Final Report

BEAUFORT SEA MESOSCALE CIRCULATION STUDY DESIGN

Contract No. 85-ABC-00272

TO

National Oceanic and Atmospheric Administration
Office of Oceanography and Marine Assessment
National Ocean Service
701 C Street
Anchorage, Alaska 99513

and

Minerals Management Service
Alaska OCS Region
949 East 36th Avenue
Anchorage, Alaska 99508

BY

Knut Aagaard
Harry de Ferrari
Patrick Kinney
Thomas Kozo
Mark Savoie

R-KLI-85-11
17 December 1985

KINNETIC LABORATORIES INCORPORATED

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Anchorage, Alaska 99510

This study was funded wholly by the Minerals Management Service, Department of the Interior, through an Interagency Agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Alaska Outer Continental Shelf Environmental Assessment Program.

Patrick J. Kinney
Project Manager

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SUMMARY

The Outer Continental Shelf Environmental Assessment Program (OCSEAP), managed by NOAA, provides the Minerals Management Service with scientific data and information needed to predict environmental disturbances and to resolve multiple-use conflicts associated with offshore oil and gas development in Alaska. This report to NOAA presents the results of an oceanographic feasibility and program design study regarding acquisition of circulation information on the continental shelf of the ice-covered American Beaufort Sea.

The purpose of this study was to investigate the feasibility of obtaining physical oceanographic measurements over the inner and outer shelf region (20 to 200 m) of the Beaufort Sea on a seasonal basis. The area of interest is partially or totally ice-covered for 12 months of the year, making many proven techniques difficult or impossible to use. Severe climate conditions also give rise to special operational and logistic considerations.

Upon review of available technologies, a number were found well suited to sampling oceanographic parameters in the ice-covered Beaufort Sea. Point measurements, in an Eulerian reference frame are the most powerful basic oceanographic sampling strategy. Eulerian techniques well suited for defining the Beaufort Shelf circulation include in-situ current meters, acoustic doppler current profilers, pressure measurements , and hydrography and water mass analysis. Another potential Eulerian technique is acoustic tomography.

A technique that has been used extensively in the Arctic and Antarctic is that of emplacing instruments on, or hanging below, the moving pack ice. Inability to obtain near-bottom measurements is a serious limitation of this technique. There are also problems with data interpretation, since the data are neither in a fixed (Eulerian) nor a water-following (Lagrangian) reference frame. However this technique is particularly useful for obtaining offshore meteorological observations as the inherent spatial scales are large, and the temporal scales are short, compared with the displacement and time scales of the platform motion. This technique can also accommodate supplemental upper ocean observations.

Based on these techniques a design is presented for a study which will provide both a kinematic and dynamic description of the circulation on the Beaufort Sea Shelf. We have recommended a well-integrated oceanographic and meteorologic approach, as both elements are essential to the understanding of shelf circulation. We have also recommended a conservative approach using proven instrumentation\ techniques and redundancies in order to ensure successful data return. The recommended study includes the following:

- A total of 27 conventional current meters equipped with conductivity and temperature sensors are recommended. These meters should be placed along three transects of moored instrumentation off the western, central and eastern areas of the American Beaufort Coast and extending from the 20 m isobath out to the 1000 m isobath. Five stations (plus one redundant station) per transect comprise the core oceanographic program, along with an additional mooring in Barrow Canyon, a known major source of water in the Beaufort Sea.

- o Two bottom mounted pressure gauges should be emplaced along each of the three transects in order to measure both the alongshore and cross-shelf pressure gradients. In addition, three pressure gauges have been included on the redundant moorings inshore.

- 0 A bottom-mounted, doppler profiling current meter should be deployed along each transect to resolve upper water column current. Two additional doppler current meters have also been included between each transect as an option.

- o A total of 8 hydrographic transects should be conducted during mooring deployment and recoveries, with at least one intermediate trip.

- o Meteorological measurements involve three offshore, telemetering stations and supplemental onshore stations. The offshore stations would use proven meteorological sensors and ARGOS or GOES satellite telemetering. Optional under-ice current meters and conductivity strings would be attached to provide supplemental upper water column data, but are of lower priority due to their interpretative limitations.

- o A highly experimental ocean acoustic tomography study is considered as an option. The point measurements obtained by the moored instruments could thus be supplemented by this technique, which essentially integrates over an area of the shelf. A spatially integrated value of episodic offshore flow would be the most important product of this experimental work. Integrated verification of our point estimates of longshore flow would also be obtained.

Logistic support can be based either on ice-breakers or helicopters for the program outlined above. Cost advantages, mobility, and greater control favor helicopter based operations.

AKNOWLEDGEMENT

This study was funded wholly by the Minerals Management Service, Department of Interior through an Interagency Agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Alaska Outer Continental Shelf Environmental Assessment Program.

We also wish to thank Dan Frye of Ferranti O.R.E. Inc. for an independent and constructive critical review of our draft report.

