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A Science Plan for a Summer Marginal Ice Zone Experiment in the Fram Strait/Greenland Sea: 1984

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EXECUTIVE SUMMARY

This document describes a plan for a mesoscale experiment to study the physical processes by which ice, water and atmosphere interact in the outermost parts of a polar icefield, the region known as the marginal ice zone (MIZ). During the last two decades a series of large projects culminating in the Arctic Ice Dynamics Joint Experiment (AIDJEX, Pritchard 1980) yielded considerable understanding of the growth, motion and decay of sea ice in the interior of the Arctic Ocean. With these experiments concluded, and coupled nonlinear sea ice dynamic-thermodynamic models in hand (Hibler 1979, Coon 1980), attention shifted to the problem of understanding the processes which occur near the open ocean boundaries of polar icefields, and which determine the advance and retreat of the sea ice edge. The exchanges which take place in this zone affect hemispheric climate and have a significant effect on naval operation and commercial fisheries.

The U.S. National Academy of Sciences has recommended studies of the marginal ice zone in their documents entitled *U.S. Contribution to the Polar Experiment, POLEX, Part 1—North* and *Part 2—South* (NAS 1974). A workshop in Monterey in 1979 (Andersen et al. 1980) summarized the extent of the problem and the paucity of our knowledge. In response to this and to a series of research recommendations by international bodies (WMO-ICSU 1975, 1978), including most recently the Joint Scientific Committee in its plan for the World Climate Research Program (WMO-ICSU, JSC 1981), efforts began towards the design of an integrated research program to tackle the problem of understanding the nature of the unconfined sea ice margin.

As a result of a workshop in Voss, Norway, in 1980, and subsequent meetings, a program emerged which has two complementary aspects. The overall problem of understanding the annual and interannual variability of the polar ice margins, and of relating these to the large-scale behavior of the atmospheric and ocean circulations, is to be addressed by a long-term monitoring and modeling program described in an associated document (*Air-Sea-Ice Research Programs for the 1980s*, Untersteiner 1983). Complementary to this program will be a mesoscale experimental program to study physical processes occurring within the MIZ and to develop models of these processes. This is known as the Marginal Ice Zone Experiment (MIZEX), and a research strategy for it, the MIZEX-I Report, was issued in June 1981 (Wadhams et al. 1981). The present document describes a science plan for carrying out the summer portion of this research.

Both the northern and southern polar regions have substantial marginal sea ice perimeters. However, the remoteness of Antarctic sea ice increases greatly the cost of multi-ship experiments with aircraft remote sensing support. As a consequence it was decided that an intensive marginal ice zone program should take place first in the Arctic area of greatest importance thermodynamically, i.e. the region north and west of Svalbard. Fram Strait handles most of the heat and water exchange between the Arctic Ocean and the rest of the world, and therefore is a crucial area for studying energy interactions across the ice margin. The shallow Bering Sea, which is a MIZ of quite different character without large velocity shear, is being studied in a parallel program which was initiated in early 1983 (Martin et al. 1982). This program will share many personnel, instruments and experimental concepts with the Fram Strait/Greenland Sea MIZEX.

Physical processes in the MIZ are different in winter than in summer, and experiments in both seasons are needed. The first major experiment is to take place during a six-week period from mid-June to the end of July 1984, and is to be preceded by an initial study in 1983. The dates are chosen to cover the melt period and the transition to summer ice dynamics. The 1983 study is designed to test whether the scales for the experimental arrays, and the cooperative measurement procedures, are appropriate for yielding the maximum amount of information. The 1984 summer experiment is described in this document, with a brief summary of the 1983 experiment (Section 4.4). Winter experiments will follow in 1986-1987.

The experiment is designed as a drifting one in which an area some 200 km square enclosing the ice edge is selected for intensive investigation. The center of the area is a ship moored to the ice some 30-50 km inside the ice edge and serving as the base for an array of transponders to measure ice deformation as well as for experiments on ice properties, the atmospheric boundary layer and the upper ocean. Other ships are dedicated to studies deeper inside the pack (requiring a heavy icebreaker), at the ice edge itself (where fronts, eddies and ice edge features will be mapped) and in the open water outside the ice edge. The work of these ships will be coordinated by a Field Coordinator aboard one of the vessels, and the concept of following the downstream development of the MIZ ice will be combined with a fixed geographical grid for CTD measurements of ocean structure. Regular remote sensing flights will map the entire "moving box" with synthetic aperture radar, microwave sensors and cameras, and will transmit imagery of the ice edge either directly to the ships by downlink or indirectly via the Tromso Satellite Station in northern Norway, which will be the communications base for the experiment. As well as being a tool to assist in the experimental scheme, the remote sensing program is designed to increase our knowledge of the active and passive microwave signatures of sea ice in summer. Included in this effort will be in situ as well as aircraft-based studies.

The scales of the arrays employed, and the set of measurements to be made, will be governed by the needs and results of MIZ modeling studies which will be coordinated through a MIZEX

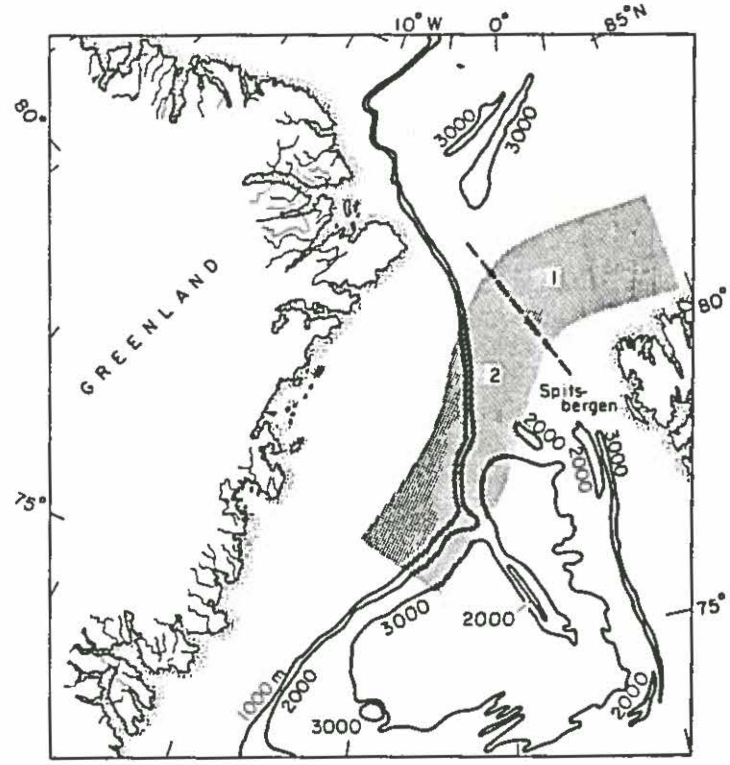


Figure 1. A possible area swept out by the experimental box in six weeks, assuming a mean advection rate of 10 cm s⁻¹.

Modeling Group. Figure 1 shows a possible area that will be traced out by the ships and arrays during the six-week period of the experiment, assuming initial deployment northwest of Svalbard. The initial region, area 1, is a zone of relatively low ice advection with normally a compact and well-defined ice edge. Once Fram Strait is encountered (area 2) the ice drift in the MIZ becomes much more rapid and the ice edge is likely to be more irregular and complex in form.

At every stage MIZEX is planned to be closely coordinated with other experiments in the region. As the ASI program develops, MIZEX will be able to define the major energy interactions which need to be parameterized for use within the larger-scale grid of the ASI program. A separate Fram Strait Monitoring Program has been proposed, sponsored by the Comité Arctique. MIZEX will cooperate closely with this program to achieve maximum scientific value and avoid duplication of facilities. Lastly, the ships of MIZEX will provide a unique platform for important biological and acoustical studies in the MIZ region. Summaries of these latter programs are given in Appendices B and C.

