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Greenland Sea Ice/Ocean Margin

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Introduction

One of the fundamental obstacles to understanding both weather and long term climate variability of polar and subpolar regions lies in knowing what controls the position and behavior of the boundary between open and ice-covered ocean, the marginal ice zone (MIZ). Over the seasonal cycle, variation in sea ice coverage of the world ocean is about 25 million km^2, roughly 7% of the total area; thus a significant portion of the ocean is at some time during the year part of the MIZ.

From the point of view of air-sea interaction, the MIZ is a very complex system: an interface between ocean and atmosphere with potentially extreme horizontal and vertical temperature gradients and large variations in mechanical properties. The 'joker-in-the-deck' is, of course, sea ice—it modifies momentum transfer from the atmosphere; drastically alters surface albedo; serves as an efficient thermal insulator; damps surface wave motion; and, because it is relatively fresher than sea water, may substantially change both temperature and salinity structure in the upper ocean by melting or freezing. Sea ice is highly mobile in response to surface wind, capable of traveling tens of kilometers per day. It thus represents a negative source of both salt and heat that can be advected long distances across water–mass boundaries by atmospheric systems. It is estimated (e.g., *Hibler,* 1979) that fresh water exported from the Arctic Basin through Fram Strait as sea ice (about 10^5 m^3 s^{-1}) is roughly comparable to the total continental runoff entering the basin. In this sense, the MIZ of the North Atlantic, despite its limited area, is the terminus of a vast territorial watershed.

Over the past decade, field experiments (notably the Arctic Ice Dynamics Joint Experiment) and theoretical modeling of sea ice and the adjacent atmospheric and oceanic boundary layers have dramatically increased our understanding of the behavior of ice-covered oceans. At the same time, there has been much interest in open-ocean frontal and mixed layer processes. In 1979 a workshop on the Seasonal Sea Ice Zone, organized by Wilford Weeks, provided the first systematic, multidisciplinary approach to identifying problems faced in understanding seasonal sea ice and provided experimental techniques for addressing them (*Andersen et. al.,* 1980).

In subsequent meetings a research strategy was formulated from which emerged a structure known as MIZEX (Marginal Ice Zone Experiment). MIZEX is an international, interdisciplinary project aimed at studying specific processes in the MIZ as part of a more comprehensive effort to understand how the annual and long-term variability of polar ice margins relate to large-scale atmospheric and oceanic circulation (Untersteiner, N., Air-sea-ice interaction research program for the 1980s, unpublished report, Applied Physics Laboratory, University of Washington, Seattle, 1983). The primary focus of MIZEX is the Greenland Sea ice edge in the region north and west of Svalbard, where most of the exchange between the Arctic Ocean and the rest of the world ocean occurs. The general research strategy, described by *Wadhams et. al.* (1981), includes field experiments planned for the summers of 1983 and 1984 (MIZEX 83 and MIZEX 84) (*Johannessen, Hibler, et. al.,* in press) with follow-on winter and summer experiments later in the decade. Complementary work is planned for the ice edge in the Bering Sea (MIZEX WEST), as described in *Eos,* December 21, 1982, p. 1220.

Scientific Considerations

For conceptual and organizational clarity, the MIZEX effort has been broken into seven subgroups: remote sensing, meteorology, ice, oceanography, biology, acoustics, and modeling. Some of the major problems and proposed work in each discipline are described below; more complete descriptions may be found in *Wadhams et. al.* (1981); and *Johannessen, Hibler, et. al.* (in press).

Remote Sensing

Given the extent and inaccessibility of areas affected by the MIZ, remote sensing is the only practical way of applying increased understanding from experiments like MIZEX to long-term monitoring and routine prediction of ice-edge characteristics. Eddy-like structure along the ice edge in the Greenland Sea has been shown by LANDSAT image (see cover). Similar images have been attained with microwave sensors (e.g., *Johannessen, Johannessen, et. al.,* in press), demonstrating the feasibility of all-weather, all-season remote observation. If MIZEX succeeds, for example, in providing reasonable estimates of cross-edge heat and mass exchange in eddy or banding processes, then routine surveillance of such features will provide much improved estimates of large scale heat and mass budgets.

From an experimental standpoint, remote sensing provides the overall view necessary to identify special features for intensive study. Because persistent cloudiness is anticipated, microwave sensors (SAR, SLAR, and Passive) will be used extensively. Studies of ice deformation obtained by tracking identifiable natural and artificial targets will complement buoy and transponder measurements.

There will also be a concerted effort to measure and understand the effect of changing surface conditions in the MIZ on scattering and emission properties.