SCIENTIFIC RATIONALE

1. INTRODUCTION

The outer Continental Shelf Environmental Assessment Program (OCSEAP) in Alaska has as its purpose the conduct of environmental studies of outer continental shelf areas identified by the Department of the Interior for potential oil and gas development. The OCSEAP provides agencies involved in outer continental shelf leasing decisions the information needed to predict environmental disturbances and to resolve multiple use conflicts associated with offshore oil and gas development.

A number of oceanographic studies have been undertaken as part of the OCSEAP within nearshore areas of the Beaufort Sea, e.g., in Simpson Lagoon, Stefansson Sound, and Beaufort Lagoon. In addition, numerous industrial funded measurement programs have substantially added to our understanding of these nearshore regimes. As a result, the current state of knowledge of coastal circulation in the Beaufort Sea, including that in the semi-enclosed lagoons and open embayments, is judged to be fairly good. Oceanographic measurements elsewhere on the shelf have been sporadic, most encompassing only small portions of the inner and outer shelf regions.

The goal of this study is to determine the feasibility of a proposed Beaufort Sea circulation project on the shelf seaward of the coastal region, and to recommend a design and implementation methodology for such a project. Specifically, sampling design, instrumentation, instrument placement, sampling frequency, data acquisition procedures, and requirements for field operations are to be considered. The purpose of the proposed circulation project itself is to provide both a kinematic and a dynamic description of the circulation over the Beaufort Sea shelf seaward of the 20 m isobath, and extending throughout the year; the intended emphasis is on synoptic current data. These data should help explain the dynamics of the longshore low-frequency flow variability, and of cross-shelf exchanges. The measurements will also be used to verify the general circulation model developed for this region under OCSEAP sponsorship.

The present understanding of the shelf circulation (cf. Aagaard, 1984 for a synopsis) is that the outer shelf is dominated throughout the year by a strong topographically steered eastward flow with significant vertical shear, called the Beaufort Undercurrent by Aagaard (1984). This vertical shear in the mean flow probably results in the mean geostrophic current in the upper part of the water column being directed westward, counter to the deeper flow. The current exhibits large low-frequency variability, much of which appears to be wind driven. It is further likely that the pronounced flow on the outer shelf is part of the large-scale circulation of the Arctic Ocean, rather than a local phenomenon. In contrast, the inner shelf appears primarily to be locally wind driven, although seaward of the shallow coastal zone this regime is very poorly sampled. Earlier work suggests that the transition between the inner and outer shelf regimes occurs near the 50 m isobath. The innermost part of th shelf under consideration, near the 20 m isobath, will in general lie near, or inshore from, the edge of the fast ice. In this region one should expect extreme seasonal effects, since the fast ice can not transmit the local wind stress to the ocean. A summary of direct current measurements on the Beaufort shelf outside the nearshore area is given in Figure 1.