1. SIGNIFICANCE OF THE MARGINAL ICE ZONE

The marginal ice zone is a significant region in two senses, firstly as a location for man's activities and secondly as an important geophysical boundary zone involving energy exchanges which require parameterization in large-scale ocean-atmosphere models.

The MIZ is subject to fluctuations due to short-term forcing (e.g. cyclone passages, eddy generation) and to longer-term factors (seasonal and interannual). Successful modeling and prediction of variations in ice edge position and ice concentration would be of great value in furthering man's activities in the region. There are several areas of special interest.

Arctic navigation

Present and future developments in offshore Arctic oil exploration, in seaborne transport of Arctic resources (e.g. liquefied natural gas, iron ore), and in the supplying by sea of rapidly growing Arctic communities all require a much better predictive capability for ice conditions. We need the ability to predict the blockage or opening of ports and channels, the opening or closure of shore leads or large leads within the pack, changes in the motion and concentration of the ice, and the development of any ice edge anomalies. Typical ice-strengthened cargo vessels, for instance, can proceed even in multi-year ice so long as the ice-field is open, but encounter difficulties in consolidated pack of any age. The richest fisheries in the North Atlantic lie close to the ice margin, and the development of Antarctic krill harvesting will produce an increase in ship activity close to the Antarctic ice edge; in both cases a predictive capability for the ice margin is highly desirable.

Biology

The biological regime in the MIZ is scarcely assessed at all, and a knowledge of the impact of ice margin processes on biological productivity would be of great value to the development of fisheries.

Naval operations

The upper ocean in the MIZ is a region of extreme acoustic variability as well as having a high ambient noise level due to ice floe collisions. These effects interfere with the propagation of underwater sound.

Climate

An indication of the variability of the MIZ in the Greenland Sea, both from month to month and from year to year, is given by Figure 2, which shows mean and extreme limits for winter and summer over a 10-year period.

As a geophysical boundary zone the MIZ is unique in the complexity of the vertical and horizontal air–sea–ice energy interactions which take place there. In response to these the ice edge moves hundreds of kilometers north and south on a seasonal cycle. If the physical processes which occur on the mesoscale in the MIZ can be parameterized and included in large-scale models such that the ice edge motion can be understood, the results will be valuable not only to man's immediate activities but also to the study of the hypothetical response of the ice-covered oceans to major global disturbances. We would then be able to answer the question: Where would the ice edge lie if significant changes in certain energy fluxes occurred (e.g. effect of a dust veil due to volcanic eruption or meteoric impact, effect of a major increase in CO_2 or other atmospheric pollutants)?

There have already been some empirical studies which demonstrate a strong correlation between ice margin variations and interannual atmospheric variability (Walsh and Johnson 1980, Kukla and Gavin 1981, Vinnikov et al. 1981), and CO_2 sensitivity simulations by Bryan et al. (1982) and Man-

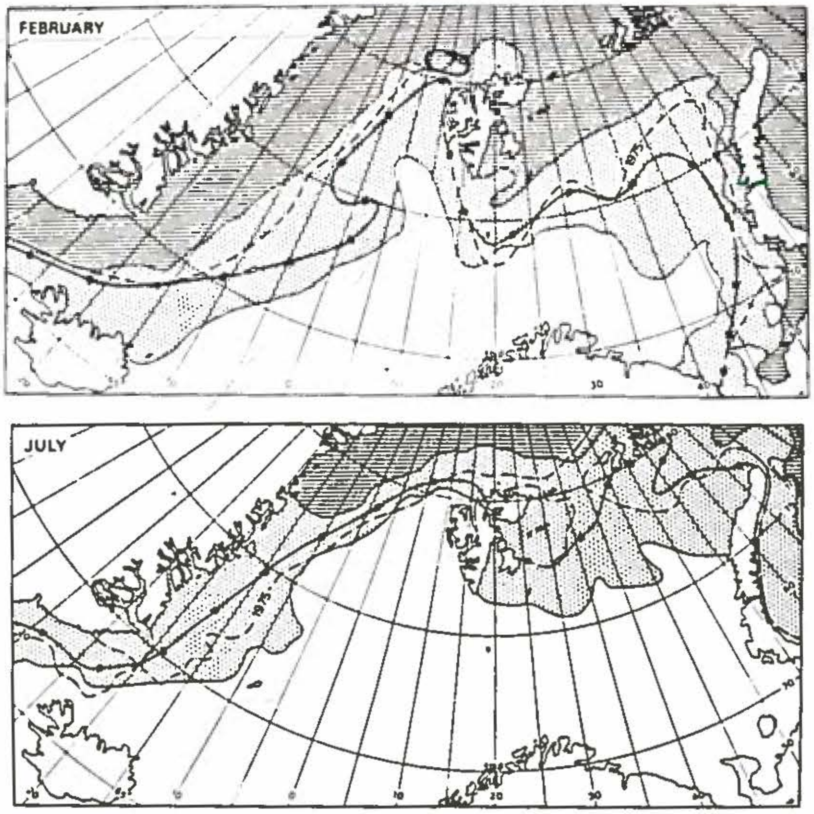


Figure 1. Mean and extreme sea ice limits at the end of February and July for the years 1966–1974 (Vinje 1977). The extreme range for % sea ice cover is bounded by the dotted areas, while the thick black line is the median limit for the decade and the dashed line is the 1975 limit.

abe and Stouffer (1979) which indicate how strongly the insulating effect of sea ice affects the polar regions' climatic sensitivity. To proceed further in these important areas of research, it is essential to have a better grasp of the physical processes which govern the ice edge position.

2. MIZ PROCESSES, MODELS AND SCIENTIFIC QUESTIONS

In this section we describe physical processes which are of importance in the MIZ region, and we consider how they may be modeled and how this leads to a set of scientific questions which will be addressed in MIZEX.

2.1. Processes

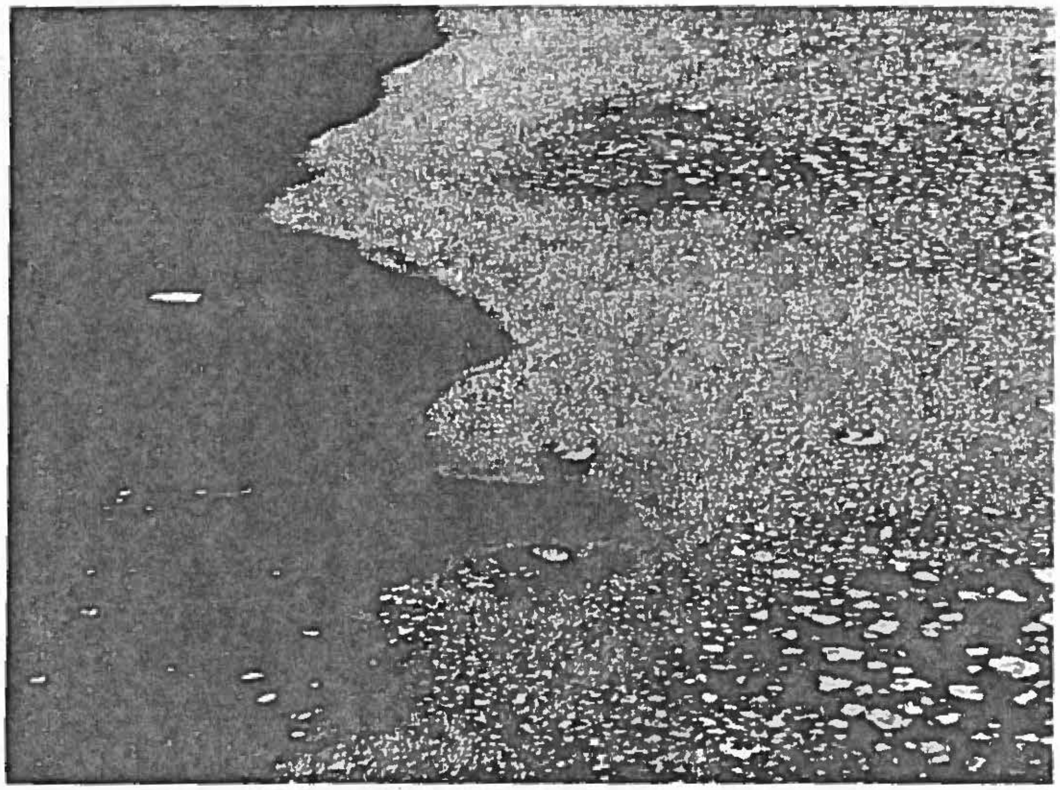
2.1.1. Ice dynamics and thermodynamics

In the ice-covered oceans the growth, drift and decay of sea ice significantly modify the atmosphere-ocean interaction. The main effects are:

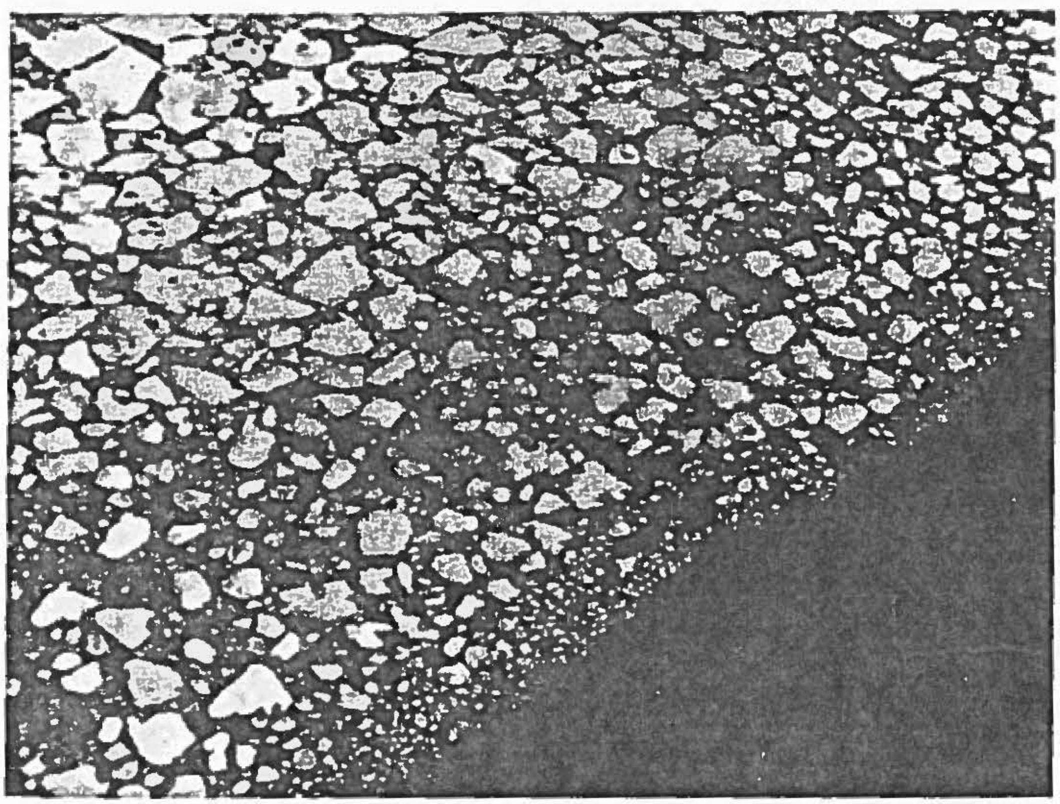
i) modification of the thermal fluxes at the air/sea interface
ii) modification of the buoyancy (salt) fluxes at the ocean surface
iii) modification of the surface albedo
iv) modification of the air-sea momentum exchange due to the ice interaction.

These modifications are particularly pronounced near the ice edge where the transition from ice to no ice occurs, and are further enhanced by the fact that the ice edge is in dynamic rather than static balance. Specifically, in the presence of a free ice edge, advective effects can transfer ice to the MIZ to be rapidly melted.

The nature of the ice in the MIZ is different from the interior pack, because of its greater freedom of movement and also because it is broken up by incident waves and swell into discrete floes which are small (about 30 m diam) close to the ice edge and which are larger at deeper penetrations where the wave field has been attenuated. These floes contain fragments of the original pressure ridges which traversed them when they were in the



a. Note small icebergs and the slicks of shallow internal waves just outside edge. (Photograph: P. Wadhams.)



b. The diameter of the larger floes is 50–80 m. (Photograph: P. Wadhams.)

Figure 3. The ice edge in Fram Strait.

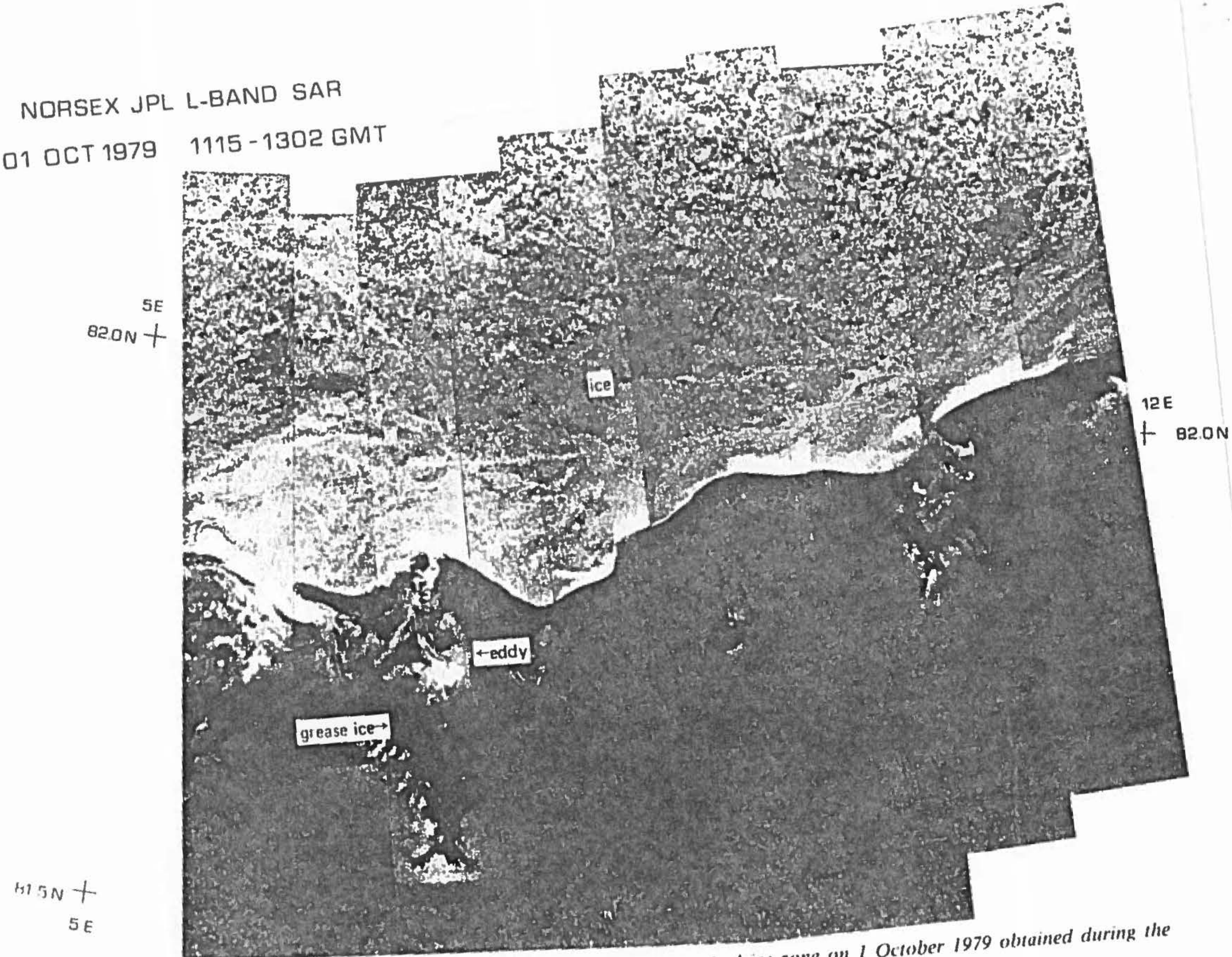


Figure 4. Synthetic Aperture Radar (1.215 GHz) image of the marginal ice zone on 1 October 1979 obtained during the NORSEX investigation. (After NORSEX Group 1983.)

