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

I. Research Strategy

Editors: Peter Wadhams, Seelye Martin, Ola M. Johannessen,
William D. Hibler, III and William J. Campbell

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PREFACE

This document describes the research strategy for a series of mesoscale studies of Arctic marginal ice zones. The main goal of this program is to gain a better understanding of the processes occurring at the ice margin. These processes are relevant to climate, weather forecasting, petroleum exploration and production, marine transportation, naval operations, and commercial fisheries. In addition, MIZEX will aid in determining what modifications to existing ice-ocean-atmospheric models are needed for better prediction near the ice margin.

These goals are consistent with recommendations made by international scientific bodies, most notably those of the Joint Scientific Committee (JSC) in its plan for the World Climate Research Programme (WMO-ICSU, 1981). In this document the JSC states that for improved modeling it is necessary: "To study the physical processes affecting interactions between air, ice and sea at the sea-ice margin and to develop methods for their adequate representation in climate models."

More specific details on initial field programs will be addressed in planning meetings in the near future. In addition, it is anticipated that other aspects of the program, such as modeling, will be addressed in future workshops, with the results distributed in a similar format to this research strategy. It is our hope that this research program will be of interest both to the research community and to funding agencies.

Comments on the program by interested researchers are invited and can be addressed to any of the editors.

The Editors

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MIZEX

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

I. Research Strategy

1. INTRODUCTION

The marginal ice zone (MIZ) is the crucial region in which the polar air, ice and water masses interact with the temperate ocean and climate systems. The exchanges which take place there profoundly influence hemispheric climate and have a significant effect on petroleum exploration and production, naval operations and commercial fisheries. To gain an understanding of these exchanges sufficient to permit prediction, there is need for both a large-scale and a mesoscale research program. The objective of the large-scale program is to understand the processes that govern the annual and interannual variability of the polar ice margins and to relate these to the large-scale behavior of the atmospheric and oceanic circulations. The objective of the mesoscale program is to understand the physical processes by which ocean, ice, and atmosphere interact in the region of the ice edge. The program scales are inextricably interrelated since many mesoscale processes, such as eddies, affect large-scale heat exchanges.

This document describes mesoscale programs for two distinct ice margins adjoining the Arctic Ocean: a deep water ice edge in the Fram Strait region of the Greenland Sea, and a continental shelf ice edge in the Bering Sea. A separate document (*Air-Sea-Ice Research Programs for the 1980s*) will describe the role of this mesoscale program within a comprehensive study of sea ice in the global weather and climate system.

Various mesoscale experiments with more limited objectives have been carried out in the MIZ, including BESEX (Kondratiev et al., 1975), MIZPAC (Paquette and Bourke, 1979), NORSEX (NORSEX, 1981a, b), MIZLANT (Newton and Piper, 1981), BERING-79 (Bauer and Martin, 1980) and BERING-81, east Greenland wave–ice experiments (Wadhams, 1979; Wadhams and Squire, 1980), drifting buoy programs (Vinje, 1977b, 1978) and YMER-80 (Ymer, 1981). The state of knowledge existing in early 1979 was summarized at the Monterey Seasonal Sea Ice Zone Symposium (Andersen et al., 1980). In October 1980 a workshop was held at Voss, Norway, to define the nature of the programs required for a concentrated study of the marginal ice zones of the Northern Hemisphere. The mesoscale program which was evolved, to be known as the Marginal Ice Zone Experiment (MIZEX), will last for several years and will involve a number of field experiments at different locations and seasons as well as a major modeling effort. The main program will take place in the North Atlantic and will emphasize the lateral and vertical heat and momentum exchanges in the air–ice–ocean system. The accompanying Bering Sea program will emphasize ice dynamics and deformation. Although in very different geographical areas, these experiments will share a common equipment pool and will be unified by a common modeling effort. The rest of this document describes the research strategy for the two experiments in turn, beginning with the Greenland Sea.

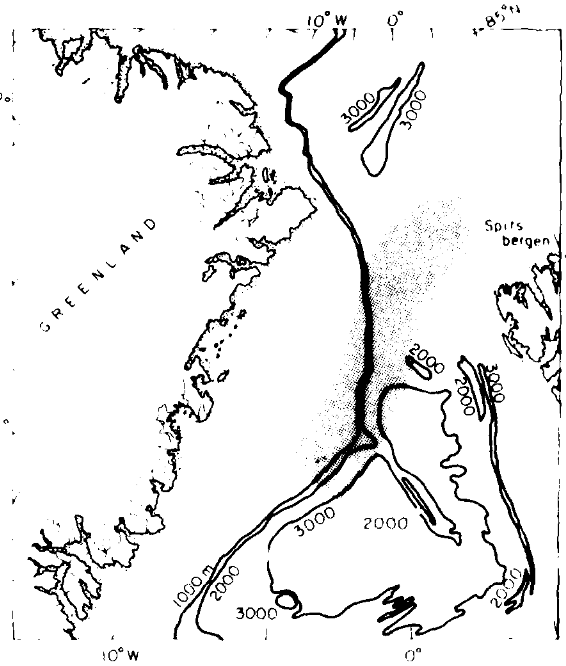

Figure 1. A possible area swept out by the experimental box in six weeks, assuming a mean advection rate of 10 cm s⁻¹.

2. THE GREENLAND SEA EXPERIMENT

2.1 Location and timing

We propose that the deep water mesoscale experiment be done in the Fram Strait off east Greenland. The two main reasons for proposing this area are:

1. It is a region of overwhelming importance for the exchange of water, heat and other quantities between the North Atlantic and Arctic Oceans.
2. It allows a natural continuation and expansion of existing programs such as NORSEX, MIZLANT, YMER-80, and drifting ice buoy programs.

The bathymetry of the region is shown in Figure 1 and the general circulation is schematically presented in Figure 2. Figure 3, from Vinje (1977a), shows the median and extreme ice edge limits for summer and winter months over a ten-year period, illustrating the range of interannual variability and the impossibility of specifying the deployment position exactly. Figure 4 (SCOR, 1979), covering a short period in spring, illustrates the high ice velocities which are attainable near the Fram Strait ice edge and shows that the downstream drift during the period of the experiment is likely to be large and to involve considerable shear between the extreme ice edge and the interior ice.

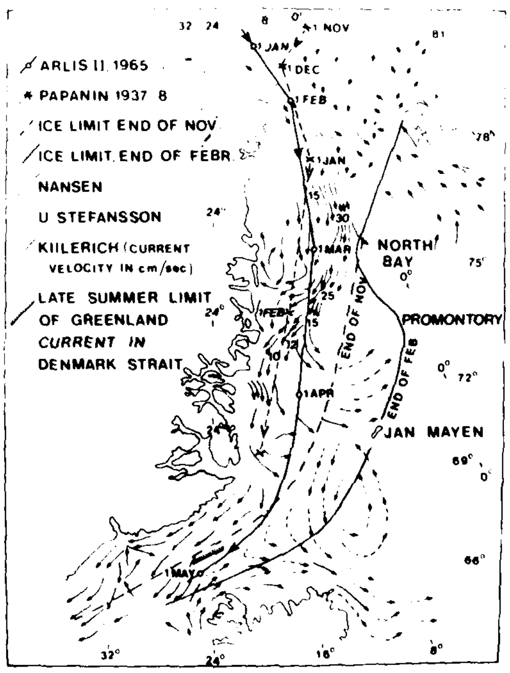

Figure 2. Late summer currents, average ice margins, and positions of two manned drifting stations at the end of each month. (After Einarsson, 1972.)