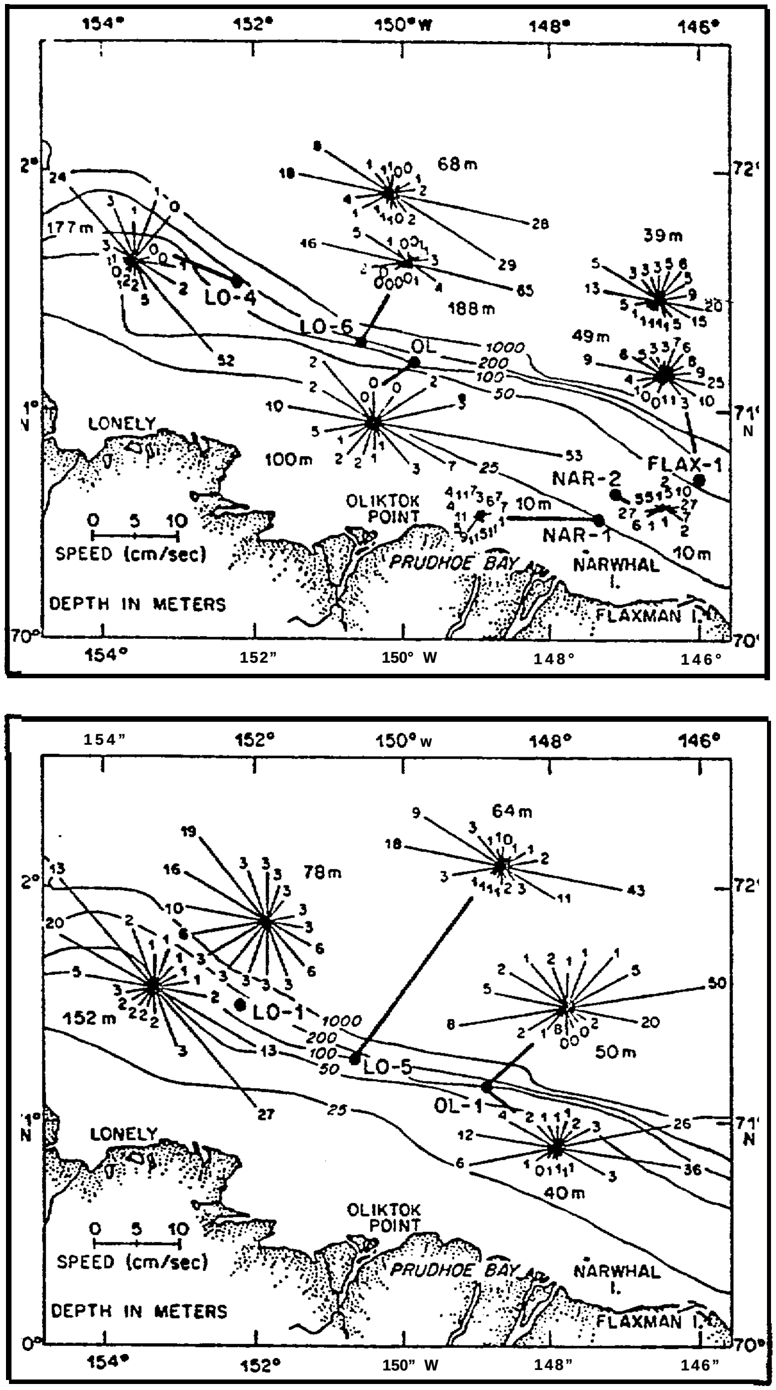


Figure 1. Current roses at Beaufort Sea mooring sites. Each vector represents the mean current in a sector of 20°, the vector length being proportional to the speed (see scale). The number at the end of each vector is the frequency of occurrence of a current within that 20" sector. Depth of measurement shown ad j scent to each rose. Heavy dots show mooring locations (Aagaard, 1984).

In the context of the OCSEAP, a special significance of the energetic circulation on the outer shelf is that it provides an efficient means of dispersal and transport of substances over long distances on the shelf. This is particularly important, since Aagaard (1984) has measured frequent cross-shelf circulation motions near the inshore edge of the Beaufort Undercurrent. Such motions, together with other cross-shelf circulation modes, could serve to connect the inner shelf regime to the large-scale offshore circulation.

Wind exerts a major influence on the physical and biological environment of the Alaskan Beaufort Sea. Surface wind conditions influence the times of sea ice break-up and freeze-up, drive or modify the circulation on the shelf, and move ice floes and potential oil spills. However, Rogers (1978) found a lack of correlation between geostrophic wind direction and the distance of the ice margin from the coast. He believed it was due to the National Weather Service (NWS) synoptic scale analysis being unusable or unreliable along the Beaufort Sea Coast, and recently NWS synoptic scale analysis has, in fact, been shown to provide inaccurate wind velocities for critical coastal areas (Kozo, 1984a). The causative factors for these failures were thermal discontinuities at sea ice-water-tundra boundaries and topograpy, both of which generate surface pressure anomalies not detectable within synoptic size observational networks (~400 km between stations). These mesoscale effects can dominate coastal winds at least 100 km offshore (Dickey, 1961; Schwerdtfeger, 1979), easily reaching the outer shelf areas.

Work by Kozo (1980, 1982, 1984a) has shown that smaller atmospheric pressure grids (100 km between stations) can improve surface wind prediction. When predictions from these small-scale grids are also inadequate, orographic and sea breeeze modeling can correct the remaining problems. Fortunately, sea breeze effects should not be a problem beyond 20 km from the coast (Kozo, 1982).

2. SCALING

The spatial scales for such a study are in part set by the extent of the study area and in part by the more intrinsic scales determined by the physics of the flow and its forcing. With respect to the former, the Alaskan Beaufort Sea shelf extends some 600 km in an approximately east-west direction, and is relatively narrow, with the 20 m and 200 m isobaths typically separated by 50 km. To the extent that external oceanic forcing is important, either offshore or upstream, these geographically set scales may require some expansion in order to determine the forcing.

With regard to the intrinsic scales, the longshore scales of shelf circulation are in general set by structure in the local wind field, major topographic features (e.g., canyons, of which none are known except for Barrow Canyon at the western end of the Beaufort shelf), and the properties of free waves (cf. Hickey, 1984 for a recent discussion). Except for topographic forcing, these length scales can be expected to be rather large for longshore flow, typically a few hundred kilometers. On the other hand, longshore correlation scales for cross-shelf flow tend to be very much smaller on most shelves, probably in part because the relatively weak cross-shelf circulation suffers from a poor signal-to-noise ratio (e.g. , Huyer et al., 1975). The intrinsic cross-shelf scales are on the order of the shelf width itself for barotropic flow, and equal to the internal deformation radius for baroclinic flow, the latter being of order 5-10 km for typical conditions on the Beaufort shelf. In addition, if the local wind field varies in the cross-shelf direction, as appears to be the case in the Beaufort Sea for sea breeze and orographic effects, these would determine a forcing length scale for the flow. The present data suggest that a significant portion of the low-frequency variability in the longshore current is in fact driven by the longshore component of the wind, with which it is nearly in phase.