interior of the pack, but it appears from submarine sonar profiles that considerable erosion of the ridge keels has occurred. The combination of less ridging with a greater number of floe edges produces air-ice and ice-water drag coefficients which are different from the interior pack and which seem, from the slender evidence available, to be somewhat higher (Johannessen 1970, Smith et al. 1970). The characteristic floe size distribution also affects the ice dynamics by determining the rate of the floe collisions by which kinetic energy is redistributed within the icefield, and affects the thermodynamics by enhancing the melt rate in summer (through lateral melting around floe edges) and the growth rate in winter (through the incessant opening and closing of new open water areas). Figures 3a and b show typical scenes at a compact ice edge composed of small floes broken up by wave action.

2.1.2. Oceanography

Oceanographic conditions in the MIZ are dominated by permanent and transient frontal systems, by eddies, and by upwelling events along the ice edge. Vertical fine structure (10 m) and mesoscale (100 m) structures formed by interleaving of Polar and Atlantic Water intrusions are also frequently observed in the Greenland Sea MIZ. These phenomena interact with the ice pack and the atmosphere. For example, salinity fronts off the ice edge develop strongly during summer due to meltwater input; eddies along the ice edge shed ice off into warmer water, thereby providing an ice export mechanism; surface boundaries of ocean fronts will limit ice extension particularly during winter because the ice will melt when forced across the boundary into warmer water by wind. Wind-driven upwelling along the ice edge is dependent on the ice roughness, the stability of the atmospheric surface boundary layer, and the ice interaction. Furthermore, there is a strong coupling between the ice pack and the oceanic mixed layer below it.

Fronts may be strong and permanent, such as the East Greenland Polar Front which separates the cold, low-salinity, southward-flowing East Greenland Current from the more saline water in the Greenland Sea; or more transient, such as ice edge meltwater fronts observed north of Svalbard. The wavelength of meanders observed on the meltwater front is in the order of 20–40 km (Johannessen et al. 1983), while the meander scale of the East Greenland Polar Front is longer (60–100 km). Several investigators, e.g. Perdue (1982), have established that the location of this front is correlated with the continental slope in the Greenland Sea, thereby implying bathymetric steering.

Along the fronts and the ice edge, *eddies* have been observed which develop from frontal meanders. In the MIZ region north of Svalbard the horizontal scale is approximately the Rossby internal radius of deformation of 10 km (Johannessen et al. 1983, NORSEX Group 1983). Figure 4, an airborne SAR image obtained in this area during the Norwegian Remote Sensing Experiments (NORSEX Group 1983), shows eddies of this type being shed from the ice edge. The image, obtained on a cloudy day, demonstrates the capability of aircraft radars in collecting sequential mesoscale synoptic information in the MIZ. Further downstream in Fram Strait and the Greenland Sea, larger eddies of diameter 50 km or more are observed (Vinje 1977, Wadhams and Squire 1983) which appear to be generated through baroclinic instability of the polar front. Figure 5 shows a temperature section across such an eddy surveyed in Fram Strait during the Swedish YMER-80 cruise (Wadhams and Squire 1983); the effects of the warm core extended down to beyond 600 m. Our present knowledge of the space and time scales of these high-latitude eddies, and their generation, energetics and role in lateral heat and mass exchange in the MIZ, is very sparse.

Transient wind-driven upwelling along the ice edge has only been observed twice, in both cases north of Svalbard: in winter by Buckley et al. (1979) and in the fall by Johannessen et al. (1983). In the winter, water was upwelled from 150 m depth to the surface in a 10-km-wide zone along the ice edge, thereby generating two fronts, one coinciding with the edge and the other parallel to the edge and 10 km off. During the fall upwelling event, where the vertical stratification across the pycnocline (located at 20 m) was very strong, only a slight rise of the pycnocline, on the order of a few meters, took place during a 2½-day 10-m-s^{-1} wind event. The upwelling is believed to be caused by changes in the wind stress across the ice edge due to the variation of the air drag coefficient between open water, broken ice floes and smoother ice, and to stability variations in the atmospheric surface boundary layer.

The planetary boundary layer and mixed layer under pack ice have been the subject of several studies, such as those of Hunkins (1966), McPhee and Smith (1976), Maykut (1977), Morison (1980) and Morison and Smith (1981). All of these have taken place in the interior pack, and it is expected that the boundary layer and mixed layer in the MIZ may behave quite differently. For instance,