Meteorology

The lower boundary of the atmosphere across the MIZ changes from a maritime regime, with low albedo and moderate temperature, to a highly reflective and, during much of the year, very cold regime. These changes, combined with dramatic variation in surface roughness, can impose large gradients in radiative fluxes, in surface stress, and in turbulent moisture and heat fluxes. Over pack ice, the boundary layer is usually stably stratified, with low, strong inversions. If this cold air is advected over open water with a strong temperature contrast, turbulence is intensified. By the same token, warm air advected over the cold surface is stabilized, with decreasing turbulence levels. Ice is generally thought to be rougher than the ocean surface, so that for the same surface wind and stability, turbulent drag over pack ice is greater than over the open sea; furthermore, roughness of the ice itself is often increased within the MIZ by rafting and pulverization. Sorting out these various effects presents a considerable challenge but is important for understanding how the ice and underlying water respond to the wind.

The MIZEX experiments will employ a variety of meteorological instruments for surface layer studies, deployed from ships and ice floes, along with aircraft boundary-layer measurements, radiosonde launchings, acoustic sounders, closely spaced surface pressure arrays, and buoy-mounted weather stations. An active atmospheric modeling component will complement the field measurements.

Ice

Sea-ice studies in the MIZ divide roughly into two classes: one concerned primarily with the thermodynamic growth, decay, and internal structure of ice; the other concerned with the mechanical properties of sea ice as a material affected by dynamical forces, mainly wind and current.

Ice in the MIZ is broken into much finer individual floes and pieces than are found in the interior pack. Attenuation of surface wave energy by the pack ice is certainly a major factor in this break-up; gradients in other forces, such as horizontal current shear, may also contribute. These interstitial areas of

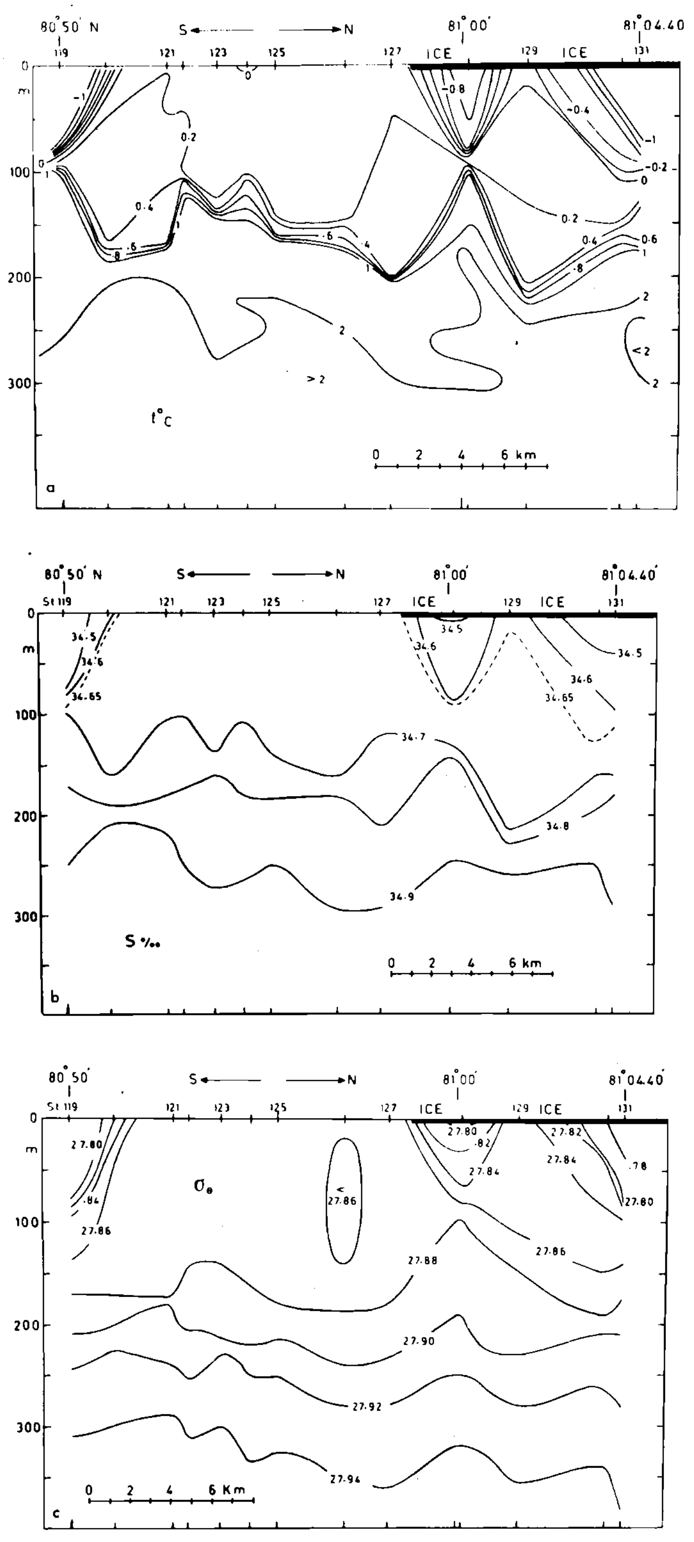

Fig. 1. Sections of temperature, salinity, and σ_θ across the Greenland Sea marginal ice zone on December 3, 1977, from *Buckley et. al.* (1979).

open water not only change the mechanical properties of the ice, but also modify the radiation balance and the mean surface temperature sensed by the atmosphere. In summer, melt rates may be enhanced by increased insolation between floes; in winter, ice production is increased by continual opening and closing.