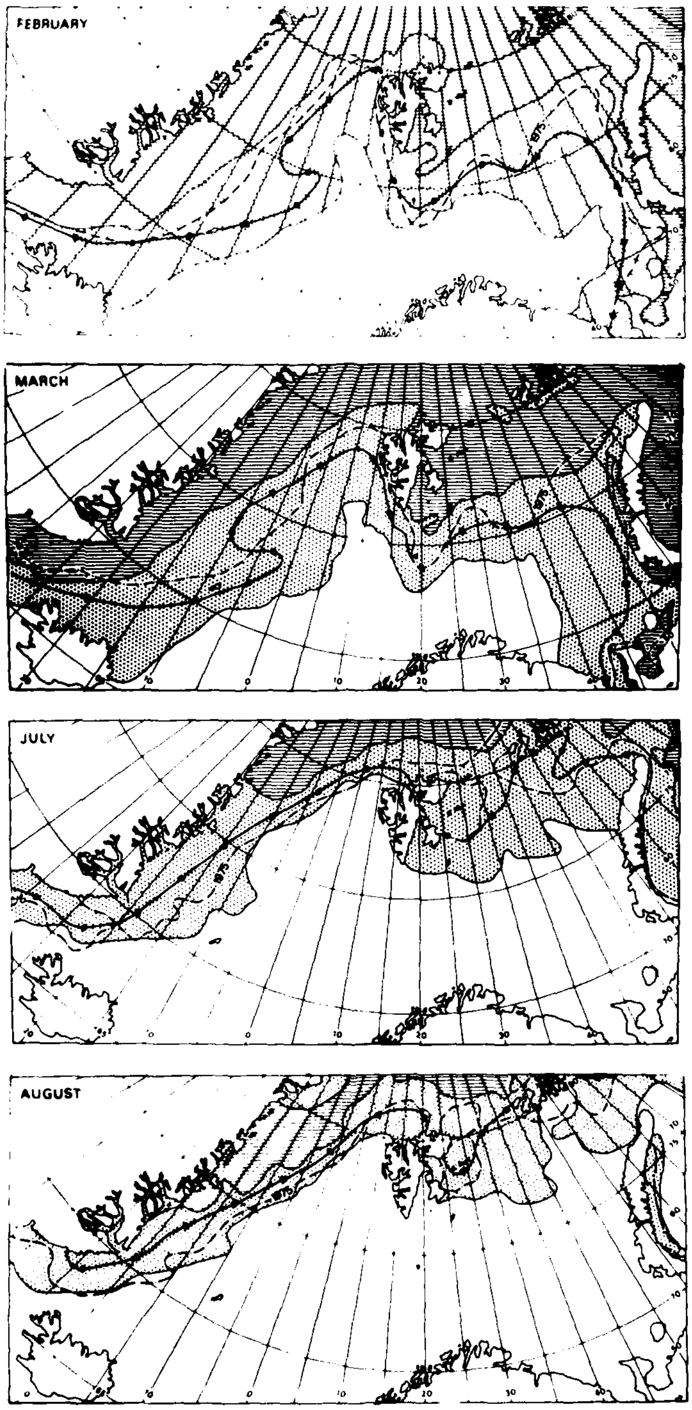

Figure 3. Mean and extreme sea ice limits at the end of each month for the years 1966–1974 (after Vinje, 1977a). The extreme range for $^1/_8$ sea ice cover is bounded by the dotted area, while the thick black line is the median limit for the decade and the dashed line is the 1975 limit.

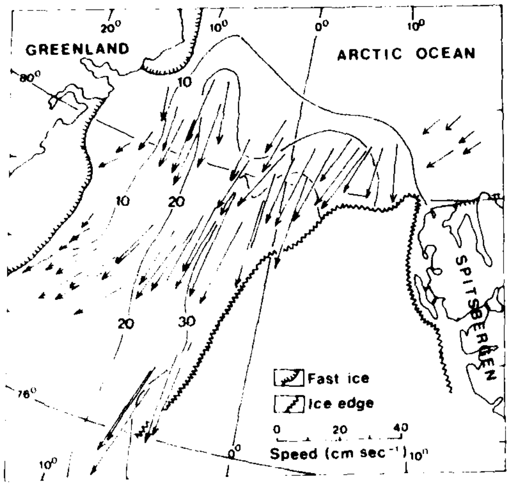

Figure 4. Drift observations from Landsat imagery, 21 April–7 May 1976 (after SCOR, 1979), contoured at 10 cm s⁻¹ intervals.

The Greenland Sea MIZEX requires at least two major field experiments, one during the summer period of ice melt and one during winter. We propose that the first experiment be a summer experiment and that it take place in 1983, to be followed by a winter experiment in 1985.

The initial deployment will take place within a box 200 km on a side enclosing equal areas of ice and open water. We choose this scale because it includes the scales of critical processes occurring within the MIZ. Long ocean swell penetrates the ice detectably for at least 100 km and can break up ice floes for tens of kilometers in from the edge; ice thickness and floe size characteristics differ radically from those of the interior ice for a distance of at least 100 km from the ice edge; ice-water eddies have diameters from 10 to 60 km; atmospheric boundary layer modification occurs within about 30 km of the ice edge; and large ice edge motions under off-ice winds affect the outermost 100 km.

The duration of each experiment will be about six weeks, not including ship and aircraft passage time. This length of time will allow the exposure of the experimental area to a variety of ice, atmospheric, and oceanic conditions. Several cyclones will likely pass through the area, causing both on-ice and off-ice winds. Further, this period will allow observations of frontal deformations; fine structure formation and decay; the location, definition and tracking of eddies; and perhaps up- and downwelling and along-ice jets.

The timing for the summer and winter experiments was determined through assessment of the times at which the most important atmospheric ice and oceanic processes occur. The conclusions are as follows:

Atmosphere	Strongest interactions	Dec-Apr
	Most quiescent period	Aug-Sept
Ice	Summer melt period	mid July-end Aug
	Most active winter growth	Dec-Mar
Upper ocean	Fully developed summer state	Aug
	Dynamic winter development	Jan-Feb
	Fully developed winter state	Mar
Acoustics	Most dynamic period	Aug-Sept
	Most quiescent period	Apr

From these and from logistical considerations, we decided that the optimum periods for each of the six-week experiments are:

Summer—mid-July to end of August (1983)
Winter—mid-February to end of March (1985)

2.2 Processes and research strategy

In this section we describe the air-ice-ocean processes which we believe to be important in the MIZ, and explain how the available platforms will be utilized to investigate them. For convenience the processes and measurement strategies are subdivided under five headings (atmospheric measurements, oceanography, ice, acoustics and remote sensing). *However, it must be understood that all of the processes are intimately connected by feedback and by cause-and-effect mechanisms so that no process stands alone.* Careful experimental design aided by initial modeling is therefore vital so that the crucial variables are measured at proper time and space scales.

2.2.1 Atmospheric measurements

There are two main reasons for making a complete set of meteorological measurements during the MIZ experiment. First, the wind stress on the ice and the surface energy budget are fundamental variables in many of the processes being investigated and so are also essential elements of any numerical model of the MIZ. Second, because air flowing across the ice-ocean boundary experiences an abrupt change in surface roughness, temperature, and moisture, MIZEX is a unique opportunity for studying boundary layer modification.

Meteorological measurements will be made both on the pack ice and over the ocean adjacent to the ice edge. The measurements at ice and ocean buoys deployed within the experimental area will include the standard meteorological variables—wind speed and direction, temperature, and humidity. In addition, a complete set of turbulence flux and radiation measurements at the ice camp and at a station off the ice will complement the standard meteorological observations.

The technology now exists for making these turbulence measurements in a polar, marine environment (e.g. Thorpe et al., 1973; Andreas and Paulson, 1979; Andreas et al., 1979). Therefore, because multiyear ice is such a stable platform, any turbulence measurements possible over land should also be possible at the manned drifting stations. Atmospheric turbulence measurements at sea will be more difficult than at the ice camp because of platform instability. Although turbulence transducers at the main ocean station can be identical to those at the ice camp, some method of preventing wave action from affecting the oceanic measurements will be necessary. Alternatively, all measurements could be made from a ship and the fluxes could be found with the inertial-dissipation method (Pond et al., 1971; Champagne et al., 1977).

Because ice motion in the marginal zone clearly responds to wind forcing on a synoptic scale, it is important to know the stress field throughout a region several hundred kilometers in diameter centered on the experimental area. This stress field can be obtained by buoy pressure measurements from a large-scale array. Banke et al. (1980) have recently shown, however, that the wind field is not enough for computing stress on ice; the drag coefficient depends strongly on the surface roughness. Consequently, ice roughness in the experimental area and over the stress array should be surveyed. Airborne laser profilometry (Hibler, 1975) seems to be the best method for such a large-scale survey.

The computation of heat fluxes using bulk aerodynamic formulae based on data collected by the ice buoys will depend on the success of the turbulence values of the bulk aerodynamic coefficients for sensible and latent heat over ice. The measurements of Thorpe et al. (1973) and Hicks and Martin (1972) range from 5×10^{-4} to 2.5×10^{-3}. The primary goal, then, of the turbulence measurements at the ice camp will be to measure the bulk transfer coefficients for sensible and latent heat over sea ice. Knowledge of the drag coefficient and of the bulk transfer coefficients for sensible and latent heat is better over the ocean (Garratt, 1977; Smith, 1980), and is considered adequate for MIZEX purposes.

The technique of measuring the stress using the eddy correlation method on data obtained from a gust probe mounted on an aircraft is particularly valuable in a MIZ experiment. The resulting large-scale averages of stress can be extrapolated to surface values. These will provide important data in the immediate ice edge areas inaccessible by other means. In addition, areal averages of ice stress integrate the effect of the ridges in the ice pack. These stress values may be significantly higher than point values, as shown in AIDJEX data. Using inexpensive, expendable airsondes, which measure pressure, temperature, dew point, and wind speed and direction, is another method of examining the boundary layer.

