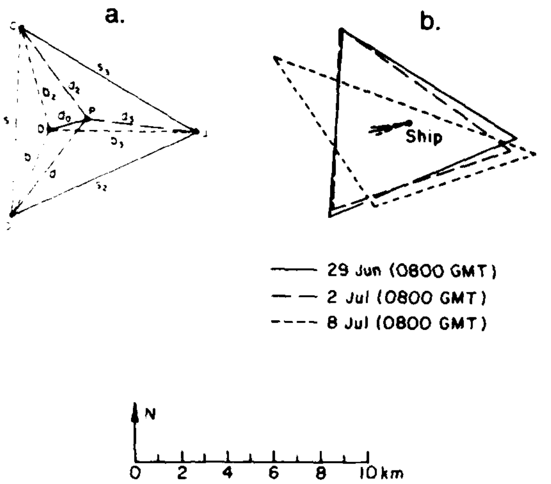


Figure 7. (a) Configuration of strain array. The triangle is plotted to scale for 29 June 0800 GMT; the ship (M/V Polarbjorn*) is located at the center point P, moored to an ice floe. Del Norte units are located at circled points. Directly measured distances (accurate to 1-2 m) are denoted by subscripted* b*'s and* d*'s, while distances calculated by triangulation (less accurate depending on geometry) are denoted by subscripted* s*'s. (b) Configuration change of the triangle over the period of the experiment.*

compact conditions with contact stresses as the main transfer mechanisms. Under more dilute conditions, collision-induced rheologies may be more applicable. Theoretical models of such rheologies (Chen et al., 1986) also predict a highly nonlinear but relatively weak interaction. Such theories need to be expanded to include floe rotation effects, although it seems likely that rotation effects will not change the stress magnitudes drastically. What seems more to the point and particularly necessary is an understanding of the transition from rapid to slow granular flow.

An especially valuable measurement for examining these rheologies is precise deformation measurement over a 20-km region at (preferably) about 8 locations, together with current and wind measurements at, say, 3 of these sites. Such measurements allow a direct estimation of rheology by statistical methods, while at the same time providing an indirect measure versus the deformation at the current meter sites that can be estimated from different rheologies. The measurement strategy pursued in summer MIZEX 83 (see Fig. 7) during the drifting phase was particularly valuable. Moreover, since in Winter MIZEX 87/89, drifting ice stations are planned, this transponder measurement strategy can be effectively utilized.

Another necessity is to have a buoy array that covers different ice regimes progressively farther away from the ice edge. This is especially needed to ascertain the difference in melting and freezing that is predicted in large-scale models.

Finally, a much-needed measurement is detailed monitoring of ice growth and decay, especially regarding differences at various thickness levels. Based on analysis of large-scale ice/ocean models (for example, Hibler and Bryan, 1984), it seems likely that considerable melting as well as freezing may occur in this region. Consequently, the advance of the ice appears much more complex than just an advancing thermodynamic freezing line. Instead, it may well be a situation where deformation can shift the growth balance back and forth very sensitively with possible feedback occurring via eddies and boundary layer modification that may irreversibly alter the balance. If we hope to understand these oceanic influences at all, it is imperative that the ablation at different thickness levels be carefully monitored and that these measurements be closely coordinated with the ice deformation program.

2.3.2 Ice and surface wave studies

The scientific objectives of the surface gravity wave and ice program are as follows:

1. To determine the contribution that surface gravity waves make to the force balance near the ice edge in winter.
2. To measure surface wave activity in relation to the ambient noise spectrum, including direct and indirect effects.
3. To monitor wave conditions in 1987 with a view to extrapolation of results into 1989, and to enable prediction of the effective penetration distance for the positioning of the 1989 ice camp. In 1989 waves will also be monitored to provide a warning to the camp if seas off the edge intensify markedly.
4. To support aircraft and Space Shuttle remote sensing overflights that use SAR and/or radar altimetry to measure waves remotely. This will be done by deploying wave buoys near the ships involved in the study.
5. To investigate changes in an incident surface gravity wave field due to the presence of the ice edge and eddies in particular.
6. To study bumping events in the MIZ at short period, and to provide time series for correlation with acoustic event signatures.

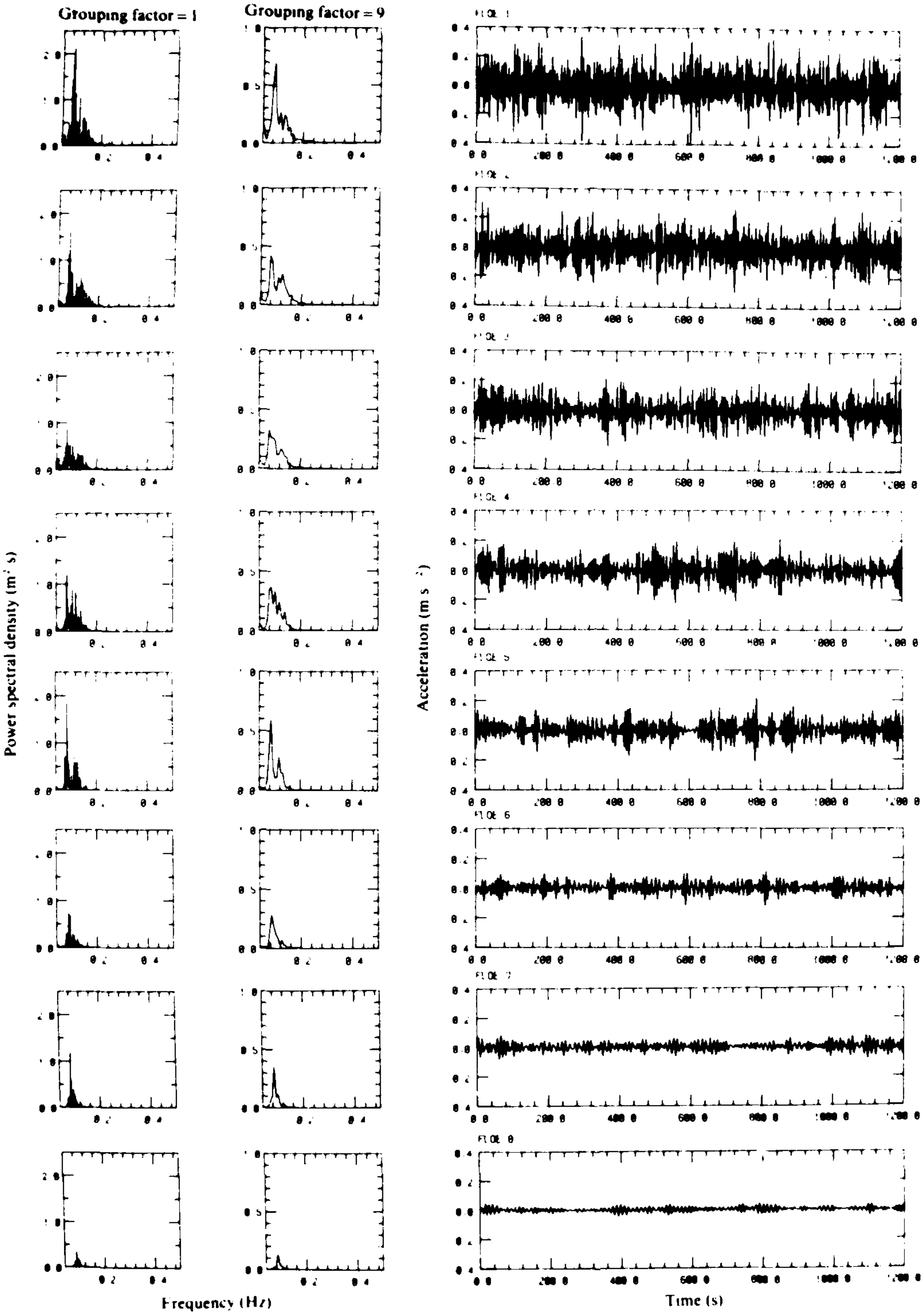
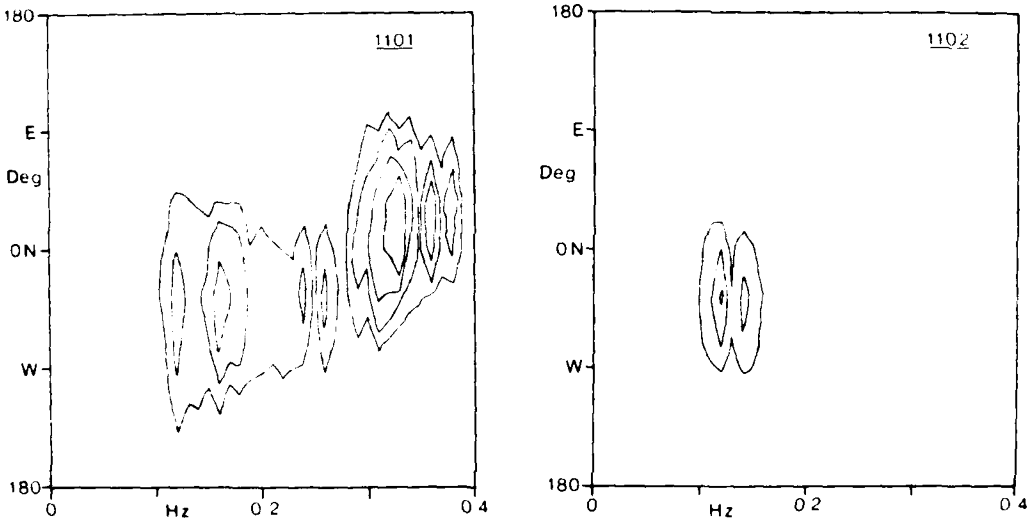


Figure 8. Time series and power spectra for a series of wave measurements collected during an attenuation transect into the Bering Sea during February 1979. From top to bottom, the stations were located at 0, 0.7, 2.2, 5.3, 10.3, 18.9, 38.6 and 65.1 km from the ice edge. Note the clear energy decay with penetration into the ice cover, and the filtering effect of pack ice on waves (from Squire and Moore, 1980).

There are three main external forces affecting MIZ kinematics at the mesoscale and smaller: surface currents, winds, and surface gravity waves. The former two contributions exert their influence over the entire MIZ and depend to a great extent on the surface and underside roughness characteristics of the floes in a particular region. The surface gravity wave effect is most important in the immediate vicinity of the ice edge. Since it will depend on the sea state off the ice edge and on floe size distribution, the ice edge band over which surface waves exert an appreciable influence in the force balance is variable. In summer, when the wave climate is undoubtedly less harsh than in winter, the band of action is narrower. Its contribution to ice kinematics in summer will probably be limited to a zone of some 10–20 km from the ice edge. In MIZEX 83/84, for instance, waves detected at more than 25 km penetration lacked sufficient intensity to contribute to the force balance. In the Bering Sea winter MIZEX, on the other hand, significant wave energy was measured on several occasions well inside the interior zone of the MIZ, especially when storms led to high seas off the ice edge.

Gravity wave contribution to the force balance is due to the radiation stress imparted on isolated floes or lines of floes from the wave reflection process. As such, the extent to which the wave influence compares with currents and winds in controlling motion will depend on the periods of the incoming sea and swell and on their respective amplitudes. Short waves are more likely to be reflected than long, but since they are also liable to be of lesser height, waves in the range of 3- to 10-sec periods (and possibly beyond) may all contribute.

The floe size distribution within the MIZ is determined principally by surface gravity waves entering and traveling into the pack. En route, the waves are attenuated by scattering, impactive collisions between adjacent ice floes, hydrodynamic losses (mainly wave-induced turbulence in the water column), and by hysteresis losses due to ice floe flexure. Sufficient data exist for the Fram Strait in summer and the Bering Sea in winter (e.g. Fig. 8) to enable a fair prediction of wave energy to be made at any point within the MIZ when the floe size distribution and concentration and the spectral character of sea and swell off the ice edge are known. Then throughout the MIZ it is a relatively simple matter to establish whether or not local ice floes will break up due to the wave action. The problem does not stop there, however, for once fracture has begun the floe size distribution is changed, with the result that the local wave inten-



a. Spectrum in open water outside the MIZ.

b. Spectrum in open water after propagation through a band of ice within the MIZ.

Figure 9. Contours of the spread in the directional wave spectrum for two samples collected either side of a band of ice outlying the main Fram Strait ice edge in summer 1984. The base level contour is at 0.0125 m/Hz/radian, and the energy increases by a factor of 2 between adjacent contours. Upper level contour is at 0.10 m/Hz/radian. Note how the wind sea is dramatically reduced, while the swell energy has a narrow spread (from Wadhams et al., 1985).

sity field alters and break-up can continue. Eventually, some steady-state MIZ morphology is attained, which persists until the wave conditions in the open sea intensify. It is also worth noting that the wave-scattering process is two-dimensional: thus the directional composition of a surface gravity wave field penetrating the MIZ will be markedly altered by the ice (Fig. 9). Similarly, reflection of the incident sea and swell at the ice margin lead to confused seas in the waters off the edge. In the presence of eddies, surface currents change direction over relatively small spatial scales, with a further distortion of the incoming waves due to current/wave interaction. The modification of the surface gravity wave spectrum by eddies presents an interesting avenue of research that has not yet been addressed. If parameterization of surface waves in the various numerical models is to be successful, directional modification of wave spectra at the ice edge, especially in the presence of an eddy field, must be fully understood.

Although the extent to which MIZ kinematics and ice floe size distribution are influenced by waves is reasonably well understood in theory, and some data exist for the Fram Strait during summer, there is a singular lack of data outside the summer months. In the Greenland Sea in winter, for example, there are very few data available on wave climate, and those that have been collected are from farther south than an experiment planned for the Fram Strait region of the Greenland Sea would wish. Furthermore, much of the data may be unreliable, since extrapolation has been used in their derivation (see for example Fig. 10). An exception is a ship-borne wave recorder study by the Institute of Oceanographic Sciences,

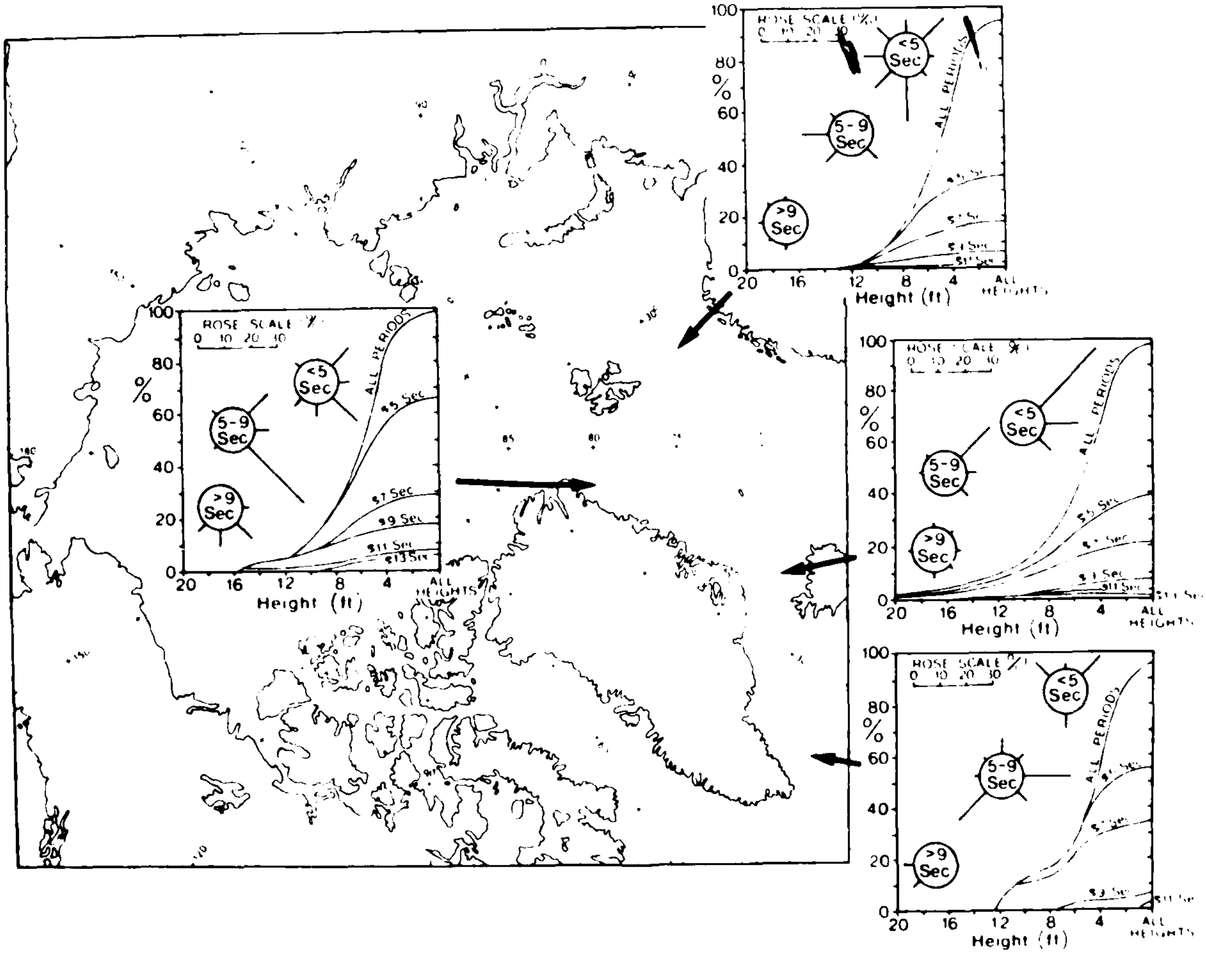


Figure 10. Accumulated frequency distribution of height-period combinations, and directional distribution of periods of surface waves for various areas in the Arctic and subarctic. These data are based on a limited number of observations. (With modification from U.S.N. Hydrographic Office, 1958)