Observations on the outer Beaufort Sea shelf have shown that although there is a pronounced vertical shear in at least part of the water column, of order 2 cm sec^{-1} per 10 m, the low-frequency variability of the current is vertically coherent over depths exceeding 100 m. Observations also have shown significant horizontal coherence in the longshore flow over the outer shelf at a distance of 63 km. The coherence at greater scales has not been measured on the Alaskan Beaufort shelf, although Aagaard (1984) has presented evidence for an inertial persistence of the flow extending eastward from Pt. Barrow from 200 km.

The time scales of the circulation are in a general sense reasonably well known from previous current measurements (e.g., Aagaard, 1984). Tidal energy levels are relatively low, but at subtidal frequencies the variability is very high everywhere on the shelf. On the outer shelf the kinetic energy spectrum tends toward red for the longshore flow component, but drops off at the lowest frequencies for the cross-shelf component. However, the flow on the outer shelf does not appear to show a seasonal variability, whereas on the innermost shelf, where local wind driving probably dominates in summer (but is suppressed in winter by the fast ice), such a signal would be expected to be large. Finally, significant interannual variability in the circulation can be expected both on the outer and inner shelf, but details are at this stage largely speculative.

3. A RESEARCH STRATEGY

Our present state of knowledge of the shelf circulation in the Beaufort Sea is thus sufficient to provide considerable guidance in developing a research strategy. It is, for example, clear from the observed low-frequency variability that very long time series measurements of the circulation are required, extending in detail for at least a year and with continued monitoring over a multi-year period. It is also clear that a simultaneous mapping of the wind field with adequate temporal and spatial resolution is required, since wind stress appears to provide major forcing for the circulation. Likewise, definition of the external oceanic forcing, both upstream from the shelf and offshore, is needed for a dynamic understanding. Finally, the circulation must be resolved at the principal vertical and horizontal spatial scales which are known or can reasonably be surmised to exist. Resolution of the vertical structure of the circulation in the upper 40 m of the ocean is probably the most difficult of these tasks because of the deep-reaching drifting ice.

METHODOLOGY

1. GENERAL CONSIDERATIONS

Both Eulerian and Lagrangian techniques are in principle capable of describing the circulation. However, lack of experience with Lagrangian devices in the Arctic, the problems introduced by deep-reaching ice in shallow water, and an exceptionally difficult sampling (detection) environment suggest that a Lagrangian approach is impractical for the immediate future. Free-floating acoustically-tracked neutral buoys such as used in deep ocean experiments are thus generally not suitable at the present time. This may change as currently projected experimental deployments of such drifters in the Arctic Ocean proceed during the next few years.

Alternatively, a large number of Eulerian techniques are potentially available, some indirect and others direct. The classic indirect techniques are primarily based on hydrographic observations and their interpretation in terms of geostrophic baroclinic flow, distributions on quasi-isentropic surface, mass and energy balances, specific mixing models, and the like. All these methodologies suffer from various fundamental limitations associated with the underlying assumptions. In addition, they have low resolving capability in the time domain. These hydrographic techniques are therefore by themselves incapable of defining circulation as required, although they have a proper and useful role in various other capacities. In particular, hydrographic techniques are vital in describing the thermohaline portion of the circulation. They also provide tracer signatures of such processes as mixing and upwelling.

An indirect technique of proven capability in similar shelf studies is sea level determinations, or equivalently oceanic pressure determinations. The use of such measurements is primarily associated with dynamic interpretations, for example in the identification of shelf waves or in determining the variability of the longshore pressure gradient. Along the Pacific coast of the United States, this latter term is of first order in the momentum equation (Hickey, 1984), and the possibility of a similar dynamic importance on the Beaufort shelf should be considered.

Other Eulerian techniques include transport measurements (i.e., velocity integrated across a section) as inferred from the EMF induced in a submarine cable (cf. Larsen and Sanford, 1985, for a recent example). However, this does not appear to be a suitable candidate technique for the present problem, in part because of the difficulty and expense of installing such cables and in part because in shallow water the effect of the sediment conductivity can easily mask the oceanic signal.

A different integral technique is velocity tomography, in which the integration is along the axis of the current component being measured. Depending on the water depth and vertical temperature and salinity structure, vertical resolution of the velocity and temperature field along the axis of measurement can be determined. A more detailed discussion of tomography is included in a later section below. Our conclusion with respect to tomography, however, will be that its application to the Beaufort shelf is at this point highly experimental.

A proven technique for mapping surface currents in open water is CODAR, which depends on Doppler-shifting of radar signals by surface roughness elements. Some experimentation with this technique in ice has been done recently in the Greenland Sea by German investigators. The general approach might prove a useful adjunct in the future, but for the present it has limited applicability to the proposed Beaufort Sea circulation project.