2.2.2 Oceanographic measurements

2.2.2.1 Introduction. Oceanic phenomena in the marginal ice zone, such as eddies, fronts and fine structure, convection, up- and downwelling, and melting and freezing, cause horizontal and vertical gradients of the oceanographic variables. These gradients lead to strong secondary horizontal and vertical circulations. Such circulations can critically affect the horizontal and vertical heat and momentum fluxes at the ice edge. The following action describes a program to study these exchanges with particular emphasis on ocean eddies.

2.2.2.2 Eddy properties and transport. At the marginal ice zone baroclinic instabilities and meanders controlled by topography generate eddies. Local, intensive curl of the wind stress may also generate eddies. Eddies in the ice edge region probably represent an important mechanism for heat transfer across the ice edge and front. They also cause acoustic propagation and scattering anomalies. Eddies observed in the Fram Strait and Greenland Sea MIZ are generally cyclonic and seem to develop in two ways; they may propagate outwards from the ice edge, as observed northwest of Svalbard in NORSEX (1981b) or they may fold back and transport warm water deep inside the ice-covered region, as observed in Fram Strait (Wadhams et al., 1979) and on YMER-80. The ice cover makes it possible to detect the surface effect of a MIZ eddy since the ice can act as a tracer for the polar water under moderate wind conditions.

In the region north of Svalbard, SAR imagery and in situ observations during summer (NORSEX, 1981b) indicated the presence of eddies with diameters of 5 to 10 km, which compares well with the baroclinic radius of deformation. The vertical scale was 100–150 m, while the mixed layer depth was of the order of 20 m. During winter, when convection causes the mixed layer to deepen to 100 m, one might expect that the horizontal scale of the eddies will increase by a factor of two or three.

Eddies along the ice edge in the Fram Strait and further south in the Greenland Sea have also been seen in satellite imagery (Vinje, 1977b) and from in situ observation (Wadhams et al., 1979).

An eddy investigation requires real time analysis of observations from microwave remote sensing and in situ observation. When an eddy starts to form, the eddy investigation requires a dedicated ship. This would have to be an icebreaker or ice-strengthened ship, since the eddy often carries an ice cover with it. A dense grid of CTD stations is required, covering the entire eddy and its environs. Lagrangian devices drifting at different levels should be deployed, both on the ice and in the open water. The eddy should be tracked until it dissipates or propagates out of the experimental area. During the eddy tracking remote sensing observations at regular time intervals are needed.

2.2.2.3 Ocean fronts. Several frontal systems are present in the experimental region. In the northern part of Fram Strait, the cold, low salinity arctic surface layer and warmer and higher salinity water of Atlantic origin converge, thereby causing a front off the ice edge. During summer the density field of this frontal zone is primarily determined by the salinity due to the melting of ice. The position of this front appears to be partially or perhaps primarily controlled by the position of the ice edge and we therefore call this an "ice edge controlled front." Farther south this front continues as a strong permanent feature separating the East Greenland Current (EGC) polar water from the warmer, more saline Greenland Sea water. The EGC polar water forms a wedge-shaped mass against the coast, with the inclination of the front being about 1 in 1000 and its surface trace corresponding roughly with the summer ice edge. There is considerable velocity shear across the front. In the northern Greenland Sea an "upwelling front" has also been observed (Buckley et al., 1979) which is transient in nature.

An experimental study of the ice edge front consists of traversing the experimental area with lines of closely spaced CTD stations. The lines will extend into the ice as far and as often as practicable. It should be noted that this technique is a necessary adjunct also to characterizing water structures associated with eddies and ice streamers near the ice edge as well as isolated eddies. Because of the dynamic nature of the MIZ, remote sensing of the surface and of ice will be indispensable because it can allow real-time control of the experiment. This requires that real-time processing and preliminary analysis be done on the observations performed by the aircraft, drifting buoys, and ships so that the CTD sections and drifting buoys can be placed correctly. If a submarine is available, sections should be run across the ice edge at different depths, sampling with a velocimeter or, preferably, with a specially mounted CTD system. By steering constant courses and recording positions, the horizontal current shear can also be estimated.

2.2.2.4 Tidal and inertial oscillations. Near-inertial and baroclinic tidal motions in an interacting icefield can produce appreciable convergences and divergences in the ice pack (e.g., Hibler et al., 1974). Periodic compression of new ice alternates with the formation of ice and brine in open water under freezing conditions. In summer the ice floes respond strongly to transient winds, producing inertial motions (McPhee, 1978); in winter the ice pack is more compact and not so responsive (Thorndike and Colony, 1980). More generally, the region of significant tidal/inertial response can be quite narrow, and relatively intense where the shelf break (baroclinic tidal generation zone) and the MIZ are nearly coincident.

To study such motions requires the use of directional arrays, and the monitoring should ideally be continued for the duration of MIZEX. Sampling should be done through the surface layer and pycnocline (upper 200 m or so) at least hourly and at three to five locations on a scale of 5-10 km. It should extend from 5-10 km inside the ice to 5-10 km outside. The instruments, measuring horizontal velocity as well as temperature and salinity, will be suspended from ice floes; this raises the complication that quasi-Lagrangian rather than Eulerian measurements are being made, requiring care in interpretation.

2.2.2.5 Upwelling. Changes in wind stress across the ice edge can introduce upwelling or downwelling. These changes can occur due to the ice interaction or to modifications to the atmospheric boundary layer stability or drag coefficient. Evidence of ice edge upwelling was obtained in an investigation north of Svalbard in December 1977 (Buckley et al., 1979). Upwelling is a transient phenomenon and needs to be detected during the field program before an intensive investigation is carried out. The scale of the upwelling is a zone up to 10 km wide stretching seaward from the ice edge. The duration of the upwelling is dependent on the wind persistence. During winter, when heavier water is upwelled, it is cooled at the surface; when wind forcing relaxes, downward convection starts and may lead to intermediate water formation.

An upwelling program should have the same mapping plan as an eddy or front program. First, zones of upwelling must be detected. Thereafter, frequent cross sections along the ice edge must be sampled and supported by aircraft remote sensing observations. Lagrangian surface and subsurface drifters must be deployed in a proper grid. It is important to carry out three-dimensional mapping of the upwelling region in order to be able to discriminate among an upwelling event, frontal meanders, and an eddy boundary, and also to establish the relationships between these related phenomena.

2.2.2.6 Small scale processes. Below the scales of eddies and fronts a variety of mechanisms exist to transfer heat and salt. These include breaking internal waves and convection—both classic convection caused by overturning at the surface and double-diffusive convection caused by the warm underlying Atlantic water. The latter type of convection manifests itself as fine structure. Our concern with these phenomena is due to the fact that each of them, regardless of scale, contributes to the overall heat flux and ice melting rate.

The surface mixed layer during summer in the ice edge region is shallow with a strong stratification. Observations from the beginning of winter (December) show that convection has increased the mixed layer thickness to 100 m or more in the ice edge region. This convection may be especially intense because the rapidly growing new ice can be swept away from the zone by the wind, thereby allowing more ice to form with a high degree of salt rejection. The same phenomenon will also take place in leads and polynyas.

In areas where fronts are generated due to the presence of ice, fine structure is generally found close to the ice edge. The presence of such fine structure indicates that small scale transfer of heat and salt is taking place. The internal wave field can be anticipated to be intense and complicated in the MIZ, which may be both a source and sink for internal waves. For mixing dynamics and acoustic considerations, it is important to characterize the directional spectra of internal wave energy, and the horizontal and vertical energy fluxes into and out of the MIZ.

The use of ice as a platform for studying these small scale processes is attractive because of the stability it provides for high-resolution data records.

2.2.2.7 Surface waves. Surface waves are a major factor determining the structure of the ice in the MIZ. The longer swells from storms in the Greenland Sea can penetrate for over 100 km into the ice (Wadhams, 1978a) and can break up floes through flexure for tens of kilometers. As they penetrate, the waves decay exponentially through scattering by floes and other mechanisms (Squire and Moore, 1980), with a decay coefficient that varies approximately as frequency squared, so that the shorter waves are damped more quickly. The result is a floe size distribution in which the maximum floe size increases with distance into the pack. Surface waves also affect ice dynamics through the radiation pressure exerted on floes by a wave which suffers partial reflection at a floe edge. Theories now exist to predict the reflection coefficient, and hence the radiation pressure, for a floe of given dimensions in a given wave field. The radiation pressure due to incident waves always acts to keep the ice edge compact (it is a compressive body force on any area element of the icefield), but if any major openings exist within the icefield, a local fetch-limited sea may generate its own downwind radiation pressure on floes; this is the basis of one theory for the generation of ice edge bands by an off-ice wind.