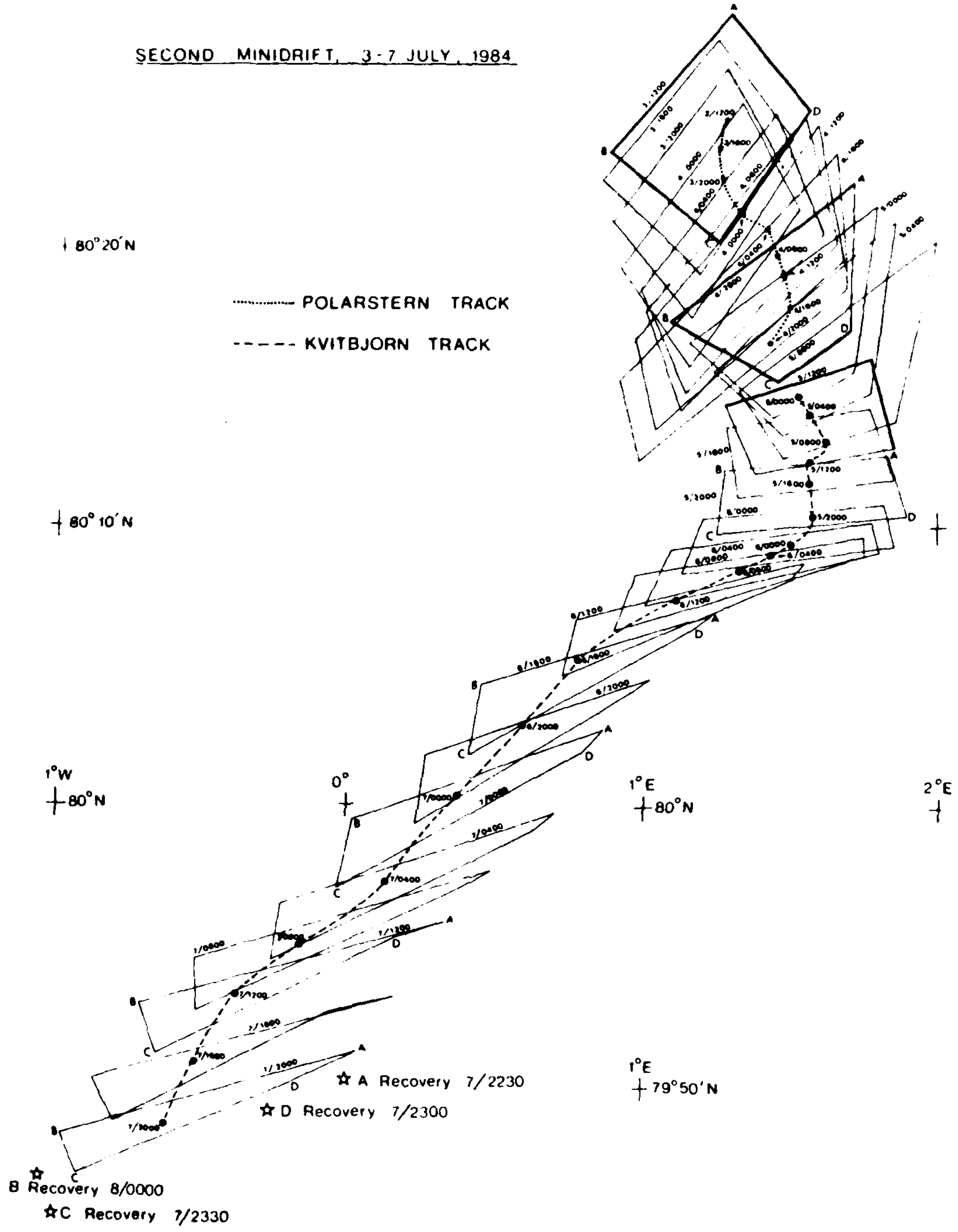


Figure 11. Drift tracks of four transponders during MIZEX 84.

which took place in the North Atlantic off the southern coast of Greenland. Loosely speaking, these data indicate an expected result, namely extremely harsh winter conditions in the winter Greenland Sea, with predominant swells of long period deriving from the south to southeast quadrant. Some wave data on the winter Greenland Sea are also available from an upward-looking echo sounder study carried out from a submarine by Wadhams (1978) in February-March 1971 at 79° to 80°N. His data show seas and swell arising mainly in the south. Amplitudes were variable, but on occasion very high; swells tended to be long. The possible presence of arctic lows causing off-ice winds up to 70 knots must also not be forgotten. With a sea/swell running from the south to southeast, and winds blowing oppositely, we would expect extremely steep seas to occur.

As with waves, few data are available on ice conditions. There have been no winter Fram Strait experiments that have assessed the morpho-geometric characteristics and thickness of the floes making up the MIZ, either remotely by means of over-flying aircraft or by in situ ship-borne studies. Furthermore, because of darkness and cloud cover, winter satellite data are limited.

2.3.3 Ice physics and ambient noise

The ultimate behavior of the MIZ under the action of meteorological and oceanic forcing, including the action of surface gravity waves in the band near the ice edge, is of critical importance to numerical modelling studies, including those relating to ambient noise. We require knowledge of the deformation and motion of the ice field over a period of many days (more than 20 × inertial period) and over a well-sampled spatial area, if correct parameterization of floe/floe interaction, and thus of a suitable MIZ rheology and ambient noise for the winter months, is to be obtained.

Although some success has been achieved in measuring MIZ deformation during previous MIZEX campaigns (e.g. Fig. 11), no data exist for the Fram Strait in winter. Without such a data set we can only guess at the nonlinear flow characteristics of a marginal ice zone medium. It is therefore an important requisite of any marginal ice zone research program that ice field deformation be monitored, as well as the forcing due to wind, current, and incident seas. The optimal measurement program would allow a large number of stations to be tracked to good accuracy over a long period of time, and would enable the long-period strains and strain rates to be found and compared to the output of various numerical models subjected to similar forcing.

Long-period strains and strain rates and their driving stresses are important to the overall envelope statistics of ambient noise levels. However, the periods measured cannot be linked directly to ice cracking events. Most noise is generated by shorter period stresses modulated by the ice deformation. An example would be the increased ice bumping caused by a 10- to 25-sec swell entering a convergent ice field. For this reason it is also important to monitor the shorter period motion of the individual ice floes.

2.4 Remote sensing

The Winter MIZEX remote sensing studies will focus on the use of active and passive microwave remote sensors, since they permit observation of ocean and ice surfaces independent of solar illumination, clouds, rain, and snow. Remote sensing is both a tool and a scientific discipline. As a tool, remote sensing techniques will be utilized to provide geophysical information on ice and ocean areas within the MIZ. Such observations have the potential to provide data on a wide variety of phenomena such as the detection of eddies, fronts, upwelling areas, internal waves, gravity waves, and ice thickness. Remote sensing is the only way to obtain mesoscale synoptic coverage of these phenomena at sufficiently high spatial resolution. These remote sensing data may provide a better understanding of the physical processes that control the MIZ.

The objectives of the remote sensing program are to:

1. Verify the capability of remote sensing to detect MIZ features such as ice and ocean eddies, internal and gravity waves propagating into the ice, and ice field characteristics under winter conditions.
2. Provide preliminary information in real time to ships and ice camps, and final data records to workers in other disciplines, on the location, evolution, and motion of the MIZ features, including data on ice type, size distribution, and concentration.
3. Quantify the relationship between the microwave ocean and ice signatures and atmospheric boundary layer conditions.
4. Combine radar altimetry and SAR data with surface wave dynamics measurements to characterize gravity waves as they propagate into the ice.
5. Determine ice type and/or ice thickness with emphasis on the effects of nilias and snow-cover characteristics on active and passive microwave signatures.
6. Combine active and passive microwave measurements to ascertain whether additional geophysical information about the winter MIZ can be obtained.
7. Explore new remote sensing techniques, including SAR phase and impulse radar measurements to obtain ice thickness.
8. Evaluate the SAR complex image characteristics (phase and intensity) to obtain ice ocean kinematic information.

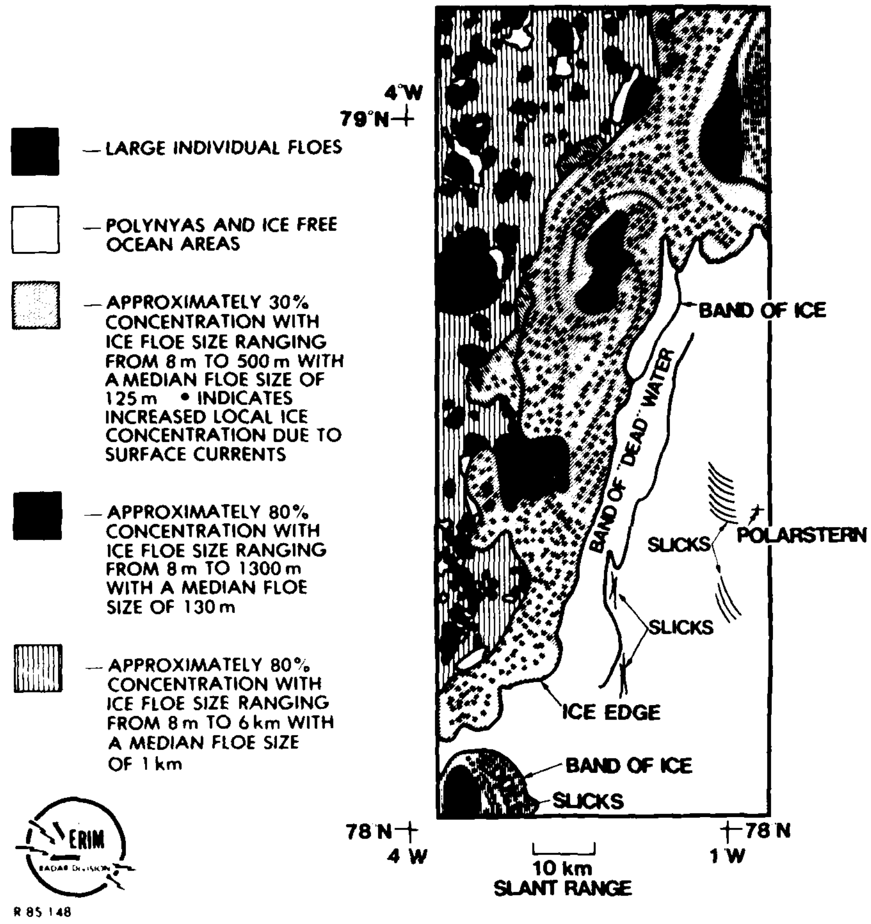


Figure 12. SAR interpretation key for the 5 July 1984 mosaic (Fig. 4).

Remote sensing imagery obtained from satellites (Nimbus-7 SMMR and NOAA-8 AVHRR) during MIZEX 83/84 were used to map the general location of the ice edge as well as many ice edge features, such as eddies, in the entire Fram Strait. These data were invaluable in monitoring the temporal evolution of the MIZ and provided a synoptic context for various ice/ocean phenomena observed during the experiment. They were also useful in determining propagation of eddies, meteorological conditions, and motion of large (5 km or more) ice floes. Sequences of high-resolution passive microwave and radar imagery obtained from aircraft every few days over a period of 7 weeks also monitored temporal changes in MIZ conditions that were important to studies of ice-ocean eddies, the propagation of gravity waves into the ice, ice kinematics, ice concentration, floe size distributions, and ice type discrimination (see also Section 2.1).

Eddies seen in AVHRR imagery have also been observed on SAR images of the MIZ. Figure 4 is a mosaic of the L-band (23.5-cm wavelength) data collected on 5 July 1984. The three eddies clearly observed on the mosaic (see Fig. 12 for an interpretive key) were also observed on the 4 July AVHRR infrared image. Note from the blow-ups in Fig. 4 that individual ice floes can be resolved on the 3-m resolution radar data. These eddies are visible on the SAR data because surface currents associated with the eddy align and consolidate (due to current shear) small (50- to 500-m) floes of ice. These small floes, which were broken up from larger floes by wave action, are in effect surface current drifters that are very bright radar reflectors to the SAR.

The SAR has also detected eddies in the ice-free ocean areas adjacent to the ice edge. In MIZEX 83, an ice tongue structure and trapped polar melt water, indicating the presence of an eddy, was observed by a SAR to the north of the Molloy Deep over a 4000-m bathymetric depression. The SAR image obtained on 11 July across the melt-water boundary shows an area of low backscatter in the cold water region. Coincident with SAR data collection, in situ ship measurements of air and sea temperature and wind speed and direction across the melt-water/Atlantic water boundary showed a water temperature change of 0.5 °C to 3.5 °C (thus confirming the presence of the eddy) with an air temperature of 1.5 °C. Wind speed was 4 $m\ s^{-1}$ from 028°. Previous studies of the Gulf Stream boundary have demonstrated that SAR can detect fronts and eddies due to changes in backscatter caused by variations in atmospheric stability as well as current shear (Ross, 1981). A possible explanation for the features in the SAR MIZ image is the presence of a stable atmospheric boundary layer over the cold melt-water region that suppressed capillary and ultra-gravity wave formation, resulting in low radar backscatter. This stability question, and how the stability affects the SAR backscatter return, is still under study in the Winter MIZEX program.

A number of eddies were extensively sea-truthed during MIZEX 84 with the aid of SAR imagery. The SAR real-time output images were used to relocate the center of the eddies, and ships and aircraft were directed to them so complete temperature, salinity, and density profiles could be obtained.

In addition to providing mesoscale information on ice-edge and eddy formation, the SAR has also been used to provide detailed high-resolution information via manual interpretation of the digital SAR data (for example, see Fig. 12). Manual interpretations of the mosaics from each day's flight were based on features observed in the X-band (3-cm wavelength) and L-band data. These channels provide complementary information: the X-band gives better ice/water contrast and therefore good floe definition, whereas the L-band provides more detail on features within the floes and on ocean wave features.

The high-resolution SAR and SLAR imagery (French B17 and NOAA P3) also provided information on gravity waves. Wind-generated sea and swell gravity waves were observed in both the SAR and SLAR MIZEX 84 data. Initial examination of the data indicates the wave energy is dissipated quite quickly by the small individual ice floes colliding with each other. The SAR did not observe any gravity waves in the ice that were more than 25 km from the ice edge. Whether this same wave energy dissipation occurs in the winter MIZ is a key objective of the proposed 1987 and 1989 experiments.

Internal waves located both in ice-free areas of the MIZ and within the pack were observed by the SAR and SLAR. Open water internal waves are observable due to surface current straining of the SAR ocean Bragg wave (Alpers, 1985), while the internal waves within the ice are visible via the same mechanism as the eddies; that is, differential surface currents cause small ice floes to align themselves to the surface current field.

During MIZEX 83/84, aircraft SAR, SLAR, and PMI data were evaluated to determine ice types and thus to infer ice thickness. The study of summer data indicated that, due to snow wetness, ice type based solely on microwave signature was hard to almost impossible to determine on days when the air temperature was near 0 °C. Winter, due to decreased free-water content in the snow, offers a more promising environment to continue to pursue ice type identification and direct measurement of ice thickness. Passive microwave techniques have a demonstrated potential to identify first-year, open water, and multiyear ice in winter (Gloersen et al., 1978). However, active microwave devices such as the SAR have not been sufficiently validated with respect to classifying ice types. For example, one question is whether the SAR can discriminate new grease ice and nilias from calm areas of open water. And although winter ice type signatures are well documented for central Arctic regions, the existing electromagnetic scattering models for SAR ice need to be tested for winter MIZ conditions using in situ observations obtained coincidentally with remote sensing overflights. An additional question concerns the use of two SAR polarizations and phase differencing to detect ice thickness directly. The combination of active and passive data may provide a means to directly extract ice thickness as well. These questions will be addressed during the winter experiments.