Water near the margin may contain more sensible heat than is usually found in the Arctic mixed layer, giving oceanic heat flux a greater role in the thermodynamic energy balance that controls ice thickness. The mass balance of ice regulates buoyancy flux into the oceanic boundary layer; thus, if oceanic sensible heat is available, the growth rate can serve as an important feedback parameter.

Kinematics of ice motion in the MIZ are also of much interest. Buoy and satellite imagery studies indicate comparatively large shear normal to the ice edge and divergence along the East Greenland Drift Current. MIZEX will also study attenuation of inertial and tidal oscillatory motion.

Measurements planned include detailed studies of changes in mass, concentration, and floe size distribution, along with energy budget observations and properties of ice measured both in situ and cored for more extensive laboratory analysis. Radar positioning techniques and satellite navigation will be used to study kinematics of the ice drift field with an array of drifting buoys. In addition, mean motion, wave and collision accelerations, ablation, and other properties will be studied at the extreme ice edge, including eddies and bands.

Oceanography

Modification of the upper ocean across the ice edge is often extreme, with large changes in temperature and salinity, large horizontal gradients in vertical density structure (with corresponding geostrophic shear), and rapid variation in surface momentum and buoyancy flux. At times, the MIZ coincides with the surface manifestation of a permanent, oceanic front (e.g., the East Greenland Polar Front), which may in turn be tied to a topographic feature (the shelf break); but as is the case in many marginal seas and in most of the Southern Ocean, the ice edge itself often forms a rapidly migrating, oceanic frontal zone. These fronts exhibit a variety of interesting features: eddies (see cover figure and *Johannessen, Johannessen, et. al.*, in press), fine structure (*Paquette and Bourke,* 1981), jets, and meanders. A summertime Soviet project at the Chukchi Sea MIZ noted a jet, directed along the ice edge so that open water was on the right, that persisted for the duration of the experiment regardless of wind direction (*Nikolaev,* 1973). The jet, which meandered on scales of about 90 km, probably resulted from geostrophic adjustment between relatively warm and saline water from the south and a lens of water freshened by ice melt.

Ice-edge upwelling and other mesoscale circulations appear in the MIZ; they are thought to be driven by surface gradients in stress or buoyancy flux. The Chukchi ice-edge jet mentioned above seems to fall in the latter class, since it was apparently independent of local wind. On the other hand, *Buckley et. al.* (1979) observed a large upwelling event north of Svalbard in early winter (Figure 1), which they attributed to a surface stress gradient much like coastal upwelling. In this case it is hypothesized that sea ice, because of its greater upper surface roughness, imparts more momentum to its underlying boundary layer, causing Ekman divergence at the ice edge.

Boundary layer and surface layer processes are also an active area of research. Rapid melting at the ice margin can yield in the upper ocean an input of fresh water at a rate comparable to that of a torrential rainfall, creating a stable boundary layer analogous to the nocturnal boundary layer of the atmosphere. *McPhee* (in press) offers the resulting reduction in drag on the ice underside as an explanation for divergence of bands of sea ice away from the main pack under off-ice winds. Absorption and reflection of surface gravity wave energy is also a significant factor in the MIZ, invoked to account for the relatively sharp ice edge often observed. Wave radiation stress has also been suggested as a primary factor in the formation of ice-edge bands (e.g., *Wadhams,* in press).

An ambitious oceanographic measurement program is planned for the MIZEX experiments, including current meter moorings, both bottom anchored and suspended from the surface; extensive hydrography from ship and helicopter; profiling current meter systems; boundary layer turbulence measurements; expendable temperature and velocity probes; high frequency acoustic sounding; and Doppler acoustic current meter mapping. In addition, deployment of surface (and perhaps subsurface) drifters is planned, with CODAR measurements of surface velocity on each side of the ice margin. Tracer studies, which have recently been used to identify residence times of subsurface water north of Fram Strait (*Ostlund et. al.,* 1982) will be extended to the MIZ.