Satellite techniques are also primarily capable of dealing with the surface motion. However, for purposes of identifying the surface manifestations of ocean eddies and fronts, and of defining ice motion (including by synthetic aperture radar techniques), satellite remote sensing has potential applicability to the proposed project, primarily in the analysis phase.

A technique which has long standing in the Arctic is measurements from drifting ice. The inherent difficulty in such measurements in general is that their interpretation is problematic, since they provide information neither in a fixed reference frame nor a water- or phase-following reference system. (Only in unrealistically simple flows, or in enormously over-sampled configurations, can such measurements in general provide adequate ocean circulation descriptions.) Their principal limitations in the present application relate to 1) not providing an adequate definition of the low-frequency variability (because of the displacement of the platform), 2) not providing constant-geometry cross-shelf profiles (because the horizontal shear in the ice field distorts the array, 3) not allowing sampling deep in the water column (because the ice drift does not follow isobaths, thus limiting the vertical extent of the suspended instrumentation), and 4) creating additional noise in the measurement of absolute motion (because of uncertainties in platform displacement). Finally, the expected life time of such drifting instruments over the continental shelf is unpredictable, but probably short.

Nonetheless, there are certain oceanic measurements which are suited to drifting platforms, principally in the upper ocean, and we shall consider these later. The one major exception to the above remarks regarding interpretation is the requisite meteorological measurements, for which the inherent spatial scales are large and the temporal scales are short, compared with the displacement and time scales of the platform motion. For example, pressure measurements from instrumented ice floes have proved an invaluable tool in synoptic atmospheric surface mapping in the Arctic (cf. Thorndike and Colony, 1980). We develop this theme for the Beaufort Sea in the meteorology section.

2. OCEANOGRAPHIC MOORINGS

The core of our recommended oceanographic program is a set of long-term fixed instrumented installations of sufficient spatial density to resolve the principal features of the circulation. Based on the known or physically realistic length scales of the longshore flow, we recommend sampling in three sections across the shelf, the offshore terminus of the sections lying near (A) 153°, (B) 146°30′ and (C) 142°15'W (cf. Figure 2 for section locations). These sections are thus about 240 km and 160 km apart. By spacing the sections unequally in this manner, the range of longshore length scales which can be resolved is increased slightly. Since the flow is topographically steered, the sections should be oriented normal to the local isobath trend in order to sample equivalent cross sections of the flow. The selection of each section location was influenced by the desire to be removed from large changes in the isobath trends (which would locally perturb the flow), and