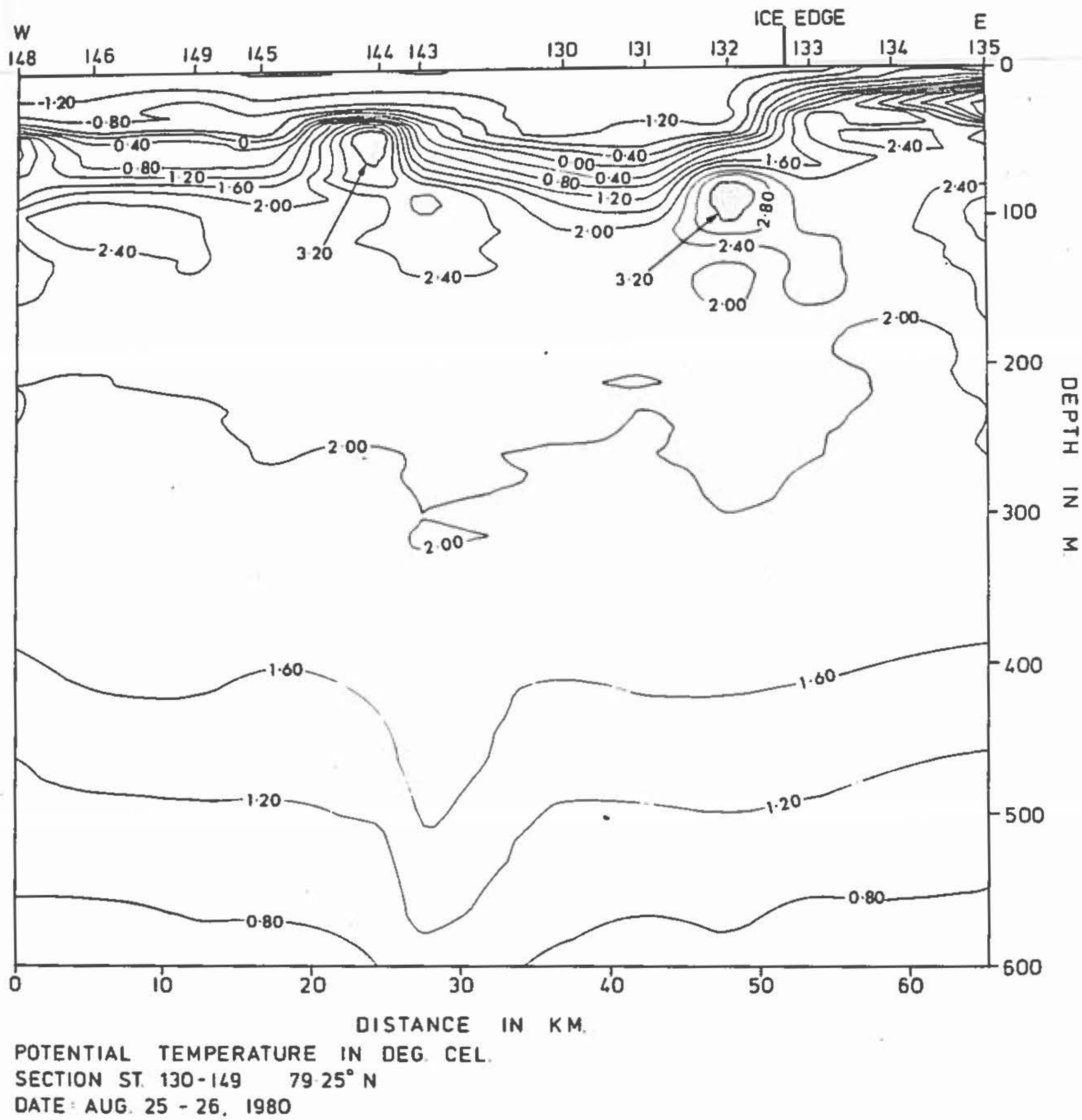


Figure 5. A temperature section across an eddy observed at the ice edge in Fram Strait, 79°15'N, 00°38'E, during the YMER-80 cruise, August 1980. The eddy is at station 144 and an ice edge front can also be seen (after Wadhams and Squire 1983). Shading indicates entrained Atlantic water warmer than 3.2°C.

the few measurements of air and water drag coefficients for MIZ ice suggest that they are greater than over the interior pack or open water (Johannessen 1970, Smith et al. 1970), while recent theoretical work by McPhee (1981) suggests that in summer the water drag coefficient is very low because of the effect of meltwater on the boundary layer. In the mixed layer it is possible that one-dimensional models of behavior are no longer appropriate because of the large horizontal density gradients which may introduce vertical velocity shears, eddies or disruptions in the internal wave field.

2.1.3. Meteorology

The principal *atmospheric processes* that are important in the MIZ are those which control the ice edge through exchanges of atmosphere and ocean or ice surface. The influence of the ice edge on the atmosphere is also of primary interest.

Wind stress is the atmospheric momentum flux at the surface. It contributes to ice drift, wave and current generation, and mixing in the upper ocean. The magnitude and direction of the stress are determined mainly by the gradient of sea level pressure and the stratification and shear in the atmospheric surface layer and planetary boundary layer (PBL). These effects are dependent on boundary layer exchange processes and mesoscale circulation features, thus creating a feedback between the pressure field and stress field. Wind stress is coupled to changing surface roughness in both the ice and the ocean. Critical MIZEX problems involve determining the wind stress under a variety of synoptic conditions, stratifications and surface characteristics.

The *sensible heat flux* to and from the atmosphere strongly influences ice growth, the temperature of the ocean surface, and convection in the upper ocean. Its magnitude and direction are a function of the temperature difference between the atmosphere and the surface, and, as in the case of stress, the details of the turbulent transfer are dependent upon stratification and shear in the surface layer and planetary boundary layer. In some cases, however, as when deep convection is generated during air mass modification, there may be strong vertical coupling between the surface and the mid-troposphere. Feedback may be involved if this convection further influences synoptic development. Relevant MIZEX problems involve relating the sensible heat flux to the ambient synoptic conditions and boundary layer characteristics.

The physics of water vapor transfer (evaporation and condensation) are analogous to those of sensible heat, and all the preceding remarks apply. Precipitation, usually rain or snow, enters MIZ problems in several ways. Precipitation over the ocean decreases the salinity of the mixed layer and affects thermohaline convection, and over ice may cause melting or a change in surface wetness. Snow over ice surfaces usually causes an albedo change, and strongly influences the heat transfer by conduction; it may also slightly alter the surface roughness.

The solar and infrared *radiative fluxes* are large terms in the energy balance of both the ocean and the ice. Both quantities are critically dependent on cloudiness, and to a somewhat lesser degree on atmospheric constituents, especially water vapor, carbon dioxide and aerosols. Albedo variations, especially over heterogeneous snow–ice–water surfaces, influence the short-wave fluxes, while variations of infrared emissivity affect the long-wave balance. The MIZEX radiative problem is chiefly one of monitoring the fluxes at the surface together with the ambient cloud and moisture conditions.

There are numerous topographic considerations involving the Greenland land mass. These involve all scales, ranging from katabatic effects in coastal regions to large-scale, orographically induced cyclogenesis.

2.2. Models

While models describing the sea ice in the Marginal Sea Ice Zone exist, a coupled mesoscale ice-ocean simulation of the MIZ has not yet been carried out. Some ice model simulations have been done for the Greenland Sea using Hibler's (1979) dynamic thermodynamic sea ice model to predict seasonal and interannual variations in the ice edge position (Hibler and Walsh 1982), and to predict week-to-week variations in ice drift and compactness (Tucker and Hibler 1982). The large-scale simulations (Hibler and Walsh 1982) yielded a seasonal cycle with excessive amounts of ice in the North Atlantic during winter and with somewhat excessive amounts of open water in the central Arctic during summer. The poor fit to the Atlantic ice margin in winter is likely partially due to the neglect of lateral oceanic heat transport, since the ocean portion of the model consisted of only a fixed depth, motionless mixed layer together with an upward oceanic heat flux. However, a similar model has successfully simulated the seasonal cycle of Weddell Sea pack ice (Hibler and Ackley 1983) indicating that there may be considerable asymmetry between the oceanographic characteristics in the different hemispheres. In general these results emphasize the need for carrying out more fully coupled ice-ocean simulations in the marginal ice zone regions.

To model ice drift, growth and decay it is important to understand the nature of the ice rheology. In the MIZ the ice cover is more fragmented than ice in the central pack, with substantial variations in compactness. These MIZ characteristics have an unknown effect on the ice dynamics. Of particular interest is the role of internal ice stress as compared to wind and water stresses on the ice drift. On the large scale the internal ice stress has a rectifying effect on motion in the marginal ice zone. In particular, under on-ice winds, this stress tends to reduce further convergence after the ice has been sufficiently compacted. Off-ice winds, on the other hand, can cause motion with little ice resistance. Such features are characteristic of the plastic rheologies used in large-scale models (e.g. Hibler 1979, Coon 1980). However, superimposed on such a rectifying effect, random bumping or rotation of floes may produce an effective pressure term. Røed and O'Brien (1981) speculate that such an unconfined pressure may be a mechanism causing a jet-like motion at the ice edge. In addition, mesoscale simulations by Hibler et al. (1983) show the presence of wave effects during ice build-up. To methodically examine the role and effect of these rheology features on ice edge growth, drift and decay further numerical simulations are needed. Such studies can be carried out using the viscous plastic numerical model developed by Hibler (1979). This numerical model provides for the simulation of a highly nonlinear ice interaction employing an arbitrary shear to compressive strength ratio, and an unconstrained pressure term of adjustable magnitude.

The specific problem of the ocean response to wind forcing in the MIZ has been approached through analytical work invoking a stationary and inactive ice cover, which readily allows ice edge upwelling (Gammelsrød et al. 1975, Clarke 1978). However, direct observation of the MIZ reveals a highly mobile rather than inactive ice cover, and emphasizes the need for a coupled ice-ocean model. Mesoscale numerical models, coupling sea ice and ocean (Røed and O'Brien 1983) and including thermodynamic processes, are under development. They will be used in studying the influence of a moving ice cover on the oceanic circulation in the MIZ on short time scales of a few days to a few weeks.

There is also a need for more complete models of the atmospheric winds. One approach in this regard is to study the mesoscale wind and surface flux fields employing planetary boundary layer (PBL) models. Models for obtaining the surface flow, stress and heat fluxes with respect to large-scale parameters of pressure and temperature fields were developed during AIDJEX (Brown 1974, 1981). The model developed by Brown was adapted to the ocean in connection with GOASEX and JASIN for remote sensing surface truth studies (Brown and Liu 1981). In these experiments, model fields were shown to agree with point measurements to ± 2 m s^{-1} and $\pm 20°$. The geostrophic flow (derived from the surface pressure field) is corrected for curvature effects and thermal wind. It is used as the boundary condition on a two-layer similarity solution for the PBL flow. Corrections are included for stratification effects in both layers, secondary flow in the outer layer, variable surface roughness and humidity effects.