Finally, ice kinematics were also studied during MIZEX using satellite-located buoys, radar transponders deployed on ice floes, and active and passive aircraft microwave systems. The ERIM CCRS SAR and the NRL PMI aircraft produced images of the ice with sufficiently high resolution for individual ice features to be recognized. SAR and PMI-derived two-dimensional vector fields representing ice movement were constructed.

The primary objective of the remote sensing activity in MIZEX 87/89 will be to determine the ultimate capability of remote sensing techniques to provide the winter ocean and sea ice information discussed above. Special environmental conditions exist in the winter MIZ that may either inhibit or enhance the ability of remote sensors to provide geophysically useful information. These special environmental conditions include: (1) increased wind and gravity wave action at the MIZ, which could either mask the ability of the SAR to detect *eddies or enhance its ability to detect eddies due to* increased ice floe break-up; (2) low temperatures at the MIZ, which could prevent the SAR from detecting the eddies; (3) increased areal extent of the ice, which could cover the eddies with large ice floes whose drift is no longer dominated by the eddy surface current circulation; (4) cold temperatures that could inhibit the formation of polar melt water, so eddies in the ice-free areas might not be detected; (5) nilias ice may not be detectable by the SAR; and (6) colder temperatures will enhance the microwave signatures of the individual ice floes, thus potentially improving the ability of the remote sensors to detect ice types.

These uncertainties relating to winter environmental *considerations necessitate a two-phase re*mote sensing program. The first, in 1987, would be a program of modest scope to demonstrate that remote sensing can provide useful geophysical information, during the winter in particular, in identifying the ice and ocean eddies. During the 1987 experiment, the *remote* sensing demonstration will be pursued specifically utilizing synthetic aperture radar imagery from the polar-orbiting Space Shuttle. These images, generated at varying incidence angles, will be available from the reflight of the SIR-B mission, which will provide up to four overflights of the MIZEX area per day for a 10-day period during the experiment. The second year, 1989, would utilize the remote sensing information to support acoustic and oceanographic experiments as well as to pursue the remote sensing science objectives.

Combining measurements obtained by remote sensors and surface measurements is important, not only to determine an optimum remote sensing ensemble, but also to develop the predictive capabilities of remote sensors. An important example of this in the 1987 and 1989 experiments will be combining radar altimetry and SAR data to measure the power spectral density of gravity waves as they propagate from the open ocean into the ice pack. With this information, combined with ice field characteristics derived from SAR imagery and surface measurements of wave dynamics, we can attempt to develop a means to predict gravity wave penetration distance based on remote sensing data alone.

In meeting the objectives stated above, exploration of new remote sensing techniques is an important factor. Techniques using SAR Doppler information, for example, have not been extensively applied to MIZ analyses but have potential for obtaining more information on eddy currents both in the open ocean and at the ice edge, and on dis*crimination of nilias and open water*. SAR phase analysis and newly available impulse radar techniques also need to be evaluated with respect to ice thickness.

2.5 Acoustics

The acoustics objectives for Winter MIZEX 87/89 may be broadly divided into two areas: the first is ambient noise, the second is acoustic tomography and propagation.

2.5.1 Ambient noise

The overall objective of the ambient noise program is to understand the *noise-generating mechanisms* of the MIZ *in the frequency range* from 10 Hz to 20 kHz, with particular emphasis on ice-ocean eddy-related phenomena and other dynamic effects including those peculiar to winter. The specific objectives are summarized as follows:

1. To characterize quantitatively the several mechanisms of eddy-induced noise radiation.
2. To determine the importance of eddy-induced noise with respect to all other MIZ mechanisms, for example, ice compactions and divergence, and cracking due to gravity waves and internal waves. (See Fig. 13 as an example of internal waves that, through periodic banding of ice floes, can cause noise via *bumping*.)
3. To continue to quantify all relevant ice-related noise-generating mechanisms.
4. To explore the feasibility of inversion; for example, can noise measurements lead to a fundamental description of ice fracture types and distributions?
5. To integrate this knowledge with past and proposed measurement programs, including the summer MIZEX 83/84, the Norwegian P3 flights in 1985 in the Fram Strait MIZ,

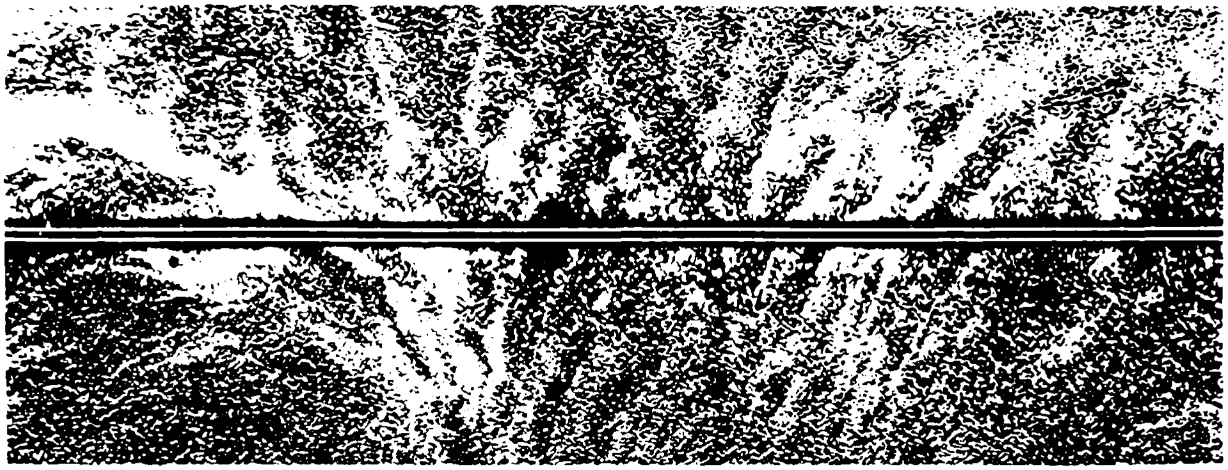


Figure 13. Internal waves observed by Ross via NOAA SLAR in MIZEX 84.

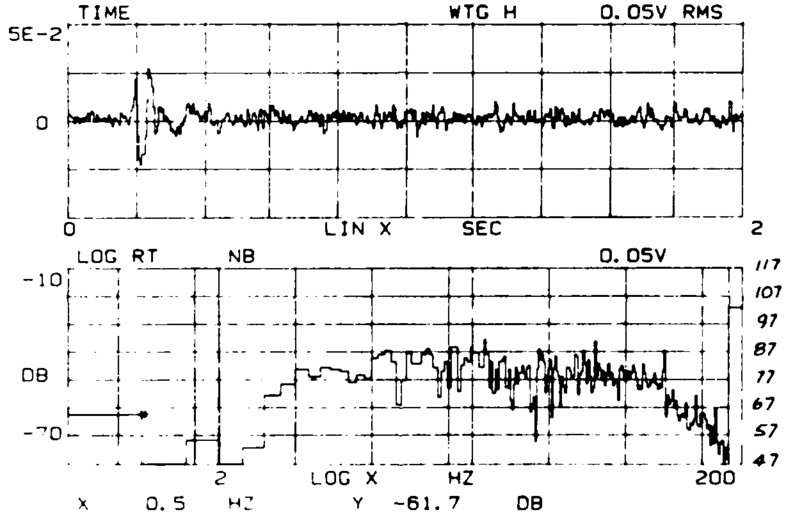


Figure 14. Event and time-dependent spectral density (in dB re 1 μPa and 1 Hz) observed in MIZEX 84 (filtered from 8 to 100 Hz). This event is hypothesized to be caused by flexural fracture of an ice floe.

and New Hampshire lake experiments in January 1987.

6. To understand seasonal (winter) effects on noise source properties. For example, to quantify and relate to summer conditions: the effects of increased wind strength and gradients; greater temperature variations; the presence of thin as well as thick ice; differences in ice fracture strength, greater current gradients; the winter surface gravity wave frequency wave number spectrum including high sea and swell heights; and differing snow dryness and thickness.

Research currently under way has identified several plausible MIZ ambient noise-generating mechanisms. These connect various environmental forcing functions with ice fracture events:

- Temperature changes (giving rise to tensile ice failure)
- Surface and internal gravity wave forcing (giving rise to flexural ice failure). An example of an acoustic event hypothesized to be caused by surface wave flexing of a floe, and obtained in the summer during MIZEX 84, is shown in Fig. 14. Internal waves can affect the occur-

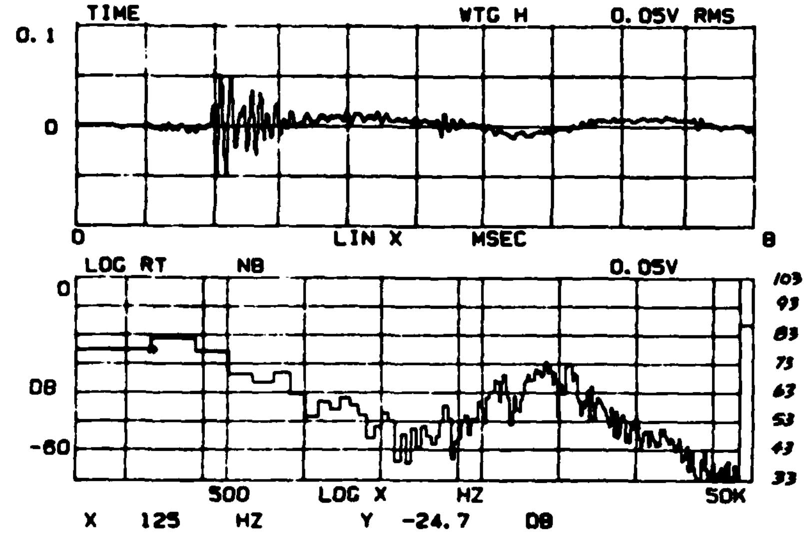


Figure 15. Event and time-dependent spectral density (in dB re *1 μPa and 1 Hz) observed in MIZEX 84 (unfiltered). This event is hypothesized to be caused by floe/floe bumping.*

Figure 16. Compact ice edge noise (top) and diffuse ice edge noise (bottom) from MIZEX 84.

rence rates of such events at least via production of convergent/divergent ice bands as shown in Fig. 13.

- Horizontal bumping (giving rise to compressive ice failure). An example of an event hypothesized to be due to bumping, and observed in MIZEX 84, is shown in Fig. 15.
- Wind/current/pressure gradient/coriolis horizontal forcing (giving rise to tensile, flexural, shear, and compressive ice failure). These mechanisms are likely to be important in regions of the MIZ with high ice concentration.
- Flotation vertical forcing (giving rise to flexural ice failure). This mechanism pertains to pressure and shear ridging, which was not observed during summer experiments and which may not be important in winter either.

More than one of these mechanisms can contribute to the observed noise field. In an ice-ocean eddy, for example, we could anticipate increased noise in regions of higher ice concentrations where incoming gravity waves and/or horizontal pressure gradients cause more frequent ice fracture events.

Similarly, we could anticipate dramatic differences in noise for on-ice versus off-ice winds. Fig. 16 shows MIZEX 84 results in which many events have been averaged. In the top graph the ice edge is compacted by on-ice winds and, over most of the frequency range, is about 10 dB noisier than in the bottom graph where the edge is diffused by off-ice winds.

2.5.2 Acoustic tomography and propagation

The propagation environment of the MIZ is one of the most complicated an underwater acoustician must deal with. It exhibits strong range dependence due to the volume effects of fronts, eddies, and internal waves, as well as bottom and surface interaction, which includes scattering from open ocean waters and ice. For the winter MIZEX the principal objective of the acoustic tomography and propagation program is understanding the interaction of the acoustic wave field with winter MIZ fronts and mesoscale ice-ocean eddies. This interaction includes the spatial and temporal coherence of the acoustic field and the partitioning of acoustic energy in both the waterborne and bottom-interacting paths and/or modes. Central to this interpretation of the propagation data is the wave number analysis afforded by the use of a large aperture array, which is planned for use in Winter MIZEX. A further objective is to understand the dependence of this interaction on the important oceanographic observables (for example, eddy-induced sound velocity perturbations and consequent space/time correlation lengths), both for forward modeling and prediction and for inverse methods including time-delay tomography and full wave (amplitude) inversion. The specific acoustic objectives are as follows:

1. To understand the observed range and Doppler spreading (scattering function) of the winter MIZ acoustic channel.
2. To understand the observed amplitude and phase fluctuations as well as attenuation and partitioning of the mean energy.
3. To understand the spatial coherence of acoustic signals for short separations (1 km) to very large separations (400 km).
4. To invert acoustic propagation data to estimate sound velocity structure, water temperature, vorticity, and heat flux on scales from the gyre scale (100 km) to MIZ eddy and internal wave scales (1-20 km).
5. To investigate the feasibility of using drifting receivers for inversion methods.
6. To investigate under-ice scattering at high frequencies (10-15 kHz).
7. To measure sound velocity in the upper several hundred meters of the bottom should the camp drift to shallow water where bottom interaction will be important.

The acoustic spatial and temporal coherence will be measured using broadband transient shots as well as long CW tones in the range from 10 Hz to 3 kHz. These data will provide direct measurement of the range and Doppler spreading (i.e. the scattering function) of the winter MIZ acoustic channel. Likewise the use of a large array with element separations to 40 km will provide direct measurement of the spatial coherence of these signals as a function of carrier frequency. Forward modeling will use direct measurements of sound velocity over the propagation path and sound channel characteristics obtained from inversion of tomographic waveform data to explain fluctuations and coherence measurements.

Ocean acoustic tomography (Cornuelle et al., 1985; Ocean Tomography Group, 1982) has been successfully used for mesoscale eddy delineation in the open ocean. In the MIZ, ocean acoustic tomography will be used to detect ice-ocean eddies, up-welling events, and meanders of the West Spitzbergen Current. Related plans of others also include monitoring of processes in the Greenland Sea including gyre scale vorticity and the formation and destiny of Greenland Sea waters (see Section 3.5).

From eddy measurements in MIZEX 83/84, preliminary modeling studies of the ray and mode time delay perturbations due to passage of a MIZ mesoscale eddy show an average of 5- to 10-ms changes in travel time over a 150-km path with useful travel time perturbations of as much as 30 m sec^{-1}. These fluctuations will occur over time scales on the order of one day or more and are within the capabilities of time delay tomography instruments.

Application of time delay tomography to the marginal ice zone began with pilot measurements during MIZEX 84 (Spindel, 1985). Tomography signals at 220 Hz were transmitted from a fixed bottom-moored source to the drifting MIT/WHOI acoustic array (STS), which was deployed in the ice near the M/S *Kvitbjørn*. These measurements reveal important results pertinent to the use of time delay tomography in the MIZ. The use of drifting receivers resulted in Doppler smearing and shifts in arrival times of the pulsed signals such that identification and tracking of particular ray paths or modes was not possible. However, when the matched filter outputs were stacked relative to a strong first arrival, thus removing the receiver relative motion, a more stable structure emerged. Fig. 17 shows the acoustic path and mode arrivals. It represents a coherent average of the matched filter outputs and shows that the

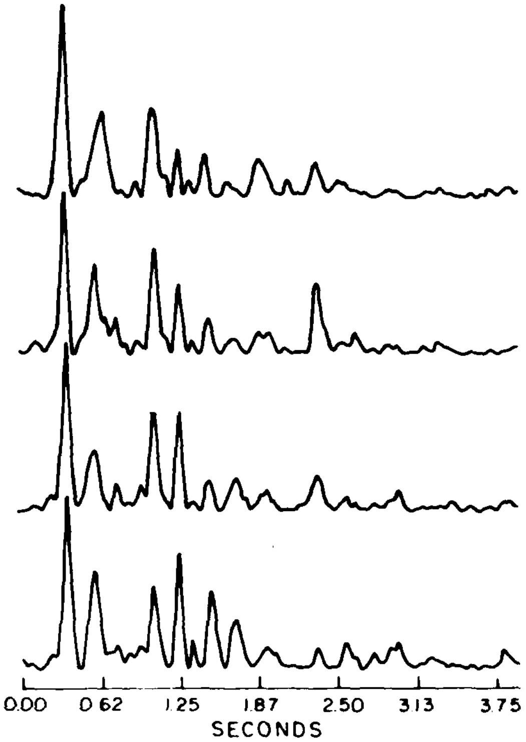


Figure 17. Each trace represents 23 coherent averages stacked by lining up the first large peak of 3.89 sec for a total of 90.6 sec of data per trace. The traces represent contiguous data with the upper trace representing the first 90.6 sec of data, the trace below it the next 90.6, etc. Note the stable arrival structure.

path/mode structure is stable and individual arrivals can be tracked when relative source receiver motion is eliminated. However, this stacking also removes the time-of-arrival perturbations due to the intervening ocean dynamics to the extent that the first arrival is sensitive to these dynamics. For this data set this first arrival was very sensitive to these dynamics, thus rendering tomographic inversion impossible. For these reasons, fixed moored sources and receivers will be used in MIZEX 89 in addition to drifting receivers.