Experiments to study waves in the MIZ must take account of the directional nature of the wave field. A directional wave buoy outside the pack monitors incident and reflected wave energy while telemetering accelerometer buoys are needed to monitor both the upwind and downwind ends of the band. Airborne SAR can detect the directional wave spectrum in open water and in icefields, and can be used to monitor wave refraction across an ice edge; this refraction may be due in part to velocity shear, but this can be determined by surface current observations so that the pure refraction (if any) associated with an ice edge can be seen.

2.2.3 Ice

2.2.3.1 Ice dynamics. 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 and inertial forces.

Internal ice stress. 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.

Measurement of the mesoscale sea ice kinematics together with monitoring of the acceleration of selected floes can greatly aid in determining the nature of the ice rheology near the ice edge. Through analysis of this deformation field in conjunction with observed wind and current fields, we can determine if such rectification effects occur. In addition, determination of ice floe trajectories allows the calculation of the amount of tidal and inertial energy in the velocity field; also the presence of ice jets can be verified or disproved. Second, data from horizontally mounted accelerometers may be used to determine mean free floe paths and to possibly correlate these path lengths with the mean ice velocity field, compactness and floe size distributions. These data will be particularly important in verification of localized models.

Inertial effects. The combination in the MIZ of small floe size and the unconsolidated nature of the ice allows significant kinetic energy to be stored in inertial oscillations of the ice and oceanic boundary layer. While the trajectories of adjacent floes may be initially coherent, floe collisions could both destroy this coherence and damp the oscillations. Under rapid growth conditions this random bumping may be reduced by ice formation. Analysis of the mesoscale kinematics can determine the coherence, damping and propagation of inertial oscillations. These measurements can be combined with CTD and current time series measurements at several locations to analyze the boundary layer characteristics.

Experimental design. To carry out a kinematic study relevant to ice dynamics, we propose to deploy an array of about six all-weather microwave transponders in a 30-km-square region inside the ice edge. Accelerometers will be located at several transponder sites. Positions of these transponders relative to a manned ice station will be remotely monitored at half-hour intervals with <10 m accuracy. The area enclosed by the array will be covered by aerial photography or SAR imagery at approximately two-day intervals and, ideally, underflown by a grid of submarine sonar profiles. Transponders should be marked in such a way that they show up on SAR and aerial photographic imagery. The array will be redeployed if it becomes excessively deformed. This mesoscale array will be embedded in a larger scale array of Argos buoys at a nominal spacing of about 100 km. While not as accurately positioned as the transponders, these buoys will provide an effective monitoring of the outer boundaries of the experimental area.

2.2.3.2 Ice structure and thermodynamics. In the summer the MIZ ice ablates more rapidly than the interior ice for the following reasons. First, the open ocean acts as a large heat source. Second, open water within the pack ice absorbs solar radiation which then increases both the bottom and lateral melt rates. Third, although the lateral area of a floe may be small when compared with the bottom area, the loss of ice due to collisions which fracture small ice pieces from the floe edge may yield considerable ablation. Finally, the absence of deep pressure ridge keels in the MIZ indicates that rapid erosion and break-up of ice keels takes place.

In the winter, the presence of frazil and pancake ice in the MIZ represents the major difference from the interior arctic ice. Both inside and outside the main ice edge, ice growth begins as a soup of suspended ice crystals called frazil ice. Then when the suspension reaches a critical density which is a function of the water temperature, salinity, and the degree of agitation, the ice coalesces into small pancakes about 1 m across. The effective ice thickness (ice volume per unit sea surface area) can be several tenths of a meter, but the vertical heat flux is scarcely reduced so that growth rate and associated brine rejection are still very large. Ice growth rates of up to 0.1 m hr^{-1} can be maintained for long periods of time as the young ice is swept away by the wind (Martin, 1981); the brine rejected causes intense convection of the surface water.

To measure the important elements of small scale heat transport involved in ice ablation and growth requires a continuous program to be undertaken from the drifting ice station. One component of this will be the direct measurement of vertical and lateral ablation growth by standard probe and surveying methods and of the disintegration of ice keels by divers. A second component, based on laboratory experiments (Josberger and Martin, 1981) and existing studies in NORSEX (Gebhart and Andunson, 1980) will be measurements of the following parameters:

- transient internal ice temperature fields, with multiple arrays of thermocouples frozen into the ice;
- fast-response temperature and velocimeter traverses and salinity sampling in leads and under the ice;
- air-ice and water-ice interface temperatures

• solar and diffuse sky radiation fluxes;
• thermal diffusivity of the ice;
• radiation absorption into the ice and underlying water.

In addition, an attempt should be made to deploy an optical visualization system under the ice to detect the convective motions in the water.

2.2.3.3 Ice topography. It is of the greatest importance to know the ice thickness characteristics across the marginal ice zone. All thermodynamic and dynamic calculations for icefields depend on knowledge of the ice thickness characteristics. The only way to obtain this knowledge reliably is by submarine sonar profiling. Manual methods (hole drilling) are prohibitively laborious and do not yield a statistically valid sample, while other surface sensing methods such as impulse radar sounding have not been developed to the point where they work reliably for sea ice. The only above-surface method of real usefulness is airborne laser profiling (Hibler, 1975): it is useful in itself for yielding top surface roughness for boundary layer analysis, and as a result of comparative laser-sonar studies (e.g. Wadhams, 1981a) it is now possible to infer a great deal about the ice thickness distribution from the results of laser profiling.

Ideally, a naval submarine should be deployed within the experimental area. It would be equipped with an upward-looking sonar, a sidescan sonar to give information on the spatial structure of bottom roughness (Wadhams, 1978b) and a sound velocity or conductivity temperature sensor to record water structure across the polar front. It would run a grid of profiling lines across the experimental area, with special concentration on the area of the ice deformation experiment where perhaps its track can be guided by transponders inserted through the ice. On a larger scale it would be of tremendous benefit to have a series of sonar transects across the entire width of the East Greenland pack ice at various latitudes, with a connecting longitudinal line, to assess the downstream progression of ice characteristics; this need not take place simultaneously with the mesoscale experiment. If a naval submarine is unavailable, efforts should be made to deploy a submersible with sufficient endurance to at least profile a grid under the ice deformation experiment. Airborne laser profiling of the same tracks as the submarine is highly desirable.

2.2.3.4 Small scale ice edge effects. The extreme outer edge of the ice is most subject to the environmental stress of the open sea, especially to the effect of waves, and responds most readily to transient forcing of any kind. As a result a number of characteristic ice edge phenomena have been observed, none of which has been fully explained, but all of which are important to the maintenance of ice edge position and to lateral exchanges of heat and mass. They include:

• the formation of a band or a series of bands parallel to the ice edge, each band being 0.1-1 km in width and up to 10 km in length;
• the stripping away of ice from the edge to form streamers perpendicular to the ice edge and a few hundred meters apart;
• a general diffusion of the ice edge under an off-ice wind, with formation of whirl- or eddy-shaped patterns of ice drift;
• the drawing away of ice into long wavelength meanders and into eddies formed by baroclinic instability of the ice edge front.

Many mechanisms have been proposed for band and streamer production, including atmospheric roll vortices, drag reduction through bottom melting, the conflicting radiation pressures of an off-ice fetch-limited sea and an incoming swell, nonlinear ice interaction in the presence of time-varying wind fields, interaction with rotary tides, and interaction with internal wave fields.

Experiments to study these phenomena require dedicated use of a ship for tracking during the lifetime of the feature under study. A number of floes are selected to define the feature and instrumented with radar transponders, telemetering ice wave accelerometers and compasses, and flags for aerial recognition. The floe thickness and bottom characteristics should be measured (using divers for the bottom) and directional wave buoys are placed nearby to define the wave field. A companion experiment, not necessarily to be done at the same time, involves total instrumentation of an isolated small floe, including anemometer and current meter string, to determine whether McPhee's (1981) drag laws for free ice drift need to be modified for small floes at the ice edge.