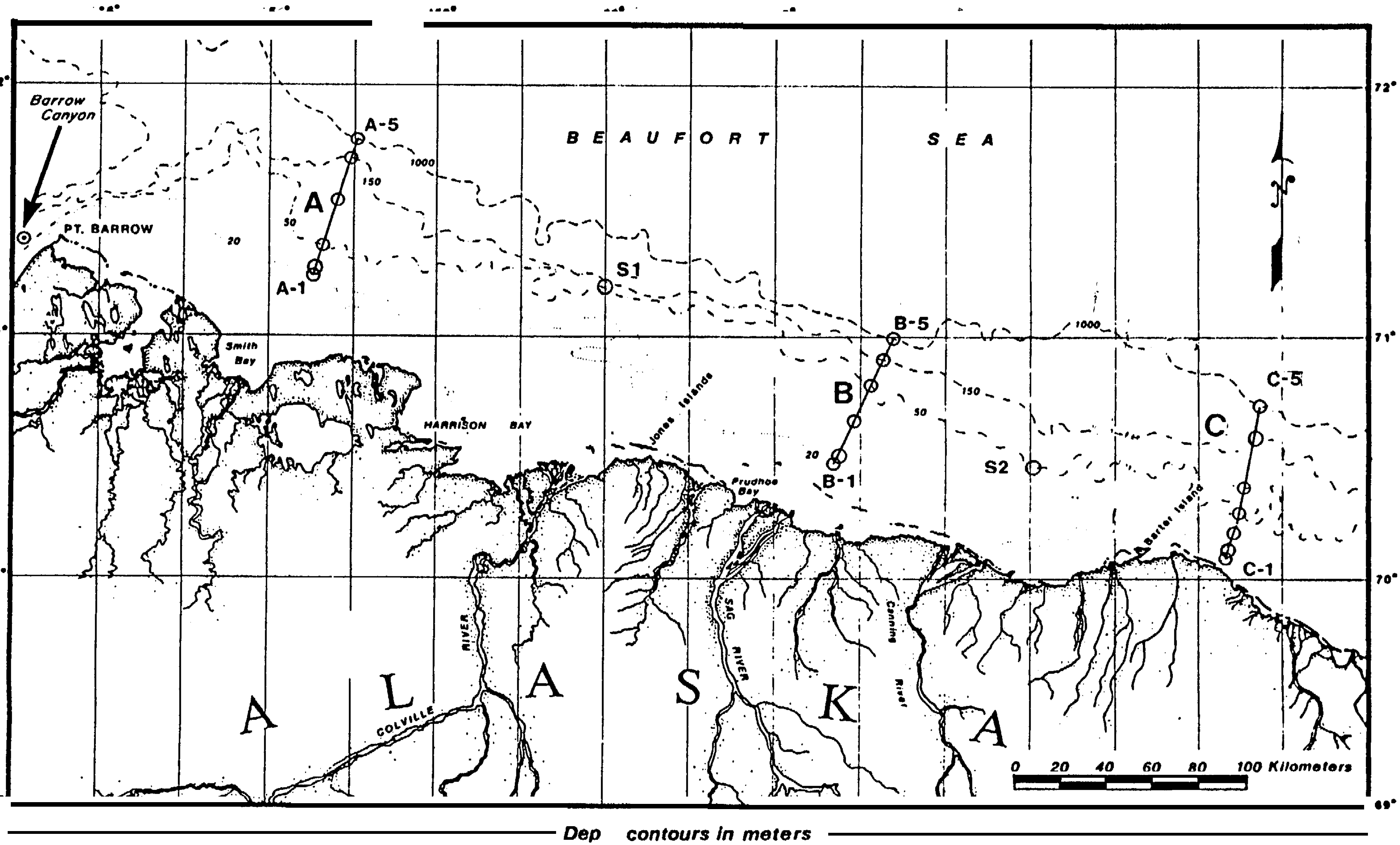


Figure 2. Recommended Station Locations.

also to be removed from the known areas of heaviest ice gouging (cf. Barnes et al., 1984). Section C is particularly important, since it represents a substantial eastward extension of earlier measurements on the shelf. In providing observations closer to Canadian waters, it may also facilitate comparisons with circulation studies presently under way by the Institute of Ocean Sciences at Sidney, B.C. To define the oceanic forcing for the shelf, we recommend that the sections be extended out over the shelf with a mooring on each line at the 1000 m isobath. We further recommend that a mooring also be installed west of Pt. Barrow, in Barrow Canyon (Fig. 2), which is a known major source of water and organisms for the Beaufort shelf, and between which dynamical connections have been argued (Mountain, 1974; Aagaard, 1984).

The recommended cross-shelf sampling on each section line includes four sites in addition to the slope location. The first of these is one representative of the outer shelf circulation, a reasonable choice being over the 150 m isobath, which is close to the shelf edge. Since the flow tends to follow isobaths, it is desirable that the sampling be at corresponding depths at each of the sections, and with one exception we follow that principle. Our next common choice of sampling site is over the 50 m isobath, which we take to represent the transition zone between the outer and inner shelf regimes. For the innermost site we choose the 20 m isobath. The latter is in general near the fast ice edge, and this is an area of considerable ice gouging. We shall deal with this problem in the next section. The suggested arrangement results in site separations over the shelf along the sections as great as 40 km (with a minimum of 8 km). This may well exceed the coherence scale across the shelf, and we therefore recommend that the largest gaps be filled with a fifth mooring in each section. This would lie between the 20 m and 50 m sites in sections B and C, and between the 50 m and 150 m sites in section A (cf. Fig. 2). For convenience we have designated the mooring sites as A-1 through A-5, B-1 through B-5, and C-1 through C-5, with A-1 representing the innermost site (20 m) in section A, A-2 the next site seaward, etc. In passing, we note that the Barrow Canyon site will be in water less than 100 m deep.

The ability to resolve the vertical structure of the circulation is limited by the hazards of the moving ice, requiring instruments to be below the reach of the ice. Expedience on this shelf suggests that 40 m below the ice is a reasonably safe operating depth (cf. Aagaard, 1984; Barnes et al., 1984), and if this is adopted as the upper limiting extent of a mooring, the upper part of the water column will be unsampled. To overcome this limitation, we recommend the use of a bottom-mounted Doppler profiling current meter at one site in each section, specifically at A-3, B-4 and C-3. This would allow full-length time series flow measurements to within about 5 - 10 m of the sea surface, the exact distance depending on total depth and on the beam geometry selected for the profiler. The current profiler at C-3 provides upper ocean current measurements in an area in which there is a pronounced offshore wind structure induced by the proximity to the coast of the Brooks Range (cf. meteorology section). Determining the effect of this anomaly in the wind forcing on the upper ocean circulation is a potentially important problem worthy of some effort. In addition, each of the profiling current meters would allow measurements of the ice velocity, from which surface currents can be inferred if the wind field is known, subject to certain assumptions involving the internal ice stress and the boundary layers. The extrapolation of the upper water column velocity structure to other sites of course assumes the shear to be horizontally invariant, the correctness of which can be tested in several ways. The first is by adding several additional profiling current meter installations as an option. Specifically, we recommend two near the 50 m isobath, one at 150°W and the other at 145°W. The two additional installations serve the further purpose of considerably extending the resolvable flow scales by filling in the very large gaps between the mooring lines A-C. The second check on shear in the upper water column can be had by obtaining synoptic hydrographic and profiling current meter (lowered or expendable) sections along each hydrographic section line, for example on deployment and recovery of the moored arrays. This is a straight forward procedure which can also be used to interpolate in a snapshot fashion horizontally between mooring sites in any given section. The hydrography should also include nutrient sampling. Still a third method is to obtain upper-ocean profiles from the several drifting ice platforms proposed for the meteorological program (cf. meteorological section below). This involves suspension of a chain of sensors in the upper ocean below the meteorological instrumentation, and utilizing the same data transmission link as for the meteorological package.