Use of sources and receivers deployed on drifting ice for tomography is very desirable for winter MIZ and deep arctic use, since bottom mooring and recovery is extremely difficult in ice-covered waters. Without tomography, sections can be taken only with icebreakers, helicopters, and/or submarines. Each of these poses serious logistical, cost, and availability problems for any kind of long-term or wide area synoptic surveys. One technique for drifting tomography for arctic/MIZ eddy or internal wave measurements would involve the use of propagation paths that have little interaction with the ocean dynamics of interest for measuring and extracting source receiver motion, for example, deep refracted paths using sources at depths designed to minimize interaction with the upper several hundred meters of the water column.

In addition to travel-time-based inversions, full wave inversion or methods involving exploitation of acoustic energy partitioning and attenuation

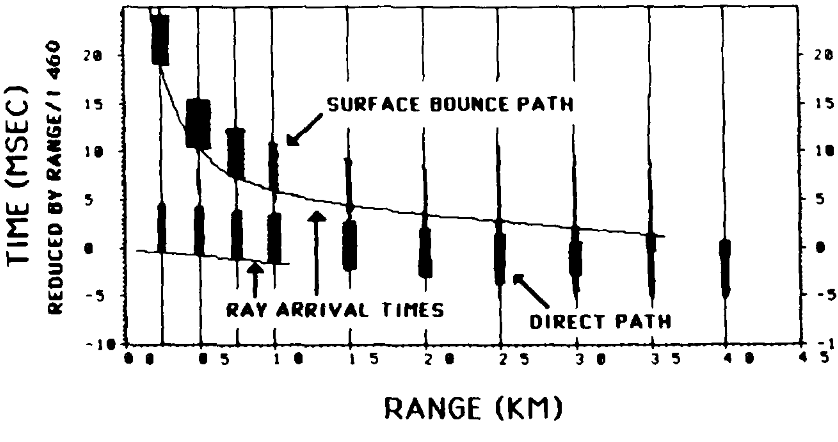


Figure 18. Predicted acoustic arrivals and measured arrivals, showing need for models beyond ray acoustics in the strong refractive paths of the upper part of the MIZ water column.

will be performed. It can be shown that methods for determining sound speed structure from acoustic transmissions that rely on ray theory are inadequate for many sound speed profiles observed during MIZEX 83/84 and for those expected in the winter MIZ. These methods fail to resolve certain areas of the medium that are unsampled in the ray approximation. As an example, Fig. 18 shows predicted arrivals for acoustic transmissions used to localize the drifting hydrophone sensors of the acoustic array (STS) deployed during MIZEX 83. The solid lines show the arrival times predicted by ray theory; the waveforms show the arrivals predicted by the WKBJ approximation. The first arrivals are from a wholly refracted path between source and receiver, while the second arrivals are for a path that reflects from the surface. Note that ray theory predicts no direct arrivals beyond about 1.1 km. This is due to a shadow zone created by a low-velocity region in the upper water column. The WKBJ approximation, however, correctly reveals the direct arrivals and accurately predicts their arrival times. This condition and similar conditions such as double ducts are ubiquitous in MIZ sound velocity profiles. Full wave theory, or at least a high order approximation, is needed to describe the measurements adequately. The increasing availability of cheap computer power has made inversion of the complete observed waveforms possible for complicated medium parameters. This can be done through iterative forward modeling, with the parameter changes needed to bring the predictions closer to the observations guided by numerical partial derivative computations.

The benefits of full-wave inversion are several:

1. There is less need to explicitly comb the data for "arrivals" that can be predicted through the limited theory applied to the forward problem.
2. Use of the entire waveform more tightly constrains the medium parameter estimates.
3. All possible information is extracted from the data, and the best medium-resolution possible is obtained for a given set of measurement locations.

The cost of this method is, however, much greater than currently employed methods and the data acquisition requirements are also very severe. In addition, it is not known how this method will perform in a temporally varying medium. Most techniques similar to this have been applied to geophysical data that contain measurement noise, but very seldom to statistical model parameters. The generalization of these techniques to MIZ science will be very useful.

3. DETAILED EXPERIMENTAL PLANS

To meet the scientific objectives described in Section 2, a comprehensive set of experiments is planned. The plans and procedures are described in this section.

As emphasized, there is a large degree of interdependence between research areas. For example, the evaluation and analysis of ambient noise in the MIZ is greatly dependent upon simultaneous knowledge of related environmental forcing fields, including winds, currents, and ice floe accelerations. Simultaneous spatial and temporal sampling of currents, water temperature, conductivity, vector winds, air pressure, and humidity provide concurrent data for oceanography, meteorology, and ice studies essential to the proper understanding of the MIZ physical processes. To meet the program's objective of acquiring a broad range of scientific data with simultaneous spatial and temporal sampling, the experimenters plan to use a newly configured sensor buoy named ARAMP (Arctic Remote Autonomous Measurement Platform). It will be a remote, battery-powered autonomous measurement system capable of concurrent sampling of all forms of environmental data, including ambient noise. Selected measurements will be telemetered via the ARGOS system for real-time evaluation, and the remainder recorded in the buoy for periods of up to 3 months. Fig. 19 illustrates the basic system concept. This sensor platform will significantly reduce the burden on both ships and helicopters of obtaining the measurements we have described, while enhancing the usefulness of the data in correlating and developing understanding of the MIZ ice/ocean/air processes and their impact on acoustic ambient noise.

With position information for each deployed ARAMP provided by ARGOS, and with as many as 70 ARAMPs deployed simultaneously in mesoscale and synoptic scale, an essential level of environmental sensing can be reached. Propagation and decay of an eddy could, for the first time, be measured at the ice edge with a spatial grid adequate to the task. Ambient noise could be correlated with eddy and surface wave parameters on a point-by-point basis, ending the uncertainties in our present understanding of the precise mechanism of noise generation. These are just two examples of the central nature of the ARAMP data ac-

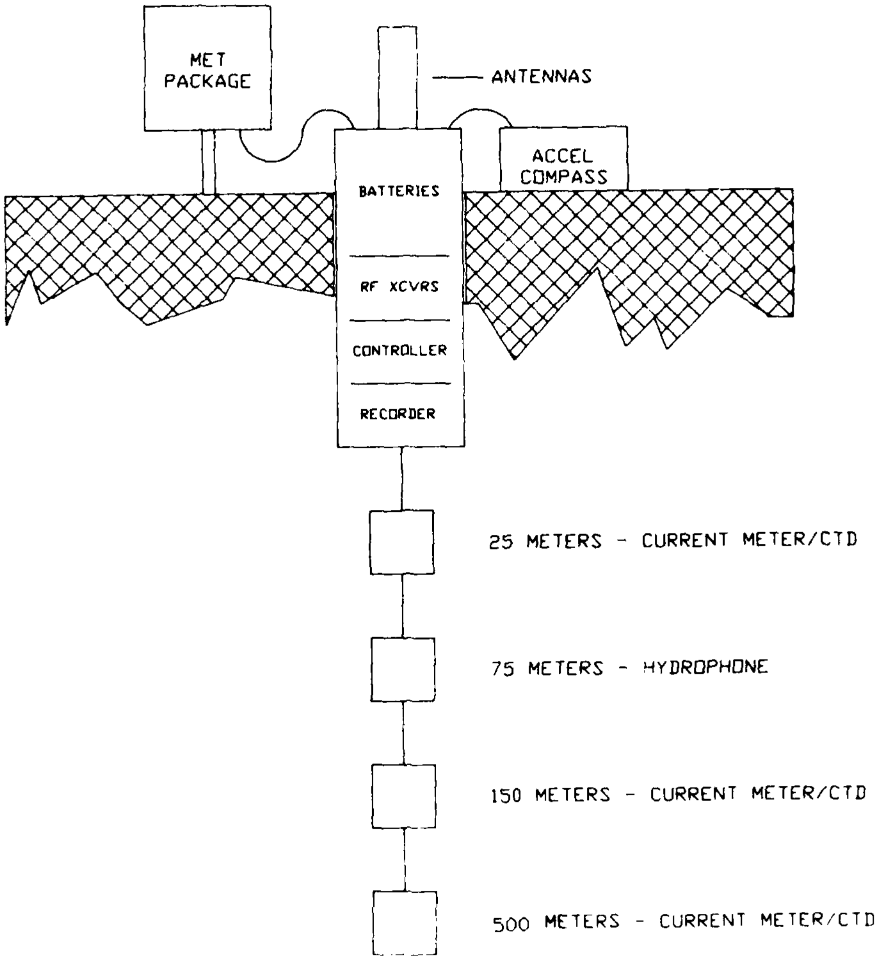


Figure 19. Conceptual illustration of ARAMP, an automated, integrated environmental measurement system.

quisition system to the Winter MIZEX in Fram Strait.

Observational systems as used in MIZEX East 83/84 will also be used in MIZEX 87/89. Indeed, such systems are still essential. The ARAMP system is highlighted in this introductory section in part because of its unique potential for obtaining concurrent observations, and in part because it is a major new instrumentation initiative for the entire research team.

3.1 Oceanography

Synoptic studies of mesoscale eddies, upwelling areas, and internal waves in the MIZ demand a measurement plan integrated with the other disciplines. Winter weather conditions and the presence of the ice pack cause considerable logistical constraints that make that real-time flexibility an important element of the operations plan.

To control and direct the experiment, real-time analyses of remotely sensed ice-edge conditions and oceanographic ARAMP and shipboard-acquired observations will be key elements in locating and tracking MIZ eddies as well as upwelling and internal wave events. To study these phenomena requires a time sequence of three-dimensional synoptic mapping of the scalar and velocity field, in general with 5-km station spacing, as well as of the atmospheric forcing fields, ice edge configuration, ice concentration, and ice melt rates. Time-series Eulerian current observations can provide information to substantially improve our understanding of the East Greenland Current-polar front system and associated features such as mesoscale eddies. These observations provide values for parameters, such as rotation speed and sense, propagation, and vertical shear, which can then be compared with results from analytical dynamic

Table 1. Oceanography measurement systems.

Sensor	*Platform*	*Observations*
Profiling instruments		
CTD	Ship	Salinity, temperature
SeSoar	Ship	Towed CTD (upper 300 m)
APS cyclesonde	Ice camp	Salinity, temperature, relative velocity (upper 200 m)
XBT	Ship/ice camp	Temperature (upper 500 m)
AXBT	Aircraft	Temperature (upper 500 m)
ADCP	Ship/ice camp	Relative current to 450 m
Non-profiling instruments		
Towed thermistor	Ship	Sea surface temperature
Thermistor chain	Ice camp	Temperature, salinity at fixed levels (down to 300 m)
Aanderaa current meters	Bergen Toroid ice camp	Ocean current at fixed levels and temperature salinity (down to 300 m)
ARAMP	Ice floes	Ice drift, temperature, salinity, horizontal velocity at fixed levels in the upper 500 m
VTS	Ice camp and floes surrounding the camp	Mixed layer/upper pycnocline mean and turbulence measurement
Wave rider buoys	Ice floes/ocean	Surface waves
Sofar floats	Subsurface floats	Lagrangian ocean circulation
VCM	Subsurface floats	Vertical velocity
Argos buoys	Ice floes	Ice drift

models to ascertain the dynamics of the features. These current observations will be provided during MIZEX by taut wire moored current meter arrays that will measure currents at different depths along a cross-fronted transect and at a downstream location. Where possible, these current moorings will be integrated with ARAMP arrays, which are to be deployed as part of the Lagrangian environmental and acoustics study program. The moored current meters will be deployed, at a minimum, for the duration of the MIZEX field program and maybe for as long as 12-13 months.

The measurement/observation equipment for the oceanography program is listed in Table 1. The scalar fields (temperature, salinity, density, and sound speed) will be mapped by CTD/AXBT/XBT/thermistor chains from ice stations, ships, ARAMP, helicopters, and aircraft as well as from towed sensors, such as the Batfish, in the open water off the ice edge. SAR/SLAR, passive microwave systems, and visual/IR observations will be used to map the ice edge location and structure and the surface expression of eddies, fronts, and internal waves. Vertical current measurements will be obtained from free-drifting floats. The velocity field will also be measured over a 1-yr period by Doppler sonars mounted on ships and ice floes and by moored current meter arrays combined with an acoustic tomography array.

3.1.1 Eddy tracking and upwelling

When one or several eddies are located, for example, via remote sensing, star pattern CTD and Doppler sonar velocity measurements and ice concentrations will be obtained and analyzed in real time. One or two eddies will then be "instrumented" with the ARAMP system (see Fig. 20) according to the initial analyses. The scalar fields, veloc-

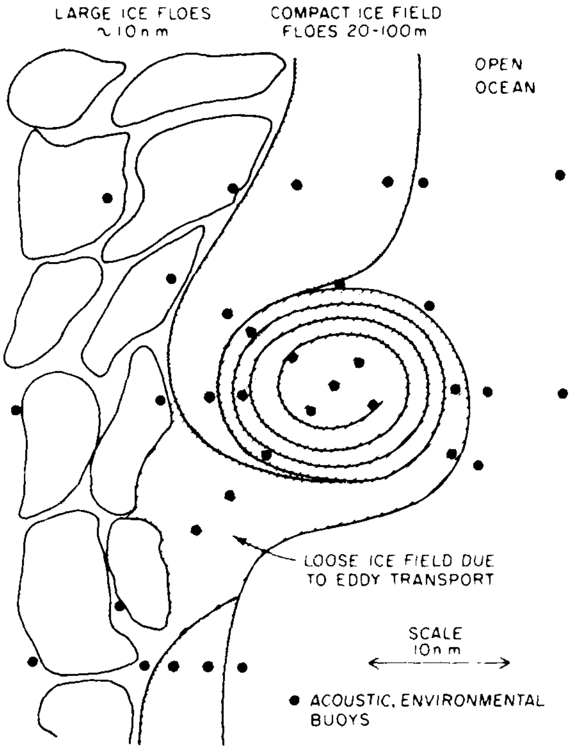


Figure 20. Schematic deployment of ARAMPs at an ice-ocean eddy.

ity fields, ice configurations and concentrations, and wind forcing will be monitored for several weeks. It is expected that when strong wind forcing is present, ice motion in the eddy will be dominated by this effect and the instruments will lose their tracer function. The ice-ocean eddy will probably still be present, but perhaps with a weaker surface signature due to wind mixing. Tracking of one or several eddies for weeks by remote sensing and oceanographic observations should provide the basis for a better understanding of the energies, propagation, decay, eddy/eddy interaction, response to strong wind forcing, and the eddy role in heat and mass exchanges across the ice edge.

Prevailing wind forcing from certain directions will also generate ice edge upwelling. If many eddies are present they will also be affected by the upwelling as indicated during the NORSEX experiment (Johannessen et al., 1983).

We are also particularly interested in studying a region where there is upwelling and where the ice edge is wavy but without the presence of an eddy. This will enable us to test the Hakkinen (1984) theory for ice-ocean eddy generation. In this case we will initially carry out hydrographic sections perpendicular to the ice edge in a three-dimensional pattern, which will be changed to a star pattern if we see that eddies start to develop. In addition, some of the ARAMP systems will also be deployed to help track the possible eddy growth.

The oceanographic structure of an eddy as observed during the summer 1984 MIZEX shows clearly that the strong vertical stratification is 'broken' in its center. This also occurs in ice-edge upwelling events. If this is also the case during winter, warmer and saltier water than the surrounding will be exposed to extreme cooling, which could result in deep convection and bottom water formation. To investigate deep convection, sampling will be carried out with emphasis on the vertical flow measured by subsurface floats in the area of 'broken' stratification as well as on air/sea/ice fluxes.

3.1.2 Internal wave field

The internal wave field will be sampled using the ARAMP buoys. This will be accomplished using thermistor and thermistor-conductivity chains in arrays on a scale of a few hundred meters and current meters in the upper and lower layers. Sampling periods for both systems will be 2 min, which is well below the Vaisala-Brunt periods. During certain time periods high-frequency sampling with a CTD system and a Doppler current meter will be added to the regular remote sensing observations. To investigate potential internal wave generation caused by the ice cover, complementary data sets will include under-ice characteristics, ice concentration, and wind forcing.