The mesoscale eddies which occur along the ice edge have already been subjected to laboratory modeling (Griffiths and Linden 1981a, b), but further numerical modeling is required in order to understand this phenomenon. We plan first to examine the dynamics of isolated mesoscale eddies found in the MIZ region through the use of an existing two-layer dynamical numerical model (Smith and O'Brien 1982). The roles of topography, vertical eddy structure, variable friction and lateral boundaries can all be addressed with the model, and there is the possibility of incorporating thermodynamics. More complete studies will likely involve the coupling of a nonlinear dynamic-thermodynamic sea ice model to an eddy resolving baroclinic ocean model. Preliminary numerical experiments will aid in the design of the eddy sampling program in MIZEX.

On a smaller scale, ocean waves are important in breaking up the ice in the MIZ, and long swell may be effective up to 50–60 km inside the ice edge. Present models of the interaction of waves with an array of discrete ice floes (Wadhams 1983) are based on scattering mechanisms and are successful in predicting the wave decay rate so long as the pack is not consolidated. They cannot, as yet, predict wave refraction within the pack or the form of the energy spectrum reflected back out into the open water. The flexural response of floes to waves can also be modeled successfully (Goodman et al. 1980) and used to predict the maximum floe size that can occur at different penetrations into the ice pack under a specified incident wave spectrum. The actual nature of the flow size distribution within this maximum size limit is not predictable as yet, but has been measured empirically.

To summarize, several of the mesoscale MIZ processes are poorly described theoretically. Regional models exist which will couple a uniform depth mixed layer both to the ice and to the deep ocean but have not been numerically investigated. In addition there is a need for development of a model for the Greenland/Norwegian Seas, employing a more complete treatment of the mixed layer and including the three-dimensional circulation of the ocean. Such studies, which are proposed in the ASI program, will help in the understanding of the physical processes which control the East Greenland and West Spitzbergen Currents and the ice edge position.

To aid in the further development of models describing the marginal sea ice zone, a subgroup of researchers interested in modeling has been organized. At the moment there are a variety of theories explaining various aspects of the MIZ. Because of this variety it is important to not prejudice the design of the experiment until different theories have withstood the test of open debate. In this regard it is felt that premature focusing of the experiment can be as destructive as inadequate focusing of the experiment. Data from the 1983 and 1984 studies, in conjunction with ongoing modeling efforts, should allow this focus to emerge.

2.3. Scientific questions of MIZ

The foregoing discussions of processes and models suggest that the determination of the major scientific questions will arise from the dialogue between the modelers and experimentalists occurring during the 1983–84 MIZEX studies. Consequently a more complete focus must await their efforts. However, at this point in time, a number of scientific questions of major importance have been identified. These include the following.

2.3.1. Sea ice

- What are the roles of the internal ice stress, floe-floe interaction, wind and water stresses, inertial-tidal forces, and wave forces in MIZ ice dynamics?
- What is the relative importance of the ocean vs the atmosphere in the decay of the ice cover and how is this affected by changes in ice concentration and floe size distribution?
- Are lateral variations in vertical oceanic heat fluxes more important than horizontal oceanic heat transport in determining the ice retreat?
- How does ice advection caused by general circulation such as the East Greenland Current, by eddies, ice bands and streamers, influence the retreat of the ice edge?
- How do the physical properties (and hence thermodynamic and electromagnetic properties) of the MIZ ice differ from those of the central pack?
- How does the ice thickness distribution and ice roughness vary with distance from the ice edge?
- What is the role of waves in the distributions of floe size and ice roughness?

2.3.2. Oceanography

- What is the three-dimensional structure of the fronts (East Greenland polar front and meltwater fronts) in the Fram Strait and Greenland Sea marginal ice zones? What is their temporal and spatial variability over a period of days? What is the relationship between the fronts, the ice edge and the bathymetry? How do instabilities, eddies and finestructure occur in relation to fronts?
- What are the characteristics of the eddy field in the MIZ with respect to space and time scales, energies, generation mechanisms, propagation and role in lateral heat and mass exchange?
- How prevalent is upwelling along the ice edge? How does it relate to the wind-stress variation across the edge and is it important to the dynamics and thermodynamics of the ice edge region?
- How do the momentum, buoyancy, and heat fluxes in the oceanic mixed layer vary with varying ice conditions (melting rate, concentration, floe size, etc.)?
- How does meltwater input affect stratification and the upper layer circulation in the MIZ? Does the meltwater, for example, generate a jet-like current along the ice edge by analogy with coastal currents, with fresh water inputs from fjords and estuaries?
- How does the internal wave field differ under pack ice and in the open ocean?
- What is the role of vertical fine-structure in the transfer of properties across the front?
- What are the sources of near-surface water?
- How long ago did fresh water runoff enter the ocean?

2.3.3. Meteorology

- How does the surface wind stress field vary with ice conditions?
- What are the energy fluxes (heat and radiation) and their relation to conditions in the MIZ?
- How is the air modified by the change in boundary conditions at the MIZ?
- How do the bulk aerodynamic coefficients change with the ice conditions and atmospheric surface layer stability in the MIZ?
- What is the relationship between synoptic scale pressure patterns and surface wind flow in the region surrounding the MIZ?
- What is the relative proportion of continental and marine aerosols in the MIZ?
- What are the effects of the aerosol populations on optical energy progagation?
- What marine aerosol enhancement occurs due to biological species in the MIZ?

3. REMOTE SENSING

Remote sensing is both a tool and a discipline. As a tool it is an essential part of fulfilling the goal of MIZEX. It is the only way to obtain mesoscale synoptic coverage at frequent time intervals and at sufficiently high resolution to provide useful information on ice and ocean parameters such as the ice edge location and structure (Fig. 4).

It is clear that remote sensing as a discipline will be advanced during MIZEX. The focus of the remote sensing experiments is on use of microwave sensors since they permit observation of ocean and ice surfaces through clouds. In spite of much research conducted in respect to microwave detection of sea ice during the last decade, i.e. BESEX, Gloersen et al. (1975), AIDJEX, Campbell et al. (1979), and NORSEX Group (1983), very little work has been done during the summer season. Many ambiguity problems are known to exist at this time of year due to snow melt and continual refreezing of ice surfaces. For example, passive microwave techniques yield good estimates of ice concentration when the ice is frozen (Svendsen et al. 1983), but we are not sure how well this technique will work for wet ice. Another example is the SAR observations. This technique presently provides information about the ice edge and structure, as well as surface and internal waves in the ocean. However, we have not yet shown how useful the SAR is for estimating ice concentration and ice floe distribution during summer, and for locating fronts and eddies in the open ocean off the ice edge in cold water.

The objectives of utilizing remote sensors in MIZEX are threefold.

1. To provide remote sensing products such as SAR, SLAR, passive imagery and aerial photography (dependent on weather) to MIZEX principal investigators. These data will be supplied to investigators in near real-time for the purpose of planning in situ data collection during MIZEX. Other remote sensing mosaics will be provided shortly after the actual field experiment to facilitate a better understanding of the synoptic scale processes occurring during MIZEX. Thus, one role remote sensing will play in MIZEX is to provide boundary conditions and baseline data of the environment of the MIZ experimental zone.

2. To carry out extensive microwave active-passive observations from aircraft, satellites (if available), and surface-based remote sensing systems, and to evaluate the ability of remote sensors to provide detailed geophysical information with respect to the ice and ocean areas found within the MIZ. In order to perform this evaluation nearly coincidentally with the remote sensing data collections, in situ physical measurements of the ice and ocean will be made. Thus, the second objective of using remote sensors in MIZEX is to evaluate existing algorithms and develop new algorithms, where appropriate, that take remote sensing data as inputs and provide useful geophysical information.