At the individual moorings in the core program, we recommend that only one current meter be deployed at the 20 m and 50 m isobath sites, so that the flotation be kept as far below the surface as possible. At the 150 m sites, instruments should be installed just below the top float at 40 m, near 75 m, and about 10 m off the bottom; while at the slope sites (1000 m depth), again just below the top float, near 150 m, and about 10 m off the bottom would provide a reasonable sampling of the water column. The mid-depth current meters will provide shear data centered on the principal density gradient, and they will also help monitor upwelling and offshore eddies. In addition we recommend installing a short temperature\conductivity chain above the bottom current meter at moorings A-2 (50 m depth) and at A-4 and C-4 (150 m depth). These would be able to detect both outflow of dense brine-enriched shelf water and the intrusion of offshore waters upwelled onto the shelf (Aagaard et al., 1981). It is also highly desirable that the current meters be equipped with temperature and conductivity sensors, since this would provide continual monitoring of the gross hydrographic structure of the section at little additional cost. Finally, sea bottom pressure gauges should be installed at two sites in. each of the three sections to detect such perturbations as shelf waves and fluctuations of the longshore pressure gradient. Our choice would be at the 20 m and 150 m sites, i.e., at A-1, A-4, B-1, B-4, C-1 and C-4, since this placement provides the largest cross-shelf coverage. However, because of the danger from drifting ice (cf. section on ice hazards and redundancy) this choice requires the use of three additional instruments at the three redundant moorings, i.e., nine in all. It may therefore be more practical to move the innermost pressure gauges to the 50 m moorings, saving three instruments, but with the loss of some data coverage of the inner shelf. We offer this as an option, to be exercised depending upon instrument availability.

All instruments should sample at one-hour intervals to provide the necessary resolution at tidal and lower frequencies.

These recommendations are summarized in Table 1, and specific instrument considerations are discussed in the section on Instrumentation below.

Table 1. Oceanographic Instrumentation Locations.

Mooring	Sounding	Current Meter Depths	T/C Chain	Pressure Gauge
A-1	20 m	17 m		yes
A-2	50 m	42 m	yes	
A-3	∿ 80 m	Doppler profiler		
A-4	150 m	42, 75, 140m	yes	yes
A-5	1000 m	42, 150, 990m		
B-1	20 m	17 m		yes
B-2	∿ 40 m	37 m		
B-3	50 m	42 m		
B-4	150 m	Doppler profiler		yes
B-5	1000 m	42, 150, 990m		
c-1	20 m	17 m		yes
c-2	∿ 40 m	37 m		
c-3	50 m	Doppler profiler		
c-4	150 m	42, 75, 140m	yes	yes
c-5	1000 m	42, 150, 990m		
s-1	50 m	Doppler profiler		
s-2	50 m	Doppler profiler		
Barrow Canyon	∿ 80 m	42, 70m		
Met St. B		20, 40m	yes	
Met St. C		20, 40m	yes	
Met St. D		20, 40m	yes	