Real-time analysis from remote sensing observations on calm days will give information on the directionality of the internal wave field and the dominant wavelength via ice convergence caused by the internal waves. Furthermore it will give an indication of ice-ocean eddy and internal wave interaction. This information will be used to position several ARAMP buoys to explore the effect of internal waves on ambient noise generation and to study the interaction between eddies and internal waves.

3.1.3 Boundary layer

Instrumentation for the upper-ocean/ice-ocean boundary layer experiment at the 1989 drift station includes:

1. Two inverted masts spaced at least 100 m apart near the manned camp with instrument

clusters at four levels, tentatively 2, 4, 7, and 15 m below the ice underside. Each cluster contains temperature and conductivity sensors and three small rotors for measuring velocity along orthogonal axes. Each sensor is sampled 6 times per second, with data collection and field processing handled by small computers. Both frames require open (warmed) hydroholes, to allow frequent adjustment and maintenance.

2. A mobile frame, 6 m long, suspended by cable, capable of reaching depths of 100 m. This frame holds four clusters similar to the above plus depth and orientation instruments. The frame was used successfully in AIWEX 85, and is used for detailed measurement of high shear regions not immediately adjacent to the ice/water interface.
3. We may deploy the 3-axis diode-laser-Doppler velocimeter developed by Flow Industries and tested in MIZEX 84 and AIWEX 85, for boundary layer studies.

An explicit boundary layer program is not included in the MIZEX 87 plans.

3.2 Meteorology

The field measurements and other data collection efforts in MIZEX 87/89 are being planned to provide information on the role of atmospheric forcing on ice, ocean, and acoustic phenomena. Fig. 21 summarizes the data sources, atmospheric processes, and features according to the scale (microscale, mesoscale and synoptic scale). The plan is based on our opinion that the primary scale to which the ice, ocean, and acoustic correlation will be applied is the mesoscale, as indicated in Fig. 21.

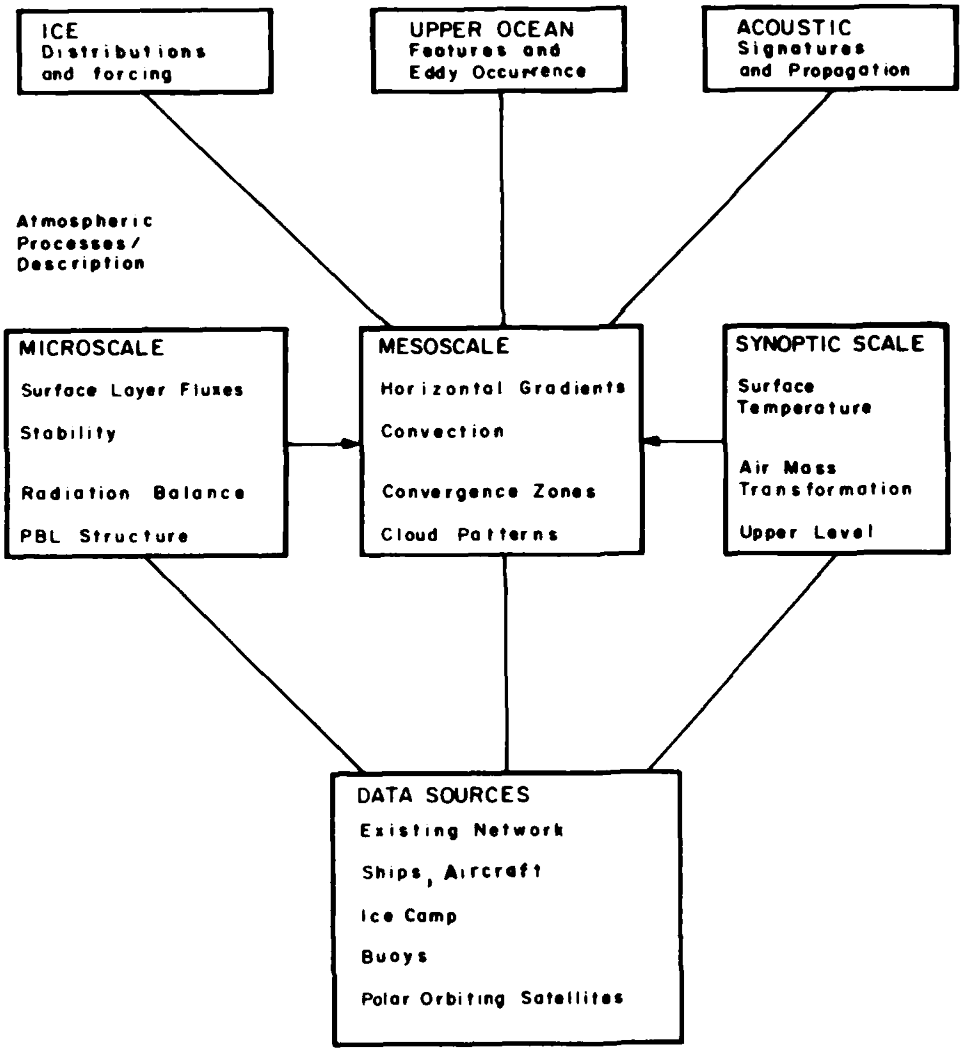


Figure 21. Summary of meteorological measurement structure.

This is because eddies and Lagrangian description are emphasized in the ocean and ice studies, and spatial variations are emphasized in the acoustic studies. Therefore, within the limits imposed by locations and number of platforms and the existing meteorological network, the microscale and synoptic scale information will be applied to obtaining mesoscale descriptions.

The field measurements in both 1987 and 1989 will make use of several platforms. Shipboard measurements will provide time series of microscale processes at different locations. Aircraft measurements will be applied primarily to mesoscale descriptions and at times when distinct mesoscale features exist in the MIZ vicinity. These features may or may not occur near the ship locations. It is expected that continuous sampling with the ship will be useful in characterizing conditions leading up to the genesis of mesoscale features, even if they occur at distant locations.

The 1987 field plan will be based on two ice ships, which will be at multiple locations within and outside the MIZ, one meteorologically instrumented aircraft (with dropsonde capability), and aircraft remote sensing. The 1989 field plan will be based on the addition of an ice camp and the addition of a large number of buoy sensor platforms (ARAMPs).

The meteorology measurements/observations to be made from the ship in 1987 and 1989 are listed in Table 2. Those ship measurements for which an ice location (third column) is identified would only occur when the ship is tied to a floe for up to 6 hr. The meteorological measurements to be made from the open-ocean ship as listed in Table 2 will be taken from instruments mounted on the

Table 2. Ship measurements/observations.

Sensor/System	*Measured*	*Ship/ice locations**
Anemometer/vane (to be selected)	Average wind speed/ direction	Bow mast Ice mast Ice tower
Radiation shielded and aspirated platinum wire thermometer	Average temperature	Bow mast Ice tower
Hygrometer (to be selected)	Average humidity	Bow mast
Sonic anemometer with thermometer	Wind and temperature, fluxes, spectral properties	Bow mast Ice mast
Radiometers	Long, short, and total downward radiation	Ship deck
Acoustic sounder	Wind profiles (ice only), inversion levels, turbulence *intensities*	Ice surface Ship deck
Barometer	Atmospheric surface pressure	Ship lab
Aerosol probes	Coarse suspended particulate matter	Ship deck
Radiosonde (Omega NAVAID)	Wind, temperature, and humidity profiles	Ship deck (2-4/day)
Hourly observations	Sky conditions, visibility, sea or ice conditions, precipitation	Ship bridge

* Bow mast—Instruments are mounted on a boom extending forward 3 m from the forward mast at a height of about 18 m.
Ice mast—3-m tower with cross bar for instruments.
Ice tower—6-m tower with four wind-speed and temperature levels.

ship. The aircraft meteorological measurements are listed in Table 3. The measurements that will be made at an ice camp and with buoys (1989) are in Table 4.

Procedures for microscale and mesoscale investigation are described in the following sections.

3.2.1 Microscale experimental plan (surface fluxes)

Ice-hardened ships will be used in both 1987 and 1989. In 1987, the ship will operate in both ice and ice-free regions. In the ice, wind stress, heat flux, and evaporation will be estimated using eddy flux (direct), profile (less direct), and dissipation (indirect) measurements. To accomplish this, portable masts will be set on the ice 50 to 100 m from the ship, with cables carrying data back to the ship. For comparison, dissipation method measurements will also be made at a carefully selected location at the bow of the ship, when the ship is facing into the wind. This method is considerably less vulnerable than eddy flux methods to errors introduced by airflow distortion around the ship. This method can be continued even if ice conditions are unsuitable for deployment of the mast on the ice, and so can provide data even in broken or loose pack ice.

To relate surface stress data on the ice to ice surface roughness, leveling lines along the upwind direction will be surveyed for up to 500 m. These will be compared with several airborne laser profile lines flown in the same direction and as close as possible (a few tens of meters) to the survey line. Comparisons will also be made between the aircraft and ship wind stress and heat fluxes measured by eddy correlation and indirect methods by having the aircraft fly several passes in the vicinity of the in-ice ship. This would most likely occur in conjunction with an aircraft flight in the vicinity of a mesoscale feature. If the feature is at another location, comparison can be made between the two. These microscale comparisons between sur-

Table 3. Aircraft meteorological measurements.

System	*Measured*
Omega drop windsonde	Wind, temperature, humidity profiles
Infrared radiometer	Sea and ice temperature
Gust probe	Fluxes of momentum, temperature, moisture
Profilometer	Surface roughness

Table 4. Ice camp and ARAMP buoy measurements/observations.

System	*Measured*	*Locations*
Anemometer/vane	Average wind speed/direction	Ice camp Buoy
Shielded thermometer	Average temperature	Ice camp Buoy
Hygrometer	Average humidity	Ice camp
Radiometers	Long, short, and total downward radiation	Ice camp
Barometer	Atmospheric pressure	Ice camp Buoy
Radiosonde (Omega NAVAID)	Wind, temperature, and humidity profiles	Ice camp (2/day)
3-hr observations	Sky conditions, visibility, precipitation	Ice camp

face and aircraft data will be valuable in interpreting the ice roughness and fluxes derived from the same aircraft covering meso- and synoptic-scale areas.

With the exception of the profile and eddy flux measurements on the ice, the open-ocean ship will perform the same measurements as the ice ship (see Table 2). The flux estimates for the open-ocean ship will be based on dissipation methods. At present, these methods are most successful for the turbulent kinetic energy dissipation rate and, hence, surface stress. There is a possibility of measuring humidity variance dissipation rates but not temperature variance dissipation rates. Estimates of surface fluxes of temperature and humidity at the open-ocean ship will rely primarily on established parameterizations. Measurements of average wind, air and water temperature, and humidity will be made at the bow of the ship along with fluxes of solar and long-wave radiation. Routine recording of ocean whitecap coverage will be made in the open-ocean ship using cameras in heated shelters and strobe systems. Whitecap decay times will be determined using a video system and a high intensity lamp.

3.2.2 Mesoscale experimental plan

Both ships and aircraft will contribute to the mesoscale descriptions. The aircraft program will be performed from the NOAA P3 operated for scientists at NOAA ERL/WPL, Boulder, Colorado. The primary field effort to obtain the descriptions will be with the aircraft and will consist of measurements at several levels along tracks determined by the location and orientation of the mesoscale feature and of selective deployment of drop windsondes. The mesoscale features of most interest are the low pressure systems that have been observed in the vicinity of the ice edge. These storms are often most intense south of the MIZ region in the area between Bear Island and the northernmost coast of Norway. Hence, aircraft measurements may be taken some distance from the ship measurements.

Mesoscale properties to be described by the aircraft measurements are the horizontal and vertical gradients of heat and momentum fluxes, vector wind temperature, and humidity over horizontal spacings of 2-5 km and vertical spacing of 20-50 m. These descriptions will be obtained with aircraft-mounted sensors and the drop windsondes. Previous successful P3 aircraft studies (Shapiro et al., 1986) of these relevant features will guide the design of the MIZEX 87/89 efforts.

The relative roles of upper level dynamic and surface layer thermodynamic forcing on the genesis, intensification, and movements of the system require data from the ships, the space shuttle, and the synoptic network.

The shipboard, ice camp, and ARAMP measurements will provide time series and reference points for aircraft mesoscale data interpretation. These will be from both the open-ocean ship and the ice ship. Both ships and the ice camp will launch radiosondes at 0000 and 1200 GMT daily, and will record cloud conditions hourly. This sampling frequency could be increased if a mesoscale system were in the vicinity and conditions permitted radiosonde deployment.

Acoustic sounders will be used to monitor continuously the turbulent intensity profiles and inversion height at both ships as well as the vector wind profile at the ice ship.

High-resolution photography from the SIR-B reflight in 1987 will provide valuable information on the evolution of clouds associated with mesoscale features at the MIZ. The coordination of the Shuttle meteorology-observing program is provided by Dr. C. Wash at the Naval Postgraduate School, Monterey, California. As such, he performs pre- and post-mission briefings to Shuttle crews, and interprets photographic records from each flight. He will be a participant in the MIZEX 87/89 planning and analysis stages.

3.2.3 Synoptic scale plans

Synoptic scale descriptions will be obtained from the existing observation network (Fig. 22), from polar orbiting meteorological satellites (NOAA, Tiros-N, and DMSP systems) from the SIR-B reflight in 1987 and from additional surface and radiosonde data obtained in the MIZ field program. These data will be used to obtain three-dimensional fields of the synoptic scale patterns influencing the MIZ mesoscale features, surface geostrophic flows, upper level waves, and associated baroclinic zones.

The initial fields for development synoptic patterns will be modified by incorporating other collected data. The basic analyses will be those produced by national and international forecast/analysis centers. The procedures for utilizing the additional data obtained during the experiment (radiosondes, surface winds) in the real-time polar forecasts have yet to be established. These could consist of reanalyses based on initial data and on additional fields using schemes developed by the centers.

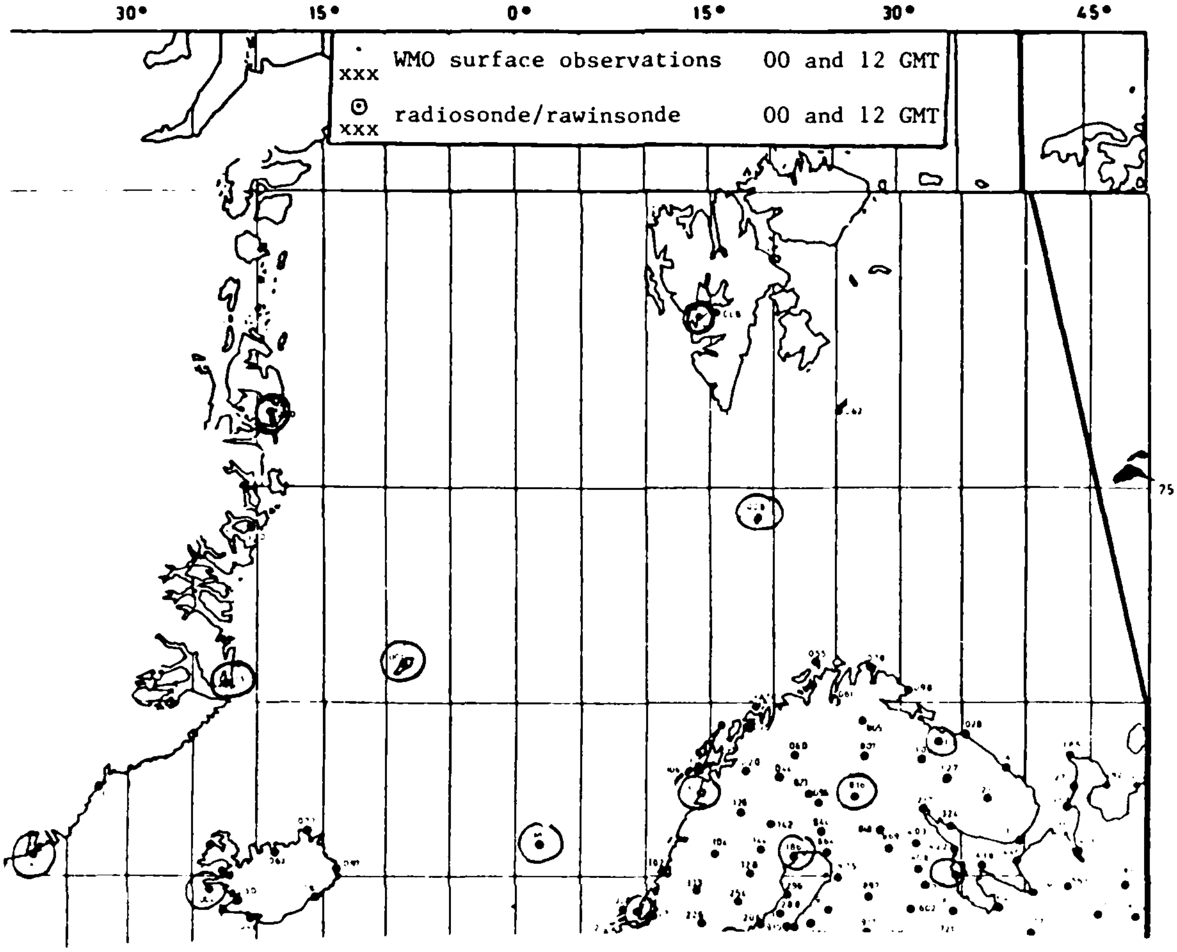


Figure 22. Existing meteorological observing network in the vicinity of the MIZ with surface and upper air (radiosonde) observation stations indicated.