3. To develop models that adequately explain and predict remotely sensed electromagetic radiation signatures of both ice and ocean features. It has long been recognized that to optimize remote sensing algorithms the theory of radiation transfer must be well understood. This better understanding of the theory of how remote sensors measure ocean and ice parameters will be a prime scientific question addressed during MIZEX.

The specific scientific questions are:

3.1. Ice

- How do we relate signatures in radar images of the MIZ to the actual microwave cross section of various ice types during the melting season?
- How do the active and passive microwave signatures of different ice types vary during the melt season? What minimum resolution (both spatial and frequency) is necessary to detect various ice types?
- Which remote sensing system, active, passive, or a combination of systems, is most effective in providing data on ice concentration, ice types, ice floe distributions, and ice and ocean kinematics in the MIZ during summer? Additionally, a set of algorithms for the above required ice information needs to be designed, constructed, and evaluated.
- Which remote sensing system, or combination of systems, is most effective in providing data on measurement of gravity waves as they propagate into the ice? Can the SAR successfully image these waves as they attenuate in the ice?

3.2. Ocean

- How do we relate microwave signatures of the sea surface to phenomena such as fronts and eddies in cold-water regions?
- Can the SAR successfully image gravity waves as they refract due to interaction with the ice edge?
- Which remote sensing system, active, passive or a combination of systems, can provide the most useful information on ocean circulation in the MIZ?
- How do conditions near the ice edge affect

Bragg scatter and hence influence radar images and wind vector scatterometry?

3.3. Atmospheric remote sensing

- How accurate are infrared and passive microwave temperature and moisture retrievals in the MIZ in view of complex PBL characteristics and extensive Arctic stratus cloud conditions?
- Can satellite visual, infrared, and microwave radiances be used to determine weather and cloud characteristics in the MIZ?
- Can remotely sensed atmospheric profiles be used to analyze the troposphere in the MIZ and to initialize regional numerical models?

4. STRATEGY OF THE EXPERIMENT

4.1. Location and timing

The MIZ of the Fram Strait and Greenland Sea has been chosen for the main MIZEX experiments because it is the region where most of the heat and mass exchange takes place between the Arctic Ocean and the rest of the world, and is therefore of crucial importance thermodynamically. Furthermore, the length of the ice edge, which is expected to be traced out by the drifting experiment, combines many of the most interesting features of all marginal ice zones.

The initial deployment of the ships and arrays will be northwest of Svalbard (Fig. 1, area 1) where the ocean structure is characterized by a meltwater front off the ice edge. The edge is normally compact and well defined, and the downstream advection of ice is relatively slow and dominated by the prevailing winds. Small eddies and upwelling have both been observed in this region, which is also the place where a warm subsurface current, which was the West Spitzbergen Current when it was at the surface, proceeds northward into the Arctic Basin to act as that basin's major heat source.

As the ships and arrays drift down into the Fram Strait (region II) they enter a zone of rapid advection where the ice drift is dominated by the strong southward-flowing East Greenland Current. This is a permanent current whose speed and course are related to bottom topography, and which has a very sharp polar front on its seaward edge associated with a large velocity shear. This favors the development of meanders and eddies, which are of larger scale than further north. There is intense atmospheric frontogenesis. The ice edge tends to be irregular in form and to show by its shape and concentration the effect of the many processes that have acted on it. A further reason for selecting the Greenland Sea lies in the assistance that MIZEX can give to the ASI program in its investigation of such problems as the source of North Atlantic bottom water, which may come from the sinking of Greenland Sea water in winter.

The timing of the experiment (mid-June to end of July 1984) is chosen to yield as much information as possible about the transition to summer conditions in the MIZ. Many cycles of melting and refreezing of the upper ice surface should occur in the early part of this period, before the final formation of summer melt ponds, and this will provide a good range of conditions for microscale measurements of ice properties and thermodynamics, and for microwave studies of the upper ice surface. The main ice, ocean and atmospheric programs will benefit from the continuous daylight.

4.2. Experimental design

As described in the *Executive Summary*, the experiment is a drifting one making use of a passive ship within the pack for many of the studies. In all, five ships are required, with five helicopters and a number of remote sensing aircraft. The drifting ship will position itself far enough into the pack (some 30–50 km) to be in a zone of large floes at high concentration, and with an average southward drift of 10 km day^{-1} it will cover a distance of some 400–600 km during the experiment.

Intense synoptic oceanographic, meteorological, and ice mapping will be carried out in fixed geographical grids (dependent on the ice edge location in 1984) in the northerly low advection region, area 1 (Fig. 1) and further downstream in the higher advective region, area 2 (Fig. 1) in the East Greenland Current. The two regions of intense synoptic mapping will each cover approximately a 100- to 200-km length of the ice edge, starting 40–50 km outside the ice margin and extending 40–50 km into the pack. The drifting ship, the ice-strengthened ship and the open-water ship with the ice deformation, meteorological pressure and the ocean mixed layer arrays will drift throughout the regions and provide observations of ice drift, and oceanographic and meteorological parameters. The ice-strengthened and the open-water ship will follow parallel tracks. The oceanographic grid lines are directed perpendicular to the ice edge, and tentatively spread 5–10 km apart with oceanographic stations spaced 2–4 km apart in order to resolve the smallest eddies with a diameter of 10–15 km. Grid point distortion due to ocean advection and slow-moving ships will be corrected by applying a Space-Time Objective Analysis scheme (Carter and Robinson 1981). We are proposing that AXBT mapping of the high advection region in the East Greenland Current, area 2, start at the same time as the mapping in the low advective region in the north, so that the synoptic temperature field for the Fram Strait–Greenland Sea will be simultaneously observed at regular intervals during the 6-week experiment.

In the open ocean off the ice edge, several subsurface current meter moorings will be deployed as well as Argos and RDF drifters, and surface current measurements will be accomplished by the CODAR system.

We hope to obtain sufficient flight time for the remote sensing and meteorological aircraft to overfly the mesoscale experimental area every 2 to 3 days. An aircraft coordination center located at Tromsö Satellite Station in northern Norway will coordinate all aircraft flights and quickly transmit selected remotely sensed information back to the scientists on board the ships to aid in the execution of the experiment.

To achieve our scientific aims it is necessary to use the following range of reliable state-of-the-art measuring systems:

Atmosphere	Standard ship meteorological instruments. Eddy flux, profile and dissipation sensors, aerosol counters, radiometers, acoustic sounder, radiosondes and pressure sensors on ships and buoys. Gust probes, dropsondes, scatterometer and other remote sensors from aircraft.
Ocean	CTD, batfish, free-falling velocity probes, current profiling systems, Argos-tracked drifters and CODAR radar for surface current and expendable probes for temperature and salinity profiles.
Ice	Deformation array, floe collision sensors, directional wave buoys, upward-looking ice profilometer, sonic ablation detector and parachute-dropped buoys tracked by Argos.
Remote sensing	X-, C-, L-band airborne synthetic aperture radars. Ka-band imaging radars, multifrequency microwave radiometers and scatterometers. Portable in situ ice dielectric system. In situ multifrequency scatterometers and multifrequency passive microwave array. Raft-mounted Lunenberg target calibration lenses.

The role of these and other instruments in the overall plan of measurements is described in detail in Appendix A.

4.3. Platforms

The work program, described in detail in Appendix A, requires the participation of five ships, of which three must have the capability of operating in ice. The division of work among the ships is summarized in Table 1.