Biology

In high latitude biological systems, the ice edge region has higher levels of primary productivity than surrounding waters. *Alexander* (1981) shows that over a third of the total primary productivity in the southeast Bering Sea comes in the single month of May, coinciding with the ice edge bloom. Associated with the bloom is a concentration of marine mammals and birds at the ice edge, with some species adapted specifically to the ice-edge habitat. There are several competing hypotheses for the presence of the bloom, among them: (a) a benevolent environment furnished by a shallow, high-nutrient, mixed layer stabilized by melt water; and (b), increased nutrient levels associated with ice-edge upwelling. Recent work describing the halocline of the Arctic Ocean (e.g., *Aagaard et. al.,* 1981) has emphasized the role of the broad Arctic shelves in maintaining the cold, saline layer of water that separates the relatively fresh Arctic mixed layer from underlying Atlantic water. Presumably, modified shelf water upwelled by processes at the ice edge could supply the needed elevated nutrient levels. If such upwelling is intermittent, the biological signal from each event may provide a 'memory' that is lacking in measurements of the physical properties alone.

Biological measurements in MIZEX will include phytoplankton biomass, phytoplankton species, nutrients, zooplankton biomass and diversity, and a variety of chemical components.

Acoustics

The acoustic climate of the MIZ is complex. Ice itself is noisy in the region where surface wave energy is attenuated by jostling and fracturing of ice floes. Ambient levels are highest at the ice edge but fall off faster in the iceward direction, an effect attributed by Diachok (see *Andersen et. al.,* 1980) to much higher reflection losses at the ice–water interface compared with the open sea surface.

The sound-speed profile is subject to large variations caused by frontal and eddy structure in the MIZ; these variations degrade horizontal coherence of acoustic wave fronts, and therefore the performance of directional acoustic arrays. Since acoustic tomography is potentially an important tool for measuring eddy structure in the MIZ and because synoptic ice-roughness mapping is possible by acoustic backscatter techniques, it is important to determine variability and predictability of sound-speed structure.

Acoustic measurements in MIZEX will include fixed and free drifting sonobuoy arrays, ambient noise including directional information, a tomography experiment, plus seismic reflection and refraction experiments.

Modeling

Credible models of MIZ processes across the whole range of disciplines is a major goal in the MIZEX effort. A partial list includes: sea-ice radiation, thermodynamics, ridging, breaking, and rheology; atmospheric and oceanic boundary layers; eddy generation; frontogenesis and maintenance of fronts; quasisteady, mesoscale circulations in atmosphere and ocean; fine structure and cross-frontal mixing; biological processes; internal waves; sound path and acoustic tomography; and many others.

In addition to their role as end products, models will be used prior to the experiment and in the field to optimize sampling strategies.

Organization and Planned Field Work

The experiment's basic organizational body, the MIZEX Science Group, consists of seven 'Discipline Chairmen' and nine 'National Coordinators' assisted by executive and logistics managers. The Science Group is responsible for determining overall scientific directions and for serving as liaison between scientists and national advisory and funding agencies. Two project offices and a logistics office have been established, publication of a newsletter has commenced, and a MIZEX Bulletin for presentation and discussion of scientific matters is planned.

The MIZEX 83 field project is scheduled for June–July 1983, beginning in the Greenland Sea north of Svalbard (the precise location will depend on ice conditions). The ice-strengthened research vessel *Polarbjorn* will spend about 6 weeks on site, functioning first as a drifting ice station and then performing measurements in the region just seaward of the ice edge. She will be joined for about ten days by the icebreaker *Polarstern* for cooperative work in and near the MIZ. The Norwegian Polar Institute vessel *Lance* will also perform cooperative measuring programs in the vicinity. A number of fixed-wing aircraft from the United States, Canada, France, Denmark, and Norway will carry out remote sensing missions, and two helicopters will aid scientists in deployment and sampling operations.

MIZEX 84 is a much larger project, with five vessels and numerous aircraft and satellite platforms on hand for most of the 6-week field program in June–August 1984. One ship will serve as a drifting station within the ice pack for the entire experiment. *Johannessen, Hibler, et. al.* (in press) describe the scientific plan in detail.

Experience gained during MIZEX 83 will be used to design the 1984 experiment. Following 2 or 3 years of data assimilation, there will be additional summer and winter experiments in the Greenland Sea.

Operational planning for MIZEX 84 is under way and will be completed at a meeting in Bremerhaven, Federal Republic of Germany, in November 1983. Discipline workshops will be held this spring to encourage input to the planning process from all interested scientists. Specific plans or suggestions should be discussed as soon as possible with the discipline chairmen or national coordinators, whose names and addresses and information on administrative matters may be obtained from Dean Horn, MIZEX Executive Officer, Arctic Programs Code 425AR, Office of Naval Research, 800 N. Quincy Street, Arlington, VA 22217 (telephone: 202-696-4118).

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