The data base for preparing synoptic analyses in the region of the MIZ is at present very coarse. As proposed for Winter MIZEX, the addition of 10 or more met-equipped buoys and two upper-air stations will provide a unique data base for examining the dynamics of meteorological processes in the vicinity of the MIZ. This understanding will in turn lay the groundwork for evaluating and interpreting remotely sensed satellite data in polar regions.

In particular, the MIZ offers a unique opportunity to evaluate and use microwave satellite soundings and microwave images from the polar-orbiting DMSA to enrich the synoptic-scale analyses. MIZ ground truth data will be used to validate and improve satellite retrieval algorithms for temperature profiles, precipitation, cloud water, surface wind, and ice edge data in this data-sparse region. Then the polar orbiting satellite data, with its 10-25 km spatial resolution and nearly 90-min sampling period, will be used to enhance the conventional analyses and provide detailed measurements of important MIZ mesoscale phenomena such as arctic lows.

3.3 Ice physics

3.3.1 Ice kinematics and thermodynamics

The acoustics program in 1989 will provide a means for measuring ice deformation on the mesoscale (~ 40 km) and less. An acoustic array will be ice-camp-deployed; it will be capable of receiving signals that can be processed coherently over a 40-km aperture. A by-product of the use of the sensor tracking system (STS) developed to provide instantaneous (30-sec) array element locations is the ability to measure ice deformation at 30 or more locations on this time scale. The rapid temporal sampling rate and dense spatial sampling will allow the use of spatial sub-arrays for estimation of the spatial variability of ice deformation processes. This should allow the resolution of effects on ice motion of phenomena such as short-period (30-min), 2-km wavelength internal waves that have scales too small for other measurement methods, but are observed on SAR images. The tracking system allows estimation of strain rates to periods shorter than 20 min. In addition to the estimation of strain parameters with periods greater than 10–20 min, dynamic modeling of the ice field allows us to estimate and/or bound driving forces and energy input to the ice motion. If this is coupled with under-ice current and wind stress measurements on a scale similar to the array size, then air/sea/ice interaction models may be verified.

Ice deformation over a 10–15 km scale will also be measured in 1989, if possible, with use of up to 7 ARAMP systems. Each ARAMP would have to have positional accuracy better than that of the ARGOS system, and GPS possibilities are presently being investigated. Principal uncertainties with GPS are associated with unit cost and availability for ground systems with the requisite resolution.

Opportunities for the use of the Del Norte transponder system for measurement of ice deformation, as in MIZEX 83/84, are virtually zero. A ship would have to maintain station within radar range (30 km) of the Del Norte array, but present measurement plans call for the ice ship to be continuously occupied with various transects. (A Del Norte array could be used at the ice camp in 1989, but the acoustic sensor tracking system there provides the desired data anyway.)

The mass and heat budgets will be monitored by means of top and bottom ice ablation measurements, radiation measurements, and thermistor-based temperature measurements in the upper few meters of the ocean. In particular at the 1989 ice camp, we have in mind a very modest program that will provide basic information on changes in the state of the ice and the reasons for these changes. Our primary emphasis will be on conditions at the ice/water interface. We plan to install electric thickness gauges and thermistor arrays at several locations in the vicinity of the ice/ocean boundary layer experiment. In addition, we might instrument several sites on an adjacent floe if it were significantly different from the primary floe. We would couple this with routine information on air temperature, cloudiness, snow depth, and radiation fluxes at the upper surface.

3.3.2 Ice and surface wave studies

The Winter MIZEX experiments planned for 1987 and 1989 have a stated requirement to collect detailed wave measurements outside and inside the ice edge with the following aims:

1. To quantify wave-generated acoustic noise in the presence of pack ice; incoming waves will contribute to the spectrum of ambient noise detected at any location in the MIZ through floe/floe collisions, wave-induced fracture events, capsizing of ice floes due to wave erosion, and turbulence introduced by the penetrating sea.
2. To determine the radiation pressure effect of intense winter surface gravity waves and to relate its magnitude to other forcing mechanisms in the MIZ.
3. To collect sufficient wave data in 1987 to enable a reasonable estimate to be made of the conditions likely to be met in 1989. It is planned to deploy an ice camp surrounded by a grid of acoustic instruments (STS) in 1989, which will gradually drift towards the edge region, crossing an eddy en route, we hope. Ideally, the array should survive for 30 days and not break up through wave action. The 1987 wave climate experiment will help to design the correct configuration relative to the ice edge.
4. To provide surface truth for aircraft and Space Shuttle overflights.
5. To study directional wave spectral evolution within the MIZ and especially in the presence of eddies.

In addition to these wave climate aims there is an acoustical need to monitor floe/floe interaction over short periods and a modeling requirement to study deformation.

Various wave climate experiments are envisaged. In 1987 it is important that wave climate be established for correct planning of the full 1989 experiment. Directional wave measurements should take place from the ship at the ice edge on a routine basis at all CTD stations, and in detail in support of any remote sensing flights by aircraft or Space Shuttle. The remote sensing plan recommends that a novel symbiosis of instruments be included: namely a SAR and radar altimeter used concurrently. The SAR provides wavelength characteristic and directionality, the altimeter significant wave height and average period. Ground truth for this valuable pair of sensors is important, and would be obtained using a pitch-roll buoy along transects to acquire directional characteristics of the sea off the edge. Within the ice cover similar data would be collected. In addition to wave forcing, ice floe size distribution, concentration, and thickness would be obtained from aerial photography carried out from helicopter when available and by coring. It is also possible that an impulse radar presently being tested in the Weddell Sea, Antarctica, will be used to obtain ice thickness.

In 1989, a more sophisticated series of wave experiments is planned to measure ocean waves in relation to ambient noise generation, MIZ kinematics, ice floe break-up, and consequently to floe size distribution modification. Ice kinematics will be measured using an acoustic array surrounding the ice camp as described in Section 3.3. In parallel, wave measurements will be collected routinely from the open-ocean ship, using pitch-roll buoys, and from the ice-edge ship, using similar or alternative directional wave buoy instrumentation. Three-axis accelerometer units will be used to monitor waves and floe bumping events at a large number of sites within the MIZ associated with both the STS array and eddies near the edge (accelerometers are also part of the ARAMP buoy). The units will have sufficient bandwidth to satisfy ambient noise modelling requirements and will be deployed alongside hydrophones. Some wave data will also be collected at the ice camp site. We will endeavor to measure simultaneously at all sites. Wind measurements, current measurements, and these wave data will enable full interpretation of the kinematic data collected by the acoustic array. Floe size distribution and concentration will be found from helicopter-borne aerial photography, and ice thickness from coring, or better from impulse radar measurements, if this system proves effective. Priority measurements designed to provide surface truth to data collected from overflying remote sensing aircraft will also be made in the context of verifying remotely obtained wave parameters, kinematic ata, and the morpho-geometric characteristics of the ice field. The data set is intended to enable full parameterization of the wave intensity effects that lead to ambient noise generation in the winter Fram Strait MIZ.

3.4 Remote sensing

Both active and passive microwave as well as visible and infrared remote sensing systems will be utilized during Winter MIZEX. Due to weather and solar illumination considerations, the emphasis for MIZEX 87 and 89 will be on the use of active and passive microwave sensors. The sensors to be used in the Winter MIZEX program include): imaging radar (both SAR and SLAR); microwave altimeters; impulse radar; microwave scatterometers; visible; infrared, and microwave radiometers; XBTs; aerial photography; and dielectric constant measuring devices.

Fig. 23 summarizes the proposed coordination of the remote sensing activities during Winter MIZEX. A field coordination center will be maintained at the ice-strengthened ship (or ice camp) that will serve as center for all remote sensing communication. A land coordination station, located at Tromsø, Norway, will interpret aircraft

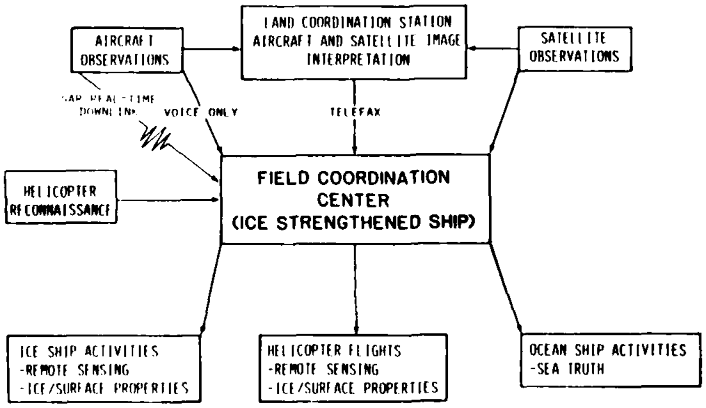


Figure 23. Approach to coordinate the remote sensing activities for the Winter MIZEX program.

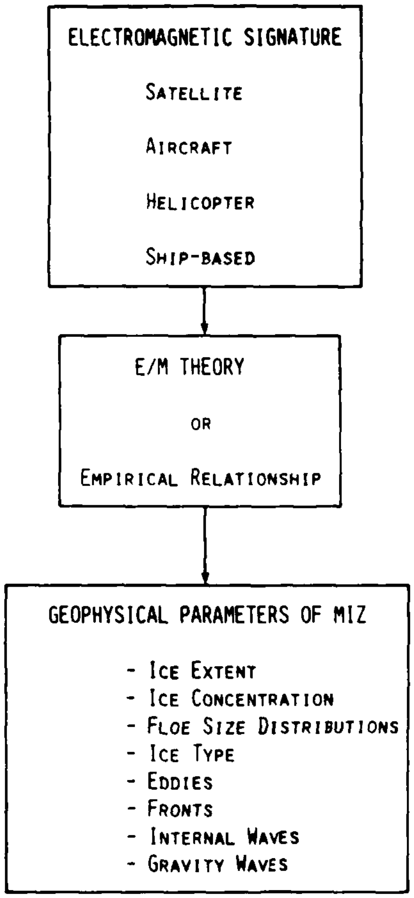


Figure 24. Relationship between the sensing electromagnetic signatures and MIZ properties.

and satellite data and transmit this information to the field coordination center. The ship will utilize this information along with SAR down-linked data, voice communication from the various aircraft, directly received satellite data, and helicopter reconnaissance flights to direct the local remote sensing activities (helicopter, ship based, and surface). The ship coordination center, via the Tromsø satellite station, will orchestrate all remote sensing aircraft flights so that the active/passive microwave imagery and the altimeter data are collected simultaneously. In addition, the ship will coordinate the placement of the in situ sensors (for example, AFAMP buoys and the gravity wave-measuring buoys) that will be used to validate the remote sensing data. This approach was used successfully in the summer MIZEX 83/84 programs.

The goal of the remote sensing studies is to utilize electromagnetic signatures as provided by satellites, aircraft, helicopters, and ship-based systems to predict geophysical parameters of the MIZ. This is accomplished via a theory or empirical relationship (see Fig. 24). During the Winter MIZEX programs, the approach will be to use satellites to provide the synoptic coverage of the entire Greenland Sea, aircraft to provide the higher resolution look at specific 100- × 100-km areas within the MIZ, while the helicopter, ship-based, and surface (in situ) measurements provide very high resolution local coverage. The role of the helicopter, ship-, and surface-based measurement is to validate the satellite and aircraft data (see Fig. 25).

Tables 5, 6, and 7 list the proposed remote sensing ensemble for MIZEX 87/89. Presented in the table along with each proposed instrument is the frequency, resolution/coverage, and the MIZ characteristic it directly or indirectly measures. As indicated in Tables 5, 6, and 7, the helicopter and ground-based measurements will include brightness temperature, radar backscatter cross sections, ice thickness, and dielectric properties for water and various types of ice during different weather conditions. Measurement groups will be located in the ice-drifting ships and camps, as well as on the ice-edge ships. On the former, their task will be to concentrate on detailed temporal studies of selected ice types. On the latter, it will be to study different ice types as the ship makes transects into the ice. Helicopter-borne instruments link both mesoscale programs and provide high mobility to study ice conditions within the experimental region.

Surface measurement will be made of the physical-electrical properties of various ice and snow types present at the active-passive remote sensing test sites to help in understanding the microwave interaction processes involved. Physical property information to be acquired includes small-scale surface roughness, snow wetness, grain size, salinity distribution, temperature, snow thickness, and scatterers in the ice. Dielectric constant measurements will be made to describe various ice types at X-L-C bands 13.7, 35, and 90 GHz. Scenes of special interest will include surfaces that have melted and refrozen; ice ridges, multiyear, first-year, and thin ice of various thicknesses; and melt ponds and open water under calm and windy conditions.

A unique opportunity for remote sensing of the winter MIZ occurs in 1987. The SIR-B Shuttle reflight mission is scheduled for launch on 18 March

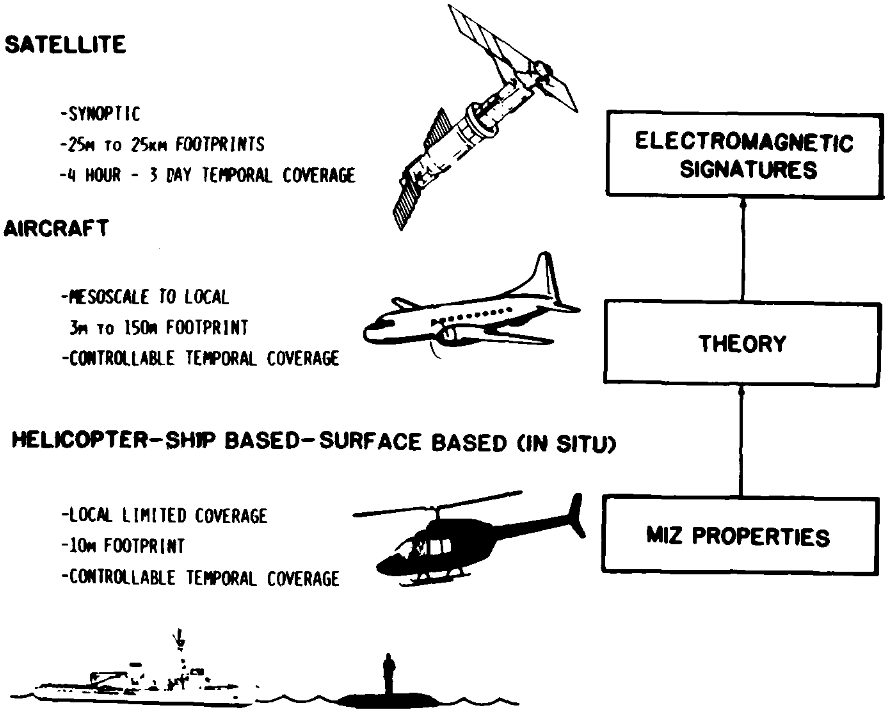


Figure 25. Winter MIZEX remote sensing data collection scenario utilizing satellites, aircraft, helicopter, ship-based, and surface sensors.

1987 into polar orbit, which will provide excellent coverage of the MIZ region. Given the presently planned nodal crossing configuration, the MIZEX site will be overflown four times each day for the 10-day duration of the Shuttle mission. The SIR-B Shuttle will carry on board an L-band synthetic aperture radar and a high-resolution large-format camera. The SAR system will feature a 3-m resolution capability from space, with incidence angle variability from 20 to 60°. The large-format camera will have a resolution of approximately 10 m. With respect to the remote sensing science objectives, the space-based SAR offers the unique advantage of providing synoptic imagery of the entire MIZ region from a stable platform and from numerous incidence angles, both of which are of critical importance to the objective of determining radar reflectivity of various sea types. Specifically, the variable incidence angle SIR-B data will be used to determine the specular and volume scattering contributions from first- and multiyear sea ice. In addition, the onboard camera is an excellent source of ground truth, provided the area imaged is cloud-free. Together these systems provide an unparalleled opportunity to obtain high-resolution synoptic coverage of a significant portion of the polar regions during the period of Shuttle operation.