2.2.4 Acoustics

The marginal ice zone is one of the most variable environments encountered by an underwater acoustician. Among the potential complexities are variations in the sound speed profile (SSP) caused by oceanic fronts and eddies and the character of the ice/water surface near the MIZ. The SSP variations have a dominant effect on long range, low frequency sound propagation for passive sonar systems while the ice/water surface introduces scattering phenomena at higher frequencies in the operation of active systems. Moreover, ice activity and breaking waves lead to ambient noise which is distributed across all frequency bands. The important point is that the complex oceanic ice and atmospheric processes at the MIZ strongly influence the sound propagation, so it is imperative that acoustic experiments be done simultaneously with the monitoring of these processes during MIZEX. A further objective is to determine if there is sufficient stability in the acoustic field for it to be a useful synoptic measure of the MIZ processes. The SSP is strongly modulated by processes in the upper ocean and this influences the acoustic propagation in three ways.

2.2.4.1 Multipath. The multipath structure, or time spreading, is determined by the character of both the spatial and time-dependent SSP in the MIZ. For example, some of the recent NORSEX and Naval Research Laboratory data indicate local surface ducts. Depending upon their thickness and gradient relative to "cut off" criteria, these ducts can support low-loss near-surface propagation modes. A converse to this is that the multipath structure is governed by the oceanic environment, so it is important to determine if this multipath can be "inverted" to "measure" the environment.

2.2.4.2 Fluctuations. Dynamical changes in the oceanic environment alter the multipath continuously; in particular, very small changes in the resulting SSP affect the relative phasing of these paths significantly. This leads to fluctuations, or frequency spreading of transmitted signals through the MIZ.

2.2.4.3 Coherence. In uniformly stratified oceanic environments acoustic wavefronts are very coherent horizontally. This coherence is an important parameter for arrays in the detection and localization of sources of acoustic radiation. Lateral variations in this stratification, such as those which occur near the MIZ, reduce this coherence and degrade the performance of an array system. Since arrays are the primary means of obtaining directional information for both scientific investigation and sonar systems, it is important to determine their effectiveness near the MIZ.

2.2.4.4 Experimental design. The basic experimental arrangement consists of a source ship outside the ice edge and a receiving array inside deployed from the manned drifting station; additional sonobuoys will be inserted through the ice. Measurements can then be made of:

- propagation (including forward scattering) under the ice
- fluctuation statistics and temporal scales of signals received across the MIZ
- the coherence of transmitted sound fields
- directional ambient noise spectra
- acoustics signature and noise generation mechanism of specific noise sources such as ice fracture, collisions or rafting
- reverberation (backscattering) around the MIZ, including multifrequency backscatter to monitor biomass.

In addition, experiments can be carried out to assess whether there are any acoustic paths stable enough to determine the relevant dynamic scales in the MIZ, and to determine the minimum number of acoustic channels to achieve a reliable propagation condition. Sidescan and upward-looking sonar profiling to determine ice bottom roughness have already been described, and, if the MIZ lies over a sheif, bottom refraction and reflection experiments should be done using sources deployed from the manned drifting station to determine the nature of the sea bed from an acoustic point of view.

2.2.5 Remote sensing

2.2.5.1 Aircraft remote sensing. Aircraft remote sensing is an essential part of all mesoscale marginal ice zone experiments. It is the only way to obtain mesoscale synoptic information at frequent enough time intervals and at sufficiently high resolution of crucial sea ice and ocean parameters, i.e. ice concentration and ocean wave spectra. In this regard, it is fortunate that MIZEX was preceded by a decade of intensive sea ice and ocean remote sensing experiments—AIDJEX, BESEX, and NORSEX—in which active and passive microwave observational techniques were explored and improved. During BESEX (Gloersen et al., 1975) and AIDJEX (Campbell et al., 1978) sequential microwave remote sensing aircraft flights were used during various seasons and weather conditions to measure ice concentration over mesoscale areas as large as 2×10^4 km^2 at intervals of several days. During the NORSEX 1979 experiment (NORSEX, 1981b), sequential imaging radar mapping by aircraft provided mesoscale high resolution data on the structure of the MIZ and on ocean eddies and waves.

The success of MIZEX depends on obtaining sufficient flight time with the correct mix of aircraft and sensors so that the mesoscale experiment areas can be overflown every 2-3 days during the 6-8 week period of each experiment. A variety of aircraft are needed. High altitude aircraft carrying imaging radars are needed to acquire sequential radar images of the entire experiment area. Low level aircraft flights with passive microwave sen-

Table 1. Key sea ice and ocean parameters and sensors.

1 = prime sensor; 2 = auxiliary sensor

	Imaging radar	*Radar altimeter*	*Passive microwave*	*Scatter-ometer*	*Laser profilometer*	*Gust probe*	*Photog-raphy*	*Infrared imager*	*Infrared profiler*	*AXBT*
Ice concentration	2	2	1	—	—	—	2	—	—	—
Ice type	2	—	1	1	—	—	2	—	—	—
Ice roughness	2	—	—	2	1	—	—	—	—	—
Surface wind (over ice)	—	—	—	—	—	1	—	—	—	—
Surface wind (over water)	—	1	—	1	—	1	—	—	—	—
Ocean waves	1	1	—	1	2	—	—	—	—	—
Sea surface temp.	—	—	1	—	—	—	—	1	1	—
Ocean temp. profiles	—	—	—	—	—	—	—	—	—	1

sors, scatterometers, laser profilometers, and photography are necessary to acquire data on a variety of sea ice and ocean parameters at selected locations within the experiment area. Table 1 lists the key parameters to be observed and the sensors that will be used to observe them.

2.2.5.2. Microwave properties of sea ice. Surface-based measurements of microwave properties of sea ice (e.g. emissivities, scattering coefficients, relative permittivity) are needed for quantitative interpretation of aircraft and satellite microwave remote sensing. These properties will be measured from an icebreaker or drifting ice station to check the validity of the present estimates at different seasons and in different geographical areas.

There is also an indication that the thickness of newly formed ice may be estimated from microwave measurements (NORSEX 1981b). Confirmation of this also needs extensive surface-based study in regions of ice formation (e.g. in polynyas and at the ice edge).

2.3 A scheme for the experiment

The summer experiment is described in this section. The winter experiment will be designed similarly, with modifications dependent on the results of this summer program and the Bering Sea winter experiments.

2.3.1 Platforms required

To carry out a six-week program with maximum efficiency, and to successfully accomplish all of the measurements required, the following platforms are needed.

1. *An icebreaker* equipped with two helicopters, to work continuously within the ice-covered zone of the experimental area, carrying out CTD mapping and deploying and retrieving buoy arrays. It will also be a platform for one CODAR (Coastal Ocean Dynamics Radar) unit, and for surface microwave measurements of sea ice.

2. *A drifting ice station* to be set up within the box at the beginning of the experiment and to remain in place throughout the six weeks unless absolute necessity requires relocation. It will serve as a base for ice dynamics, ice structure, microwave, and thermodynamics measurements, and for oceanic observations which require duration rather than spatial coverage. It will be a convenient base for many kinds of chemical and biological sampling. The optimum type of drifting station is a ship equipped with a helicopter, possibly a sealer-icebreaker of the *Polarsirkel* type, since this provides an excellent living and working platform independent of resupply. Further, this station could serve as the coordinating center for the experiment, since there will be several ships and aircraft involved in simultaneous operations.

3. *An ice-strengthened ship* to carry out work along the ice edge itself, concentrating on ice and ocean processes at the very edge and doing CTD mapping.

4. *A research ship* without ice strengthening to carry out the primary CTD mapping in open water, to deploy and retrieve buoys, and to act as source ship for the acoustic experiments.

5. *Submarine.* If this is a naval submarine, it will carry out sonar profiling of the ice underside,

together with sound velocity profiling across fronts and, if suitably adapted, XBT or CTD measurements. If a submersible is available, it will carry out the same tasks but in a more specific way, operating, for instance, in concert with parties from the drifting station so that simultaneous studies of the ice underside, topside and structure can be made. For a naval submarine it is likely that no liaison in the field can take place between the submarine and the surface vessels, and that the results will be subject to pre-processing to remove sensitive information before declassification.

6. *Aircraft.* The following remote sensing program from aircraft is required to fulfill the needs of the mesoscale program.

a. SAR mapping of the experimental area every 3 days during the six-week period. When special events occur, e.g. a storm, mapping frequency should be increased to daily.

b. Passive and active microwave data to be obtained from the same aircraft as SAR (in profiling and imaging mode) and infrared/photography/laser profiles and if possible AXBTs. This should be done under different environmental conditions and during special events such as storms.

c. A combined meteorological and remote sensing aircraft fitted with a gust probe for wind stress measurement and active and passive microwave sensors for measurement of ocean and ice characteristics. Wind stress measurement is required at least every 3 days and more frequently during cyclone passages.