The icebreaker will be the R/V *Polarstern* of the Alfred Wegener Institute for Polar Research, Bremerhaven, Federal Republic of Germany. She can carry two helicopters and has space for approximately 45 scientists. The vessels to fulfill the roles of "drifting ship in ice" and "ice-strengthened ship" are anticipated to be the Norwegian ships *Polar Queen* (two helicopters, 30 scientists) and *H. U. Sverdrup* (space for 10 scientists), both of which will be chartered by the Office of Naval Research, U.S.A. One of the open-water ships will be R/V *Håkon Mosby* of the University of Bergen, Norway, with space for 10 scientists. A second open-water ship will be NAVOCEANO's *AGOR Lynch* (carrying about 15 scientists) which has been scheduled by the U.S. Naval Research Laboratory for three weeks in June 1984. Other ships that will participate in the experiment are the R/V *Valdivia* of the Institute for Marine Research, Hamburg, Federal Republic of Germany, with space for 15 scientists and the ice-strengthened vessel R/V *Lance* of the Norwegian Polar Institute, Oslo, Norway, with two helicopters and space for 20 scientists. The above set of ships will be able to accommodate the scientists and technicians required for the shipborne program.

The potential remote sensing aircraft are the CV580 of Canadian Remote Sensing Center equipped with ERIM SAR; the NRL P3, the Baron meteorological aircraft of Airborne Research Associates, the NOAA P3, and the NASA CV-990, all from the U.S.; the C130 of the Royal Danish Air Force carrying instrumentation from the Technical University of Denmark, a remote sensing aircraft from France, and a Norwegian Air Force P3.

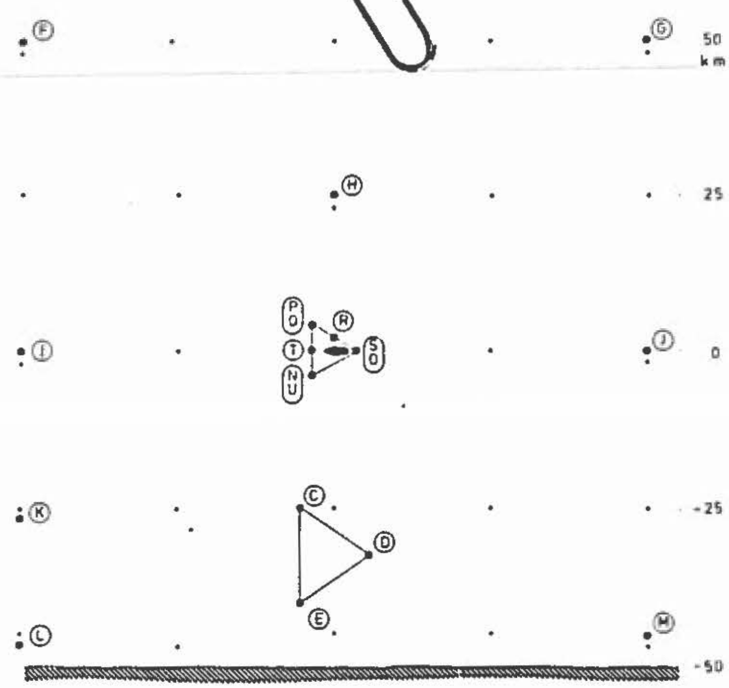
Table 1. Tentative distribution of work commitments among platforms.

Platform	*Heli-copters*	*Work*	*Days*
Icebreaker	2	Synoptic CTD mapping in ice	22
		Deploy and retrieve met-ocean array in ice	5
		Deploy and retrieve four Cyclesondes	3
		Help ice-stengthened ship in heavy ice conditions	6
		Microwave properties of sea ice and CODAR	6
		Meteorological observations, radiosondes, acoustic sounder	
		Biological measurements	
Drifting ship in ice	2	Ice deformation and dynamics	
		Ice structure studies	42
		Ice thermodynamics	
		Cyclesonde deployment and retrieval	
		Microwave properties of sea ice	
		Hourly meteorological observations, radiosondes	
		Acoustic sounder, flux profilers	4
		Atmospheric boundary layer studies	
		Swallow float tracking	
Ice-strengthened ship	1	Synoptic CTD mapping	5
		Eddy CTD mapping	15-20
		Upwelling	5
		Bands and streamers	5
		Detailed examination of ice front	5-10
		Deploy and retrieve directional wave buoy	2
		Hourly meteorological observations, radiosondes	
		Atmospheric flux profilers	4
		CODAR, swallow float tracking	
Open-water ships		Synoptic CTD mapping in open ocean	(each) 23
		Eddy CTD mapping-fronts and upwelling	14
		Deploy and retrieve met-ocean arrays	5
		Hourly meteorological observations	
		Radiosondes, acoustic sounder	
		Atmospheric boundary fluxes	
		Aerosol size distribution	
Submarine (if available)		Sonar profiling—20 transects with longitudinal ties	10
		Sound velocity profiling across fronts	
		XBTs, CTD profiling across fronts	
Aircraft		SAR mapping—long-range aircraft	20 flights
		Correlative passive-active microwave data under different environmental conditions	15 flights
		Combined meteorological-remote sensing aircraft for wind stress	20 flights
		Boundary layer studies, surface temperature, albedo, roughness, ice distribution, photography.	20 flights
		Marine winds from scatterometer	20 flights
		AXBT flights	10 flights

4.4. 1983 experiment

The experiment in the summer of 1983 will have several purposes.

- It will provide observations of temporal and spatial scales of several of the processes to be studied so that the different arrays (see Fig. 6) and the measurement plan for the 1984 experiment can be optimized. The observations include ice kinematics and deformation rates; ablation and transport measurement of the thermal balance in and immediately around the ice; ice concentration, ice types and floe size distribution; energetics, structure and propagation of ice-ocean eddies; frontal characteristics; internal waves and fine structure; ocean and atmospheric boundary layer fluxes; acoustical and biological characteristics.
- It will provide observations, some of them mentioned above, needed for the ongoing atmospheric-ice-ocean modeling effort.
- It will test measurement concepts and systems such as the ice deformation array in a highly dynamic region; ice-ocean eddy in



C-P Argos positioned buoys.
C,D,E Bergen Toroid (air temperature, wind, current, sea temperature, conductivity. C has atmospheric pressure).
F,M Bergen Ice Drifters (atmospheric pressure on F).
G-L BIO Ice Drifters.
N Cyclesonde UW/Miami (current, sea temperature, conductivity).
Q Cyclesonde Miami (same sensors).
O Temperature conductivity chain, UW, current.
Q-U CRREL Del Norte Radar transponders (Q is master).
• Radar corner reflectors.

Figure 6. Arrangement of drifting buoys.

situ tracking techniques in a difficult environmental region; internal waves and fine structure arrays; new application of the CODAR radar for surface current observations and of the Cyclesonde for profiling current, temperature and salinity from the drifting ice; flux measurement arrays in the boundary layers; testing of active and passive remote sensing techniques such as the SAR for tracking the ice edge structure, ice-ocean eddies and fronts and evaluation of methods and algorithms for deriving ice concentration, ice types and floe size distributions during summer time.

- It will test methods for real time processing of remote sensing observations with downlink from the aircraft to the ships. Together with real time processing of in situ observations and application of predicting schemes of, for example, ice drift and deformation, this will aid in controlling and optimizing the measurement plan, so that tactical rules for the deployment of ships, drifting buoys, and aircraft can be prepared for the 1984 experiment.

The 1983 program will take place from early June to early August, a 60-day period. The platforms we will be using are the ice-strengthened icebreaker R/V *Polarbjorn*, for the full period, equipped with two helicopters, and the icebreaker R/V *Polarstern* and the ice-strengthened R/V *Lance* for part of the period. The remote sensing aircraft will be the Canadian CV580, U.S. NRL P3, Danish C130 and ARA Baron.

This 1983 program, together with the ongoing modeling effort, will give us a better background of spatial and temporal variability associated with the different processes, which will enable us to improve our experimental design and measurement plan for the summer 1984 experiment as well as give us the opportunity to improve our instrumentations. It will also acquaint many participating scientists with the complex environmental conditions in the MIZ.