With respect to direct determination of ice type by microwave remote sensing, an impulse radar system developed by Cambridge Consultants may be available for use during the 1989 experiment. This radar would be used from a helicopter to obtain ice thickness transects over the experimental zone for comparison with thickness values obtained by ground-truth parties and fixed-wing aircraft overflights. Since both the fixed wing (SAR and active/passive combination) and helicopter techniques are novel, it is important that adequate surface-based ice thickness measurements be incorporated into the field program. One aspect of this ice thickness ground truth effort will be the placement of radar receivers buried within the ice. These receivers will provide quantitative information with respect to microwave attenuation coefficients.

In summary, the proposed remote sensing experimental plan is straightforward. The work horse for the 1987 and 1989 experiment will be the high-resolution SAR. SAR aircraft flights will be made very other day during the 50-day experiment period. The SAR images will be transmitted down

Table 5. MIZEX 87/89 remote sensing instrument ensembles: aircraft sensors.

Instrument	*Frequency (GHz)*	*Resolution and coverage*	*MIZ characteristics provided*
NADC P3 (U.S.A.)			
Imaging radar (SAR)	9.8, 5.3, 1.3	3-m, 10-km swath width 70-km mosaics	Ice edge location Eddy structure
Altimeter	13.3	Profiler	Ice type mapping
Aerial cameras			Ocean wave spectra Floe size distribution Ice concentration Ice kinematics
USA-NRL P3 (U.S.A.)			
Passive microwave imager	90, 140, 220	15-120 m, 2-15 km swath width	Ice edge location Ice concentration
SSM/I radiometer	19,22,31,37		Ice type
PRT-5 infrared profiler	11 (microns)	100-km mosaic	Ice kinematics
INS winds	NA		
Environmental sensors	NA		
60-mm photography Hasselblad	Visible		
Stepped-frequency radiometer	4.5-7.2	Profiler	
Norwegian Air Force P3 (Norway/Air Force)			
AXBT	NA	Point measurements	Ocean temperature
NOAA P3 (U.S.A.)			
SLAR	35	10-m, 20-km swath width	Ice edge
Laser profilometer	Visible	Profiler	Floe size distribution
Gust probe		Profiler	Ice type Ice roughness Eddy structure
B17* (CNES/France)			
SLAR Photography	9.3 Visible	25-m, 20-km swath width 90-km mosaics	Ice edge location Floe size distribution Ice concentration Oceanographic information

* Potential involvement.
NADC—Naval Air Development Center.
NOAA—National Oceanic and Atmospheric Administration.
CNES—Centre National d'Etudes Spatiales.
NRL—Naval Research Laboratory.

to the ship in real time and interpreted to detect and locate eddies and internal wave fields. The ships and acoustic sensors will be directed to sea truth locations based on the SAR data. If the SAR downlink does not operate satisfactorily, the SAR data will be interpreted at Tromsø and cartoon images will be transmitted to the ships, as was done during MIZEX 84. The AVHRR images, weather permitting, will also serve as inputs for the sea truth coordination. It is anticipated that each SAR flight will cover a 200- × 200-km box centered on the test area. The passive microwave flights will be flown concurrently with the SAR flights to effect the required active/passive microwave study. The

Table 6. MIZEX 87/89 remote sensing instrument ensembles: satellite sensors.

Name	*Instrument*	*Type*	*Resolution and coverage*	*MIZ characteristics provided*
Shuttle imaging radar (SIR-B)	SAR	L-band	30 m, 50 km × 1000 km	Ice edge location Eddy structure Ice type mapping Ocean wave spectra Floe size distribution Ice concentration Ice kinematics
NOAA-7/8* (US/NOAA)	AVHRR	Visible & infrared	1 km entire Fram Strait	Meteorology Ice motion Ice edge location Eddy structure
Meteor (Soviet)	OLS	Visible & infrared	5 km entire Fram Strait	Meteorology Ice motion Ice edge location Eddy structure
DMSP (US/DOD)	OLS	Visible & infrared	1 km entire Fram Strait	Meteorology Ice motion Ice edge location Eddy structure
Cosmos 1500/1600	SLAR	Microwave	1 km, 1000 km swath width	Meteorology Ice motion Ice edge location Eddy structure

* Primary utility.

NOAA—National Oceanic and Atmospheric Administration.

DOD—Department of Defense.

DMSP—Defense Meterological Satellite Program.

AVHRR—Advanced Very High Resolution Radiometer.

OLS—Optical Line Scanner.

SLAR—Side-Looking Real Aperture Radar.

real-time SAR data will also be used to direct the ship-based heloscat and other ship-based measurements.

Acoustics experiments are planned for both the 1987 and 1989 field programs, with the most intense effort planned for 1989. Part of the 1989 field program will be a continuous year-long tomography and propagation experiment using moored instruments that will be deployed in summer 1988 and recovered in summer 1989. This latter effort is also a part of the Greenland Sea Project.

3.5.1 1987 field experiment

The 1987 acoustics experimental work will be focused on ambient noise data collection. These data will be collected using the remote autonomous measure ment system (ARAMP) already described. For this experiment only a small number of these buoys will be available; this will be the first field deployment of these instruments. Ambient noise will also be taken using P3-deployed AN/SSQ-57A sonobuoys. The acoustics work for the 1987 program is intended to be limited in scope, with the primary focus and major effort occurring in 1989.

3.5.2 1989 field experiment

The overall experimental geometry for acoustics in 1989 is shown in Fig. 26. The heart of the acoustics experiments planned for 1989 is the ice camp with the acoustic receiving arrays. A 30-element array will be deployed that consists of a 1- × 1-km aperture with 20 hydrophones hardwired to the MIT/WHOI digital data acquisition system. An additional 10 hydrophones with RF telemetry linked to the data acquisition system will be deployed at sparse spacing to achieve total sensor separations on the order of 40 km. All the phones will be tracked acoustically using an 8- to 13-kHz pinger

Table 7. MIZEX 87/89 remote sensing instrument ensembles: ship- and ground-based sensors.

Instrument	*Instrument platform*	*Frequency (GHz)*	*Resolution and swath*	*MIZ characteristics provided*
Drifting-ice ship station				
University of Kansas:				
Microwave step frequency Scatterometer	Helicopter	1 to 18 selected	Profiling	Ice type, EM properties
Dielectric constant measurements	Ground	1 to 4	Point measurements	EM ice properties (reflection, penetration, etc.)
University of Washington:				
Passive microwave radiometer	Ground	10, 18, 37, and 90	Point measurements	Ice type, EM properties
Ice-strengthened ship				
*France CNES:**				
RAMSES microwave active radiometer	Ship-mounted	8-18 selected (9, 13.5 used extensively)	Point measurements	Ice type/EM properties
(ERASME scatterometer)	Helicopter	5.35	Transects	
ERIM:				
Resonant cavity (dielectric constant measurements	Ground	1, 10, 100 MHz	Point measurements	EM ice properties X-C-L SAR Calibration
Incident power measurements				Microwave penetration
Snow-free water measurements				
Cambridge Consultants:				
Impulse/Radar	Helicopter	100 MHz	Profile	Ice thickness

* Potential involvement.
CNES—Centre National d'Etudes Spatiales.
ERIM—Environmental Research Institute of Michigan.

sensor tracking system (STS) to measure intersensor time delays for instantaneous sensor location every 30 sec. In addition to the large-aperture horizontal array, a smaller aperture horizontal array for mid-frequency analysis will be deployed, as in summer MIZEX 84, but improved in handling and anti-strum capability. A vertical array is tentatively planned as well.

An HLF-3 low-frequency modulatable acoustic source will be deployed at a northern camp, whose site is shown approximately in Fig. 26. In addition, shots will be deployed from this location. Towed acoustic projectors are tentatively planned for deployment from an AGOR in open water. The towed projectors can be maneuvered to ensure propagation through eddies when they are identified as the experiment unfolds. Shots including SUS's will also be deployed from helicopter and P3 aircraft.

A propagation range consisting of three moored acoustic transmitters and receivers (transceivers) will be deployed in the spring/summer of 1988 and recovered in the spring/summer of 1989. In Fig. 26 their locations are designated as A, B, and C. These transceivers constitute the northern array of the larger Greenland Sea tomography experiment described below. The locations of the three moorings have been arranged to provide propagation data in a completely ice-free sea during and after deployment in spring/summer 1988. As the ice edge migrates southward during the fall, it will first partially cover the east-west transmission

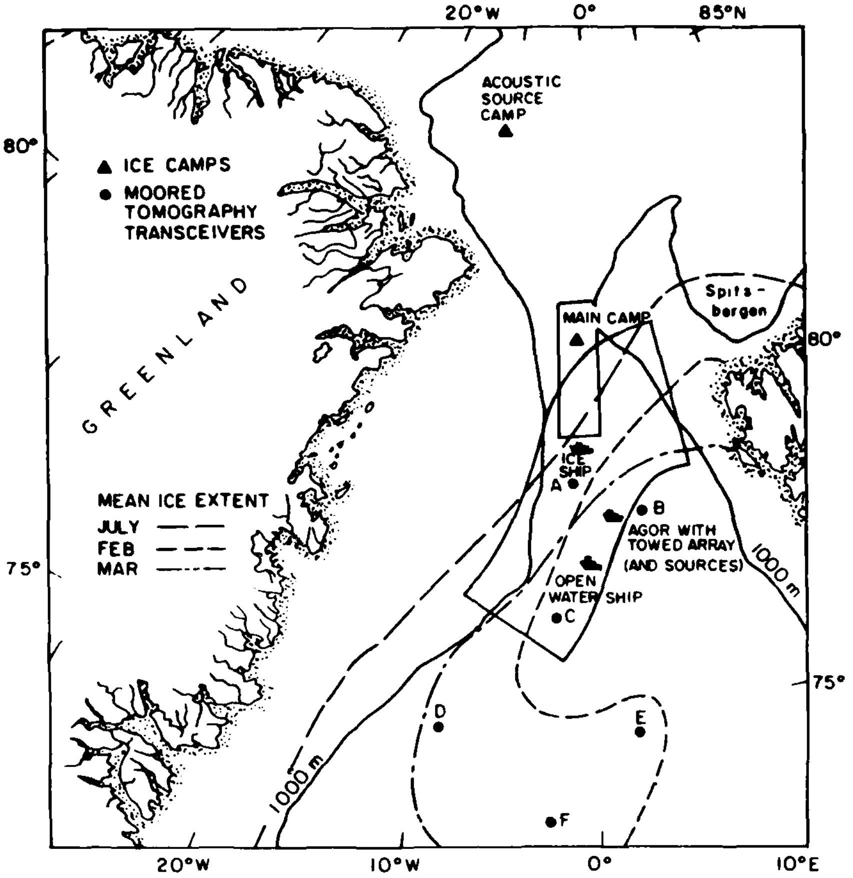


Figure 26. Acoustics field positions in 1989.

path between moorings A and B and the north-south path between A and C. During its maximum southward extension it could possibly cover the entire propagation range. During the spring of 1989 the ice will recede, creating again an ice-free propagation environment and exposing the mooring for a planned 1989 recovery. The acoustic signals from these three transceivers will provide propagation paths to the MIZ ice camp in March and April 1989, for forward propagation measurements as well as tomographic inversion possibilities using the receivers of the low- and mid-frequency drifting arrays at the ice camp.

The transceivers will transmit acoustic signals according to a fixed, repetitive schedule throughout the year. Signals will be recorded by the transceivers themselves and at the MIZEX ice camp when it is established in March of 1989. The actual signal will be a maximal length shift register sequence that phase-modulates a 400-Hz acoustic carrier. It will have a source level of 186 dB *re* 1 μPa and a bandwidth of 100 Hz. The spectral content of the signal consists of a strong line at the 400-Hz carrier frequency and discrete lines separated by $1/T$ Hz where T is the duration of the shift register sequence. Typical durations are about 5 sec, so that lines are spaced 0.2 Hz apart from 350 to 450 Hz, thus providing a rich spectrum for wideband analysis. This signal is similar to signals transmitted in previous tomography studies and similar to the one transmitted during a preliminary acoustic source test in MIZEX 84 (Spindel, 1985).

Comprehensive ambient noise samples will be taken by both drifting arrays at the main camp, by the ARAMP buoys, and by P3-deployed sonobuoys. The array data will provide ambient noise directional characteristics as well as spatial discrimination for event isolation. The ARAMP buoys will be deployed in an eddy as indicated schematically in Fig. 20, and will provide a truly unique data set of ambient noise as generated in an ice-edge eddy with the concurrent and simultaneous environmental data taken by the ARAMP system. In contrast to earlier arctic ambient noise measurements, we plan acquisition of very long time series, in some cases as long as the entire period of the field program. Such long time series have now become necessary to compare more fully with dynamically evolving environmental forces.

An integral part of the MIZEX 89 tomography and propagation program is the Greenland Sea tomography experiment, which is part of the Greenland Sea Project. Six tomographic instruments, including the three discussed above, will be deployed as shown in Fig. 26. The southern array, consisting of the instruments marked C, D, E, and F, has a scale of roughly 300 km, and encloses the Greenland Sea gyre. The purpose of this array is long-term monitoring of the gyre in conjunction with the more temporally concentrated CTD measurements of the entire MIZ experiment. There are interesting questions regarding the formation and destiny of Greenland Sea waters in addition to questions about seasonal changes in the Greenland Sea that can be effectively observed with such an array.

The northern array, consisting of the instruments marked A, B, and C, has several functions in addition to eddy tomography. They enable observation of frontal dynamics and their impact on acoustic propagation. Beyond inversions to reveal spatial and temporal information about ice-ocean eddies, meanders of the West Spitzbergen Current and even upwelling events may be sensed. The northern array combines with the southern array to provide additional independent paths through the Greenland Sea and to extend the tomography measurement northward. These tomography experiments will be conducted by the Woods Hole Oceanographic Institution and the Scripps Institution of Oceanography, with the former placing emphasis on the northern array and acoustic propagation through the ice front, and the latter concentrating on the Greenland Sea gyre.

In addition to tomography using low-frequency (400 Hz) sources and receivers, inversions at internal wave scales will be performed using the sensor tracking system high frequency (8-13 kHz) pings within the large horizontal array to be deployed at the ice camp.

Finally, full wave inversion methods will be applied to three data sets:

1. Long-range explosion data from the northern ice camp, P3, and helicopter aircraft. The short duration of an explosive source senses the water column in a particular state of fluctuation and provides a snapshot of the structure at a given instant. Full-waveform inversion of the data from a single shot provides a picture of the medium at this instant. Since one goal is to determine the sub-bottom properties (which are static), then we must either: a) ensure that the temporal variability of the ocean has little influence on our data at the frequencies of interest (40 Hz) or b) account for the ocean dynamics by running the experiment several times, allowing separation of the dynamic and static parts.

Shot and CW transmission data from the central Arctic indicate that the stability of the water column is sufficient to allow average water column models to be used to back out geometrical effects to obtain sub-bottom sound-speed and attenuation structure using data below 40 Hz. CW transmission data from the MIZ show that the water column in this area is 3-10 times less stable, with the lower figure resulting from paths completely under the ice, and the larger figure for paths crossing the ice edge. It is not known at this time how much variability is acceptable to successful full-waveform inversion, so multiple shots will be dropped for each path to obtain an ensemble of realizations. With these data we feel that we will be able to determine the sub-bottom structure and quantify the ocean variability. Since many of the shots will have completely ice-covered paths, we feel that these data will show stability closer to that of the central Arctic than to the ice margin and techniques used for the central Arctic will be applicable here.

2. 400-Hz tomography source data. These data are to be obtained over periods spanning many fluctuation periods in the medium. The use of full-wave theory may benefit the spatial resolution obtainable from such data. However, it will probably be more fruitful to explore statistical inversion models to characterize the medium's temporal statistics. The acquisition of these data is probably beyond the capabilities of the moored instruments' internal recording systems, and reception via the drifting acoustic array will be essential. Thus, issues regarding use of drifting sensors for tomography will be addressed with these data.

3. STS (sensor tracking system) transmissions. The large number of sensor tracking system sources and receivers operating in the 8-13 kHz range offers an opportunity to study in detail the lateral variability of the upper 200 m of the ocean on the internal wave scale. Modeling has already shown the need for higher order approximations than ray theory to predict observed arrival times (see Section 2.5). An additional objective afforded by these data will be the examination of the statistical properties of the under-ice surface, at least as it is influenced by scattering at these frequencies.