7. *Satellites.* The high-resolution visible and infrared imagery from the forthcoming Landsat and NOAA satellites will provide useful correlative data for MIZEX when weather permits. More valuable in the field will be real-time imagery from Tiros-N and Nimbus satellites received on board to give the instantaneous position and shape of the ice edge. Regarding microwave imagery, which would be of the greatest value, the Nimbus-7 SMMR may have ceased to function by 1983 and the next available sensor will be the DMSP-SSMI (Satellite Scanning Microwave Instrument), due for launch in early 1984.

8. *Buoys.* The satellite-tracked or telemetering unmanned buoy is a highly cost-effective means of collecting data. Such buoys will play a vital part in the large-scale monitoring program that will be part of MIZEX. Their use in the mesoscale program is described in the next section.

2.3.2 Design of the array

The ice dynamics experiment essentially consists of an ice motion monitoring program fixed in a

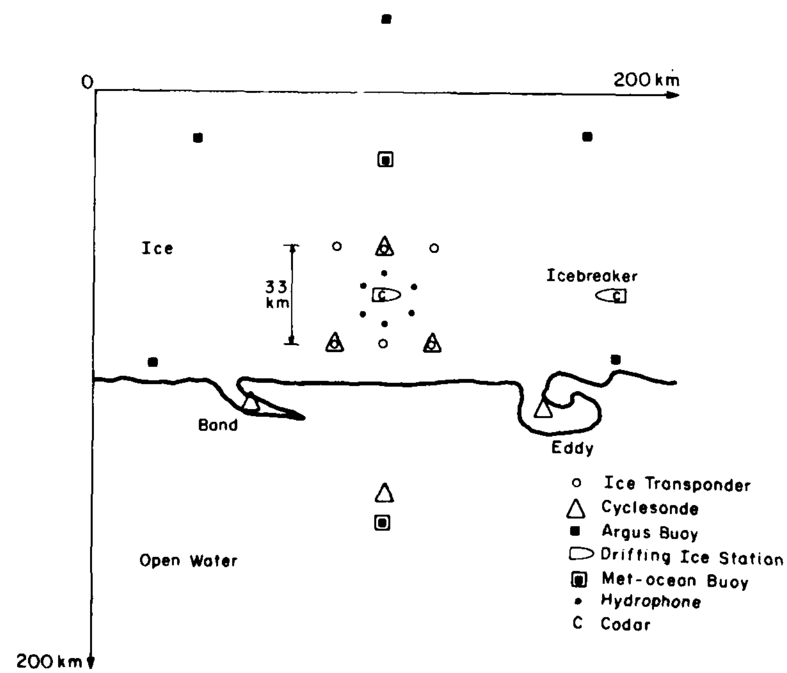

Figure 5. The ice dynamics experiment and other arrays and buoys.

Table 2. Breakdown 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 three Cyclesondes	3
		Help ice-strengthened ship in heavy ice conditions	Up to 6
		Microwave properties of sea ice and CODAR	6
Drifting ship in ice	1	Ice deformation and dynamics	
		Ice structure studies	
		Ice thermodynamics	42
		Cyclesonde deployment and retrieval	
		Hydrophone deployment and retrieval	
		Microwave properties of sea ice and CODAR	
Ice-strengthened ship		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
Open water ship		Synoptic CTD mapping in open ocean	21
		Eddy CTD mapping—fronts and upwelling	12
		Deploy and retrieve two met-ocean arrays	4
		Acoustic source	5
Submarine		Sonar profiling—20 transects with longitudinal ties	10 for naval
		Sound velocity profiling across fronts	20 for sub-
		XBTs, CTD profiling across fronts	mersible
		Small-scale ice underside study (submersible only)	5
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

Lagrangian grid moving with the ice plus several mapping missions. The ice motion will be measured with about a 5- to 10-m accuracy in a 30-km-diameter array using microwave transponders. The array will be established around the drifting ice station, on which positions will be automatically recorded. At three of the transponder sites Cyclesondes will be deployed to remotely monitor upper ocean salinity, temperature, and current profiles. In addition, recording accelerometers will be placed at at least three transponder sites. An Argos buoy array with a position accuracy of 200 to 400 m will be deployed at radial distances of about 100 km. The arrangement of the grid is shown in Figure 5.

Valuable supplementary data to the position measurements come from photographic and/or SAR coverage obtained primarily from aircraft. However, as a back-up, a helicopter can be used, which could combine photographic flights with maintenance of the transponder array.

Figure 5 also shows what other instrumental arrays can be expected to be in use in the ice or ocean at any given moment.

Argos buoys are installed at 100-km intervals throughout the ice-covered region of the box and along the ice edge. Since differential ice drift will cause the buoy array to become heavily deformed during the experiment, some recoveries and/or further deployments may be necessary during the six weeks. The buoys record position, air temperature, and surface pressure, and can be installed by parachute.

Met-ocean buoys make simultaneous meteorological and oceanic measurements at a single location. Buoys are employed both in the ice and in open water. The buoy in open water is moored and has a string of current meters and thermographs as well as atmospheric sensors. This buoy will be relocated following the movement of the ice. The buoy in the ice is installed through a floe and drifts with the pack, making the same measurements. The open sea buoy can be combined with a directional (pitch-roll) wave buoy to continuously monitor the incoming directional wave spectrum; a second pitch-roll buoy would be installed close to the ice edge by one of the ships for airborne SAR wave experiments only. Three Cyclesondes are installed through ice floes by helicopter from the drifting ice station, coincident with three elements of the ice strain array. Two Cyclesondes are installed in eddies or streamers or at the extreme ice edge. One is moored outside the ice edge, possibly connected to the open-sea met-ocean buoy.

Hydrophones for the acoustic experiments are installed 5 to 10 km from the drifting ice station. Six are required and they remain in place throughout the experiment.

CODAR is a radar system used to sense surface current shear between the ice and the open water. It operates on a 50-km baseline and has power requirements in the kW range. *If CODAR is to be used, it is only feasible to install the two CODAR elements on the drifting manned station and on one of the other icebreaking ships, and to carry out occasional experiments when the two ships are in the correct relative positions (i.e., on a line parallel to the ice edge).*

In addition, surface drifters and drogues can be deployed as part of the open sea program, and it would be valuable to deploy about 10 Swallow floats at different depths just outside the ice edge.

Table 2 summarizes the breakdown of work commitments among the various platforms.

3. THE BERING SEA EXPERIMENT

3.1 Introduction

The Bering Sea ice cover has a winter maximum areal extent that covers nearly the entire Bering Sea continental shelf (Fig. 6). In the summer the region is ice-free. Because the Bering shelf is the site of a major international fishery, a region slated for offshore petroleum development, the principal habitat for several large populations of marine mammals and seabirds, and of growing importance as a transportation route to western arctic waters, there exists a need to understand the Bering Sea MIZ properties.

While Bering Sea MIZ processes have much in common with the Greenland Sea MIZ, there are several important regional differences. First, the Bering Sea shelf has depths between about 20 and 150 m, while the Greenland Sea MIZ overlies oceanic depths. Second, ocean currents have only a small effect on the Bering Sea MIZ, while the East Greenland ice is strongly coupled both to the East Greenland Current and to the breakdown of this current into eddies. Third, while much of the Greenland Sea ice cover is multiyear ice which is advected into the region from the north, virtually all of the Bering Sea ice is first-year ice formed south of the Bering Strait. *Despite these differences, the two MIZs have many common features, which we discuss below.*

In the following sections we first summarize the atmospheric, oceanic, and sea ice behavior in the Bering Sea. We then discuss two specific field experiments, one aimed at understanding the ice deformation processes, the other at understanding regions of high ice production. Because many of the research tools and techniques described in Section 2.2 will be common to both the Greenland and Bering MIZs, the present section concentrates on a description of the field experiments.

3.2 Background

3.2.1 Atmospheric and oceanic behavior

The atmosphere provides the driving force for the most obvious MIZ processes. The predominant winter weather over the Bering Sea consists of cold northeasterly winds driven by the Aleutian low pressure system to the south or southeast and the Siberian high pressure system to the northwest (Kondratiev et al., 1975; Overland, 1980). During the November–February ice growth period, the cold northeasterly winds dominate with approximately twice-monthly interruptions by warm southerly winds caused by cyclones moving eastward along the Aleutian Islands. Then from March to June, the ice pack decays completely due to increased frequency of storms and warm southerly winds.

Oceanographic conditions in the Bering MIZ are uncertain. Most of the oceanographic data taken on the Bering Sea shelf are from summer, while most winter data are only from the southeastern Bering Sea shelf (Hood and Calder, 1980). Winter data from other areas such as around St. Lawrence and St. Matthew Islands have been taken within the past one or two years, but have not yet been fully analyzed.