4. LOGISTICS

The following is a preliminary statement of logistic concepts consistent with the plans described. It will require complete, detailed development according to operational plans yet to be evolved.

4.1 Overview

Winter MIZEX ship-borne operations in both 1987 and 1989 will be staged primarily out of Bergen, Norway, except that the U.S. open-ocean ship (probably an AGOR) will be loaded at a U.S. port yet to be designated. The main ice camp is planned to be deployed by fixed-wing aircraft from Nord, supported by helicopters and/or the ice ship as required and practicable. The satellite ice camp (acoustic source) will also be deployed by fixed-wing aircraft from Nord. A MIZEX shore-based coordination center for aircraft field operations will be established at the Tromsø Satellite Telemetry Station. This center will also be the focal point for operating-area weather and ice forecasting coordination and support to the field operations.

Overall coordination for Winter MIZEX operations will be vested in a field coordinator plus assistants as required. Program coordination will follow the procedures used in MIZEX 83 and 84. For Winter MIZEX 87/89, the chief scientist on the ice ship will also function as field coordinator. Each platform and the ice camps will have a designated chief scientist.

4.2 Overall schedule

The overall schedule is presented in Table 8. The time period covers February through April to include the predeployment activities and experiment area surveillance. The start date, to be determined, will be based on platform availability, with load-out starting on Day 1.

Table 8. Winter MIZEX overall schedule.

Feb-Apr 1987 (days)	*Event*	*Feb-Apr 1989 (days)*
-30	Commence monitoring satellite imagery	-30
- 5	Ice reconnaissance flight	- 5
	Commence special weather forecasting for the operating (OP) area	
0	Establish Tromsø Communication and Coordination Support Center	0
	All field material, equipment, and personnel in Bergen	
6-7	Transit Tromsø to ice edge	6-7
8-10	Deploy instrumentation	8-14
	Establish ice camp (1989 only)	
11-32	Ship/ice camp field research operations	15-47
	Meteorological aircraft operations on alternate days	
	Remote sensing aircraft operations	
	1987 10 SAR flights in 20 days 10 PM flights in 20 days 1989 25 SAR flights in 50 days 25 PM flights in 50 days	
33-35	Recover instrumentation	48-53
	Disestablish ice camp (1989 only)	
36-37	Transit ice edge to Tromsø	54-55
38	Offload helicopters and personnel	56
38-40	Transit, Tromsø to Bergen	56-58
40-42	Offload ship(s)	59-60

Table 9. Winter MIZEX field operations.

	Mar-Apr 1987	*Mar-Apr 1989*				
				(Probable open-ocean ships)		
Science research areas, support and operating functions	*Ice ship (30+ berths) (12 knots)*	*Ice camp* *Main*	*Ice camp* *Satellite*	*Ice ship (30+ berths) (12 knots)*	Haakon Mosby *(12 berths) (11 knots)*	*U.S. AGOR (13 berths) (9 knots)*
Acoustics	2	9*	4*	2	—	9*
Oceanography	6*	3		6*	5*	2
Meteorology	4	1		4	2	2
Ice physics (incl. photography)	3	1		4	2	—
Remote sensing (incl. ice phys. properties)	8	1†		8	—	—
Biology	2	2		2	2	—
Geochemistry	2	—		3	—	—
Helicopter support						
Crew (no. helicopters)	3 (2)	3 (2)		3 (2)	—	—
Ice camp support						
Camp manager		1				
Camp cook		1				
Radar operator		2				
Field coordination team	2	—		3	—	—
TOTAL PERSONNEL	32	24	4	35	11	13

MIZEX 87/89:
Tromsø Communication and Coordination Support Center: 4-6 persons
Remote sensing aircraft, Andøya: 20 persons
Meteorological aircraft, Svalbard and/or Bodø: 6-10 persons

* Chief scientist included.
† With support from ice ship.

4.3 Operating units and personnel allocation

Table 9 presents a preliminary summary of the ship and ice camp personnel allocations by principal science research areas and support/operating functions for both Winter MIZEX field operations. The final space allocation will be made after the operating platform commitments are confirmed and research project details are established in an integrated operating plan and detailed schedule.

4.4 Communications

Effective, reliable communications, carefully scheduled for minimal interference with research activities and data acquisition, proved to be a critical factor in the MIZEX 83/84 operations. Good communications will be even more crucial during the severe Winter MIZEX operating period. Thorough preparation and complete check-out of equipment and procedures during Winter MIZEX 87 will be given high priority. Principal communication links planned for the Winter MIZEX operations will be:

Ship to ship	Voice	HF, VHF
Ship to air	Voice	HF, VHF
Ship to shore	Voice and telefax	HF/telephone via coastal maritime radio station, typically Svalbard, and by satellite telephone
	Teletype	HF typically through Rogaland Radio

4.5 Data management

The National Snow and Ice Data Center (NSIDC), Boulder, Colorado, is presently providing data management services for MIZEX 83/84. These services include safe archiving, ready accessibility, and efficient utilization of MIZEX data through NSIDC's data archival and accession program, established data interchange standards, and coordinated data flow from principal investigators to the participating data centers and/or other researchers. These services are planned to be continued through MIZEX 89.

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APPENDIX A. BIOLOGICAL OCEANOGRAPHY, MIZEX 87/89

A1. INTRODUCTION AND OBJECTIVES

The East Greenland Sea/Fram Strait region is of extreme biological interest because it is the most northerly pelagic system of any polar region. Because of the unique physical forcing functions of the region, the biological response is closely coupled to the mesoscale physical events. For example, data from MIZEX 83 indicated that the vertical flux of nutrients via eddies was a significant factor in controlling the distribution and growth of phytoplankton during the summer (Smith et al., 1985). Furthermore, zooplankton distributions are closely tied to water mass movements and serve as a useful indicator of the presence of water of either North Atlantic or Arctic origin. The 1984 MIZEX experiment clearly showed that zooplankton reproduction is closely tied to the location of the ice edge, although the mechanisms are unknown at this time. The primary production of this region is surprisingly large when the low nutrient levels in the upper, stratified waters are considered. Preliminary results indicate that an active microbial food web must be present to regenerate nitrogen within the euphotic zone.

Little information on biological events is available for any polar region with regard to the winter/spring transition period. It can be predicted that nutrients are at elevated concentrations due to replenishment via deep vertical mixing during winter storms and during brine exclusion. Thus it can be confidently predicted that the vertical distributions of nutrients observed during the winter will be markedly different from those observed during the summer. Phytoplankton distributions and biomass during the winter and early spring, however, are completely unknown, particularly in this region. Because there are periods when ice is advected into warmer, North Atlantic water in the marginal ice zone, melting may occur that would produce a vertically stable water column for a short (less than one week) duration. Therefore it is conceivable that during the onset of light, significant primary production could occur. We would expect that, due to the increased stability in the MIZ (relative to waters removed from the ice), phytoplankton growth will precede an open water bloom, thus influencing the optical properties of the waters as well as the food web dynamics.

There is also very little information available on the distribution, growth, and reproduction of zooplankton. It has been suggested that zooplankton have two strategies for growth in polar regions. The first would be to release eggs into the water prior to the onset of phytoplankton growth. This strategy would provide a population ready to utilize the new production when it begins. As a corollary, egg production must utilize lipid reserves that were deposited during the previous growing season. The second possible strategy is to tie egg production to available food, using the spring growth of phytoplankton to trigger egg production. A major species of the Fram Strait (*Calanus finmarchicus*) appears to be dependent on food supply, but another (*Calanus hyperboreus*) apparently has adopted the former strategy of anticipating a bloom. Therefore it is possible that the population structure is dominated by the growth stages of each species during the winter/spring transition, and that this structure will change markedly through time.

It has also been postulated that the undersurface of the pack ice is the site of the first growth of photosynthetic microbes during the winter/spring transition, and that the ice serves as a refuge for species to over-winter. The concentrations of chlorophyll (an indicator of plankton biomass) in multiyear ice in the MIZEX area was found to be very low; however, chlorophyll levels were noted to be much higher in new pack ice, although distributions were extremely patchy and undoubtedly controlled by the mode of ice formation and in situ light levels. Ice biota potentially can represent a large input of organic matter to the water column if released, but the dynamics is poorly understood.

In view of the paucity of information available on the winter and winter/spring transition periods as well as the East Greenland Sea/Fram Strait region in general, the objectives for MIZEX 87 can be summarized as follows:

1. To determine the biomass, species composition, and vertical distributions of the phytoplankton and zooplankton populations prior to the onset of phytoplankton growth, and to understand the relationships with water mass characteristics, eddy formation and dynamics, ice-edge jets, ice movements, upwelling, etc.

2. To determine the concentration of inorganic nutrients in the water column during the March-April period.

3. To determine the photosynthetic response to the onset of light and the physiological responses of the resident phytoplankton present during this period. In addition, to relate the quantitative response of phytoplankton to the vertical distribution of light, so as to estimate primary production and nutrient demand.

4. To quantify the secondary production of the dominant zooplankton during this time and relate this information to the life strategies of each species.

5. To determine the fine-scale structure of biota under the ice to see if the strong vertical zonation observed in the summer is also observed in the winter/spring transition.

6. To assess the large-scale distribution of chlorophyll in relationship to the MIZ by satellite imagery.

A major goal of the Winter MIZEX 87 experiment will be to provide quantitative estimates of primary and secondary production during the onset of light, so that our understanding of the fluxes of biogenic materials can be greatly improved.

The winter 1989 experiment will be more ambitious, with programs designed to continue studies begun in 1987 and additional studies of ice biota, involving taxonomic investigations, rate measurements (productivity and grazing activity, biomass contributions of bacteria and microzooplankton), and flux determinations (flux of material through the water column as determined by sediment traps). These measurements will be conducted from the ice camp so that a stationary platform can be used to conduct the experiments. A complete analysis of the spatial and temporal variations in the area of the ice biota will also be conducted. Therefore in 1989 we will be able to have an understanding of the biota in both ice and the water column for this region.

A2. DETAILED EXPERIMENTAL PLAN

A2.1 Phytoplankton

A major goal of the entire biological program is to work closely with the sampling plan of the physical oceanographers, so that we can understand the distributions of biota within the context of the dominant physical processes. Therefore we will sample during the physical oceanographic program, which is designed to determine the importance of eddies to the entire Fram Strait region. Phytoplankton biomass will be determined by measuring chlorophyll concentrations throughout the water column. We will sample most intensively in the upper 150 m but will modify the sampling depths based on the CTD traces. Phytoplankton for taxonomic analysis will also be taken and preserved. Samples for the experimental determination of photosynthetic response will be taken from the upper mixed layer. Subsamples will be exposed to a wide range of light intensities and carbon incorporation will be measured. All data will be fitted to the hyperbolic model of Platt (for example, Platt et al., 1982), which statistically determines not only the rate of light-dependent reactions (alpha) and the maximum photosynthetic rate (P_{max}), but also the intensity of the onset of photoinhibition (I_s) and I_r, a quantitative index of photoinhibition. Photosynthetically active radiation will also be measured as well as its attenuation within the water column. By combining available light with photosynthetic response, the primary production can be estimated. By measuring the photosynthetic responses at various depths, the rates of vertical mixing of the upper layer can also be estimated.

Samples for nutrients (nitrate, phosphate, nitrite, ammonium, and silicate) will also be collected for later analysis. We do not expect nutrients to be at concentrations commonly thought to limit phytoplankton growth; we also do not expect large variations in nutrient levels, so that their use as an eddy tracer in winter may be diminished when compared to their use during the summer. Nonetheless, because few nutrient data have been collected from this period, nutrient analyses will be completed on a number of stations throughout the experiment.

A2.2 Zooplankton

Based on studies completed in other regions on the dominant species found in the Fram Strait, we expect that the distribution of zooplankton in winter will be markedly different from that observed in summer. During the summer the majority of animals were concentrated in the upper 100 m, presumably in response to the presence of elevated food levels. During the winter, however, it has been found elsewhere that the animals are more evenly distributed throughout the entire water column. To test this, we will conduct deep (to ca. 1000 m) vertical tows with opening-closing nets to accurately sample the resident populations during the winter. We realize that, because eddy tracking requires a large degree of synopticity, we will not be able to routinely complete these tows. We expect to concentrate them most heavily when we are in the mini-drift phase. During the eddy tracking phase we plan to sample only the upper 200 m with a rapid vertical tow to determine the mesoscale distribution of zooplankton and its relationship to the physical processes of the region. Animals from these tows will be utilized in laboratory investigations of ingestion, egg production, and population structure, as well as simple biomass and taxonomy. Samples will also be collected for analysis of lipid reserves taxa, and the data will be compared to the results of summer animals collected during MIZEX 84.

A2.3 Ice biota

Organisms growing on the undersurface of the ice will be sampled in conjunction with ice studies, i.e. using spire cores. Samples will be analyzed for photosynthetic biomass as well as preserved for determination of bacterial, microzooplankton, flagellate, etc. biomass. Rate process measurements will be conducted on these samples in the laboratory. Flux measurements will be conducted by suspending sediment traps beneath the ice, and the samples will be analyzed for chemical parameters at the end of a short period (days). Analysis of temporal and spatial variations in ice biota will utilize available helicopter flights to locations remote from the ice camp.

A2.4 Fluorescence

The analysis of chlorophyll, or more accurately fluorescence, has developed rapidly in recent years. Use of the Nimbus-7 CZCS (Coastal Zone Color Scanner) will be requested for this period and, if possible, other appropriate platforms will be mounted with sensors. Major problems in the use of this technology in the MIZ (and the Arctic in general) are the lack of cloudless periods over significant regions. Nonetheless, the information is invaluable in quantifying large-scale relationships among phytoplankton and various physical processes.

APPENDIX B. GEOCHEMICAL PROGRAM, MIZEX 87/89

The Arctic and far North Atlantic are among the most physically active environments in the world ocean. They are certainly the most diverse. In addition to the air/sea/ice interactions seen at high latitudes elsewhere, the Arctic Basin is more strongly influenced by river inputs than any other. If current estimates are realistic it is also strongly affected by anthropogenic inputs delivered via the atmosphere. The region is the site of deep convection in winter, which leads to the formation of some of the major water masses of the North Atlantic. The recent demonstration of changes in the *T-S* properties of these waters on a decadal time scale is a strong indication that the whole system responds directly and sensitively to climatic forcing.

Due to their inaccessibility, the Arctic and high-latitude North Atlantic are probably the least known areas oceanographically. This is especially true of the chemistry. To remedy this we propose to use the opportunity presented by MIZEX to begin a geochemical program in the region affected by seasonal ice cover. This program will have several objectives. In the Arctic we wish to examine the effects of fluvial (and anthropogenic) inputs to the surface waters, the dynamics of their removal by particulate scavenging, and their metabolic and inorganic release in deep waters. In the wintertime in the Greenland Sea we wish to establish the chemical signature of the convectively formed deep water and its imprint on the overflow waters that penetrate into the North Atlantic.

As a general aid to hydrographic interpretation and as a source of time-scale estimates we will measure the freons, F-11 and F-12, as part of this program. Of particular interest will be the effect of the seasonal ice cover on the degree of air/sea saturation equilibrium of these gases. Both the absolute atmospheric concentrations and the concentration ratio are transients, and hence both contain time information if equilibrium is reached prior to convection.

The influence of anthropogenic contamination will be investigated by systematic analyses of snow deposited on the pack ice and by sampling of atmospheric aerosols from ships. Pack ice and surface water samples will be taken in parallel with those of the snow and aerosols to estimate the cyclic contribution from sea spray.

The initial effort in 1987 will require two or, if possible, three people; the winter cruise in 1989, three or four.

Table B-1 gives the elements to be measured and their properties. The freons and several of the trace elements will be measured on board ship. The others will be returned to the shore lab for processing. Sampling for the freons will be by the conventional samplers used in the hydrographic program. A sample size of 1 liter is required. We will supply specially cleaned Niskin samplers (5-liter) for the trace element sampling, and will require about 12 ft of bench space. We are open to suggestions as to additional measurements and plan to collect samples for other investigators.

Table B-1. Elements to be measured.

Element	*Natural source*	*Anthropogenic input*
Ba	Rivers	Nil
Be	Rivers	Not known
Se	Rivers	Significant
Cr	Rivers	Not known
Al	Aeolian	Nil
Bi	Aeolian	May be significant
Fe	Aeolian	Not known
Pb	Rivers	Major
Cu	Rivers	Not known
Ni	Rivers	Not known
Cd	Rivers	Significant
Zn	Rivers	Significant