With regard to ocean currents, the data from the southeastern Bering Sea shelf show that the mean currents are weak and that the diurnal and semi-diurnal tidal currents dominate the kinetic-energy spectrum. For the entire Bering Sea shelf, the most important feature is the mean annual Sverdrup flow through the Bering Strait; this

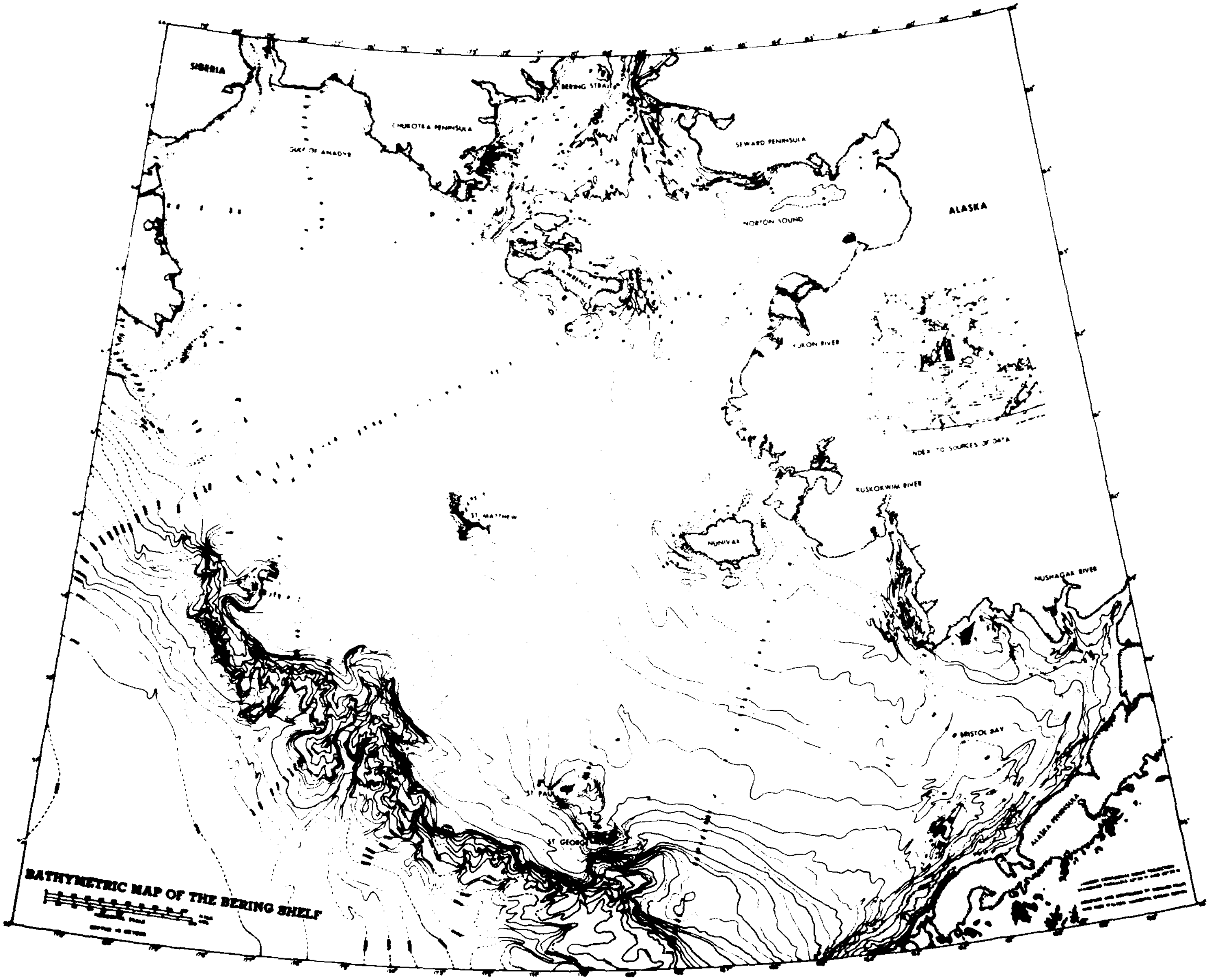

Figure 6. Bathymetric and location chart for the Bering Sea shelf. The two major polynyas are south of St. Lawrence Island and southwest of the Seward Peninsula.

feature is fed by the weak Alaskan Coastal Current, which appears to persist throughout the winter. In general, however, we expect that the mean flows over the breadth of the shelf will be weak, with most of the current energy at tidal periods.

With regard to salinity and temperature structure, preliminary analysis by Muench (unpublished) of mid-winter 1981 data shows that the water under the winter ice edge was two-layered, with cold, low-salinity water overlying warmer, more saline water. North and south of this feature, the water was vertically homogeneous. Coincidence of the ice edge with this prominent hydrographic feature suggests that they are physically related.

3.2.2 Sea ice behavior

The behavior of the Bering Sea ice divides into three phases:

1. Winter growth: December–February
2. Maximum extent: March
3. Spring decay: April–June

Beginning in early winter, new ice forms in northern Bering regions such as the Gulf of Anadyr, on the south side of St. Lawrence Island, and in northeastern Norton Sound. The predominantly cold, northeast winds then advect the ice southeastward away from these coasts, forming polynyas with very high ice production rates. As we describe further below, the southward ice advection from these polynyas plays an important role in the advance and maintenance of the ice edge position.

As the air temperature rises during March–June, ice production ceases and open water appears in the polynyas. At the same time, the southern ice edge position remains approximately constant. This again supports the idea that ice is generated in the north and consumed in the south; when the ice generation sites cease to produce ice, they give way to increasing areas of open water. As decay progresses, the pack degenerates from a continuous cover to a few large collections of floes called "ice massifs" which move about and slowly decay southwest of St. Lawrence Island.

The most important feature of the winter Bering Sea ice cover then is the apparent balance between ice production in the northern, lee-shore polynyas, a wind-driven ice "conveyor belt" to the southern ice edge, and an "ice scrapyard" at the ice edge from the interaction of ocean swell and warm seawater. These ideas follow Fay (1974), who first described the "conveyor belt" in the Bering Sea, and Wadhams (1981b), who used the "scrapyard" analogy to describe the east Greenland ice edge. The various Bering Sea field experiments cited in Section 1 show that the Bering Sea ice "scrapyard" has the following characteristics. First, propagation of ocean swell into the pack ice fractures, rafts, and ridges the ice so that the typical floe diameter is 10 m, with a 1-to 5-m thickness, compared to interior floe diameters of 1 to 10 km and 0.4 m thickness. In one sense, the distance to which this fracture zone extends into the ice interior, which varies from 10 to 100 km, depending on weather conditions, is a measure of the MIZ width. Second, during periods of off-ice winds, the ice within the MIZ diverges (Muench and Charnell, 1977), so that a previously compact ice edge develops into alternating regions of open water and regions of high ice concentration, where the long axes of these features run approximately perpendicular to the wind direction, and their width varies from 1 to 5 km.

Third, the open water within the pack leads to a locally enhanced heat and moisture flux to the atmosphere which contributes to formation of roll clouds and roll vortices. By causing local convergence and divergence at the surface, these vortices apparently limit the lateral scale of the divergent ice strips to 1 to 10 km. Fourth, wind-waves form on the open water features within the MIZ; the combination of the wave radiation pressure and the wind drag causes the bands of ice nearest the edge to move southwest into warmer water. Unpublished observations by Martin during the 1981 *Surveyor* cruise show that the typical lifetime of such a band is 2 days, and that the band velocity is 40% greater than the ice velocity in the pack interior. Fifth, the non-uniform surface stress due to the bands may cause development of internal waves which may, in turn, interact with the bands. Finally, once the band or set of bands melts, the existing ocean swell propagates farther into the ice interior, thus fracturing new ice and continuing the above process.

Physically, a major unknown in the MIZ is the cause of the initial divergence of a compact ice cover into alternating strips of ice and water. Once the divergence creates open water regions within the pack, the subsequent development of the ice bands from a combination of wind-wave radiation stress and atmospheric roll vortices seems physically straightforward. Although as yet we have no physical understanding of the cause of the initial divergence, we suspect that the cause of this divergence is an interaction of wind and current forcing with the nonlinear sea ice rheology. Verification of this suspicion, however, will depend on a combination of numerical modeling and a specific winter ice deformation field experiment.

Further, examination of satellite photographs of the ice in both the Sea of Okhotsk and the Greenland Sea shows a similar ice divergence. In addition, antarctic imagery, which is mostly cloudy, suggests that this MIZ is also divergent. Because the deformation of the Greenland Sea ice is complicated by the presence of the East Greenland Current and its eddies, we feel that the Bering Sea is the best site for an ice deformation experiment.

Therefore, a study of the Bering Sea winter ice processes may be broadly divided into two parts: an ice dynamics and deformation experiment in the MIZ, and an ice production experiment in the lee-shore polynyas. We anticipate that the deformation experiment will be carried out in winter 1983, and the polynya experiment in winter 1985. In the following we first describe the ice deformation experiment, then in lesser detail, the polynya experiment.

3.3 The ice edge dynamics experiment

The ice edge dynamics experiment is planned for February-March 1983, and will be a specific study of winter ice edge dynamics and deformation. This experiment will concentrate on determination of the ice response to wind, swell, currents, and tidal forcing, with the goal of providing data for a theoretical model of the MIZ.

The experiment will be carried out using the following equipment and platforms: moored overwinter current meters in the vicinity of the MIZ, an icebreaker equipped with helicopters for the interior work, an ice-strengthened vessel without helicopter for ice edge oceanography and band tracking, and remote sensing overflights.

Using these various platforms, we will carry out the following operations:

a. Deployment of a large-scale array of satellite-tracked position buoys over a 100-km-square box.

b. Deployment of a medium-scale (10 to 25 km) array of microwave buoys which will be tracked by the ship, using a system such as the Cold Regions Research and Engineering Laboratory (CRREL) Del Norte system.

c. Deployment of a small-scale (1 to 10 km) array of radar-transponder buoys, which will be tracked with the ship's radar.

d. Measurement, from moored current meters deployed at the beginning of the ice season and picked up the following June, of currents and tides.

e. Measurement, from ice-mounted instruments which will either record internally or else telemeter back to the ship, of the wind, wave, and current forces acting on the ice within the array. Also, determination of incident directional swell from a directional wave buoy deployed in open water.

f. Determination, from aircraft overflights discussed in more detail below, of the ice types, amount and orientation of open water areas, ice deformation, and ice surface roughness within the experimental region.

g. Determination of the salinity-temperature structure of the water column from the CTD observations, including time-series to detect the presence of internal waves.

3.3.1 Logistics—Ships

A system such as the Del Norte transponder system requires a transmitter-receiver unit on the ship to record the buoy positions. Thus, we anticipate that to carry out this experiment would require at the minimum one icebreaker dedicated to three weeks' work at the ice edge. This ship would concentrate on the deployment and tracking of the microwave transponders and the telemetry buoys. A second ice-strengthened, non-helicopter-equipped ship operating in the open water near the ice edge would run CTD sections and time-series, deploy and track the radar buoys, and deploy and recover the directional wave-rider buoy. The second ship would thus serve as an oceanographic platform, while the icebreaker would record deformation of the interior ice features.

3.3.2 Logistics—Aircraft

The remote sensing aircraft will gather data on ice types, the amount and orientation of the open water areas, ice deformation, and ice surface roughness. To make these measurements, as described in Section 2.2.5, we will rely on a combination of imaging radar, laser profilometer, and simultaneous scatterometer and radiometer measurements.

Specifically, we recommend that the region be repeatedly overflown and mapped with radar. In order to identify the array, we would tag particular floes with either large corner reflectors, such as were used on land with the Seasat SAR (Goldfinger, 1980) or with active radar transponders. Second, to provide direct measurement of the surface roughness and open water along a track line, we recommend that laser overflights be run along lines both parallel and perpendicular to the ice edge and along lines of swell propagation. Third, to allow for ice type classification within the surveyed area, we recommend overflights with the combination of scatterometer and radiometer operating at the same frequency following Livingstone et al. (1980) and NORSEX (1981b). These flights, combined with aerial photography and measurements of surface temperature, will permit, for example, estimates of new ice growth within the region.

3.4 The polynya experiment

Analysis of satellite imagery shows that most ice formation in the winter Bering Sea occurs within several relatively small polynyas, which have extremely high rates of air-sea heat exchange and subsequent ice formation. Also, Andersen et al. (1980) show that the brine outflow from similar polynyas around the Arctic Basin may contribute to deep water formation. The objective of a polynya field study, then, will be to determine the ice production rate and resultant oceanic salt flux as a function of wind speed and air temperature. The experiment should yield insight into the role of the relatively small scale polynya dynamics on large scale ice production and deep water formation.

Martin (1981) summarizes the heat exchange and ice growth mechanisms in polynyas, and shows that the ice forms there as small crystals called "frazil" ice. In the Bering, these polynyas are located in the Gulf of Anadyr off Siberia, and south of Cape Prince of Wales and St. Lawrence Island in Alaska (Fig. 6). Similar polynyas also occur in the Chukchi Sea, the Sea of Okhotsk, and along both the East Greenland coast and the Antarctic coast. The St. Lawrence Island polynya is the simplest study area for the following reasons: 1) It is bounded on its upwind side by a zonal coastline, which will greatly simplify estimates of water, ice, and salt balances. 2) The region south of St. Lawrence Island is one of weak nontidal currents. 3) Finally, available time aboard an icebreaking vessel required for work in a polynya dictates our focusing upon the simplest large-scale polynya.

An additional reason for carrying out a polynya experiment is that there are thus far no measurements of the atmospheric heat and momentum flux at conditions of high winds (greater than 20 knots or 10 m s^{-1}) and low temperatures (less than -20°C). Similarly, there are no analogous measurements of the resultant oceanic salt flux. The results of unpublished numerical and laboratory modeling reveal that the ice production rate at 20 m s^{-1} and -30°C is about 0.1 m hr^{-1} or 2 m day^{-1}. The St. Lawrence polynya is on the order of 10^4 km^2 in surface area; the Bering Sea area is on the order of 10^6 km^2. Therefore, to produce enough ice in a continuously running polynya to cover the entire Bering to 1 m depth would take about 40 days. Further, ice cores taken both during our 1979 observations and during BESEX show that at least 30 to 50% of the vertical extent of cores taken consisted of frazil ice, suggesting that the ice originated in a polynya.

To carry out an integrated field study of this polynya will require a combination of over-winter moored current meters, deployment of air-droppable buoys for ice motion, atmospheric surface pressure and temperature, a winter icebreaker cruise inside the polynya, and instrumented aircraft overflights of the polynya. With this instrumentation, we would study mechanisms and rates of ice formation under low-temperature, high-wind-speed conditions, effects of this ice production and the resultant brine exclusion on the underlying water, and effects of surface waves and currents on the ice production.

3.5 Timing of the experiments

3.5.1 Preliminary investigations

This work includes the winter 1979 and 1981 field work carried out primarily under the OCSEAP program. Analysis of the 1979 field trip is described in Pease (1980), Walter (1980), and Bauer and Martin (1980). The 1981 field data are presently being analyzed; we have begun to apply existing numerical ice cover models (Hibler, 1979) to the MIZ using the data from BERING-81. Finally, there will be one additional CTD survey of the MIZ in March 1982.

3.5.2 The ice edge dynamics experiment

This experiment will take place during the time of maximum ice extent in mid-winter 1983 and will focus upon air-ice-water interactions in the region of ice disintegration and decay along the Bering ice edge.

3.5.3 The polynya experiment

This experiment will take place during the period of maximum ice extent in mid-winter 1984 or 1985 and will focus upon air-ice-water interactions in the St. Lawrence polynya, a major ice-production region in the northern Bering Sea.

3.5.4 Analysis and synthesis

This phase will extend into 1985-86 and will include analysis of the data from the field programs, writing-up of results, and synthesis of the Bering MIZ results with incoming results from the Greenland Sea program.

4. COORDINATION OF EXPERIMENTS

The management of international experiments of this type requires project offices to be established in each of the countries that will be major logistical centers. For MIZEX the countries will be the United States and Norway. In addition, there must be a system to permit close collaboration and communication among the many other national groups (Canada, Denmark, Finland, France, Great Britain, Sweden, West Germany, etc.) involved in the experiments. This would take the form of a data network such as "Telenet," together with an offset newsletter.

For the Greenland Sea experiments a field office will be established in Tromso, as it was for the NORSEX experiment, and the Tromso satellite telemetry station will play a vital role in coordinating aircraft operations and in receiving and retransmitting satellite imagery. At the ice edge itself, the ship frozen in the ice will act as the coordinating center for all the vessels involved. For the Bering Sea experiments the field office will be in Anchorage, as it was for the BESEX experiment, and will serve to coordinate aircraft and ship operations.

There must be data banks established in Norway and the United States to preserve and make available in usable form the data from the experiments. This system should be in place before the field experiments begin. Plans must be made for permanent storage of the data at some suitable facility (e.g. a World Glaciological Data Center) so that access is not lost after the programs finally terminate.

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