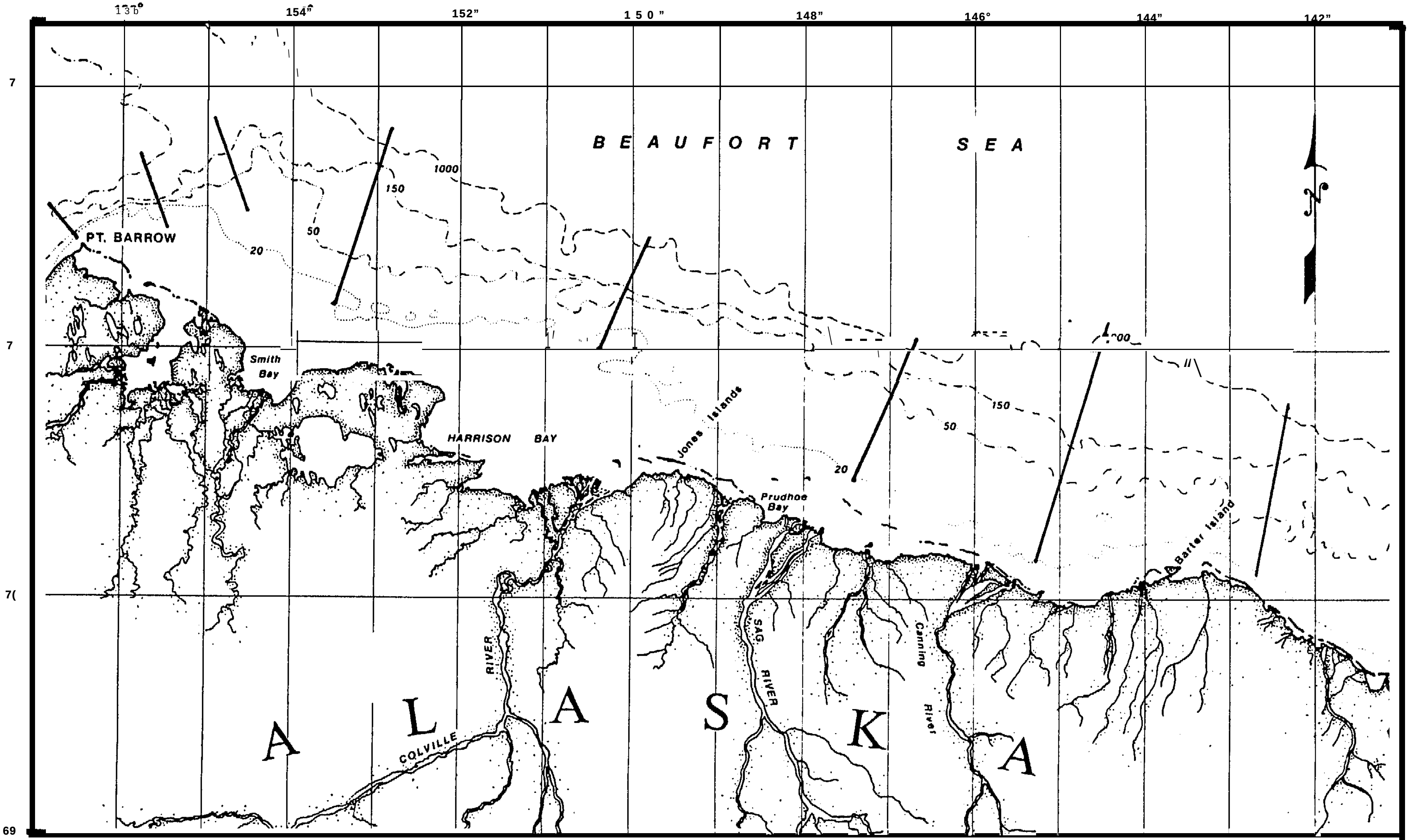
3. ICE HAZARDS AND REDUNDANCY

Moorings seaward of the 20 m isobath, i.e. , all except A-1, B-1 and C-1, do not have exposure above about 40 m and are thus relatively safe from ice damage, although ice contacts can not be precluded even at 60 m depth (Reimnitz et al., 1984). However, the 20 m moorings have significant probability of being impacted, since the sea floor is densely gouged well seaward of this depth (Barnes et al., 1984). The hazard can be evaluated in the following manner. From Barnes and Rearic (1985) the average dated gouge ensemble on the Beaufort shelf inshore of the 25 m isobath represents a 2.7% disruption of the sea floor per year. This is a zone where the gouge density is of order 70 km^{-1} track line. Barnes et al. (1984) also show that the gouge density can exceed 150 km^{-1} out to about the 50 m isobath. If the gouging frequency is in constant proportion to gouge density, which is equivalent to assuming uniform recovery of the sea bottom across the shelf, then 150/70 x 2.7% ≃ 6% of the sea floor is disrupted each year in the most vulnerable area (490/70 x 2.7% ≃ 19% in the most extreme case of Table 1 , Barnes et al. , 1984). This is a lower bound on the impact probability for instruments or components sitting above the bottom; the upper bound is unknown, but surely higher. Our recommendation is therefore that the innermost moorings (A-1, B-1, C-1) be made redundant by deploying an identical set in the immediate vicinity. Gouging statistics (Barnes et al., 1984, Table 1) suggest that a horizontal separation of 150 m is sufficient to avoid a single event impacting both installations, assuming they are placed normal to the isobath orientation, which is the approximate typical gouge orientation. The situation can be optimized by actually separating the moorings by a distance greater than this, to both provide redundancy and at the same time examine small-scale horizontal coherence across the shelf in the vicinity of the fast-ice edge. A separation of 2-3 km is a reasonable compromise between redundancy and additional information.

4. HYDROGRAPHY

The core program of long-term moored instrumentation should be supplemented by a set of hydrographic observations consisting at a minimum of high quality CTD profiles, and preferably including nutrient sampling as well. While these measurements will by themselves likely provide little direct quantitative information on the circulation, they serve as indicators and tracers of such processes as brine drainage, mixing, and upwelliing. They may also facilitate the interpretation of the moored measurements, both in a dynamic sense (e.g. , estimating geostrophic shear) and in providing other contexts for the moored measurements (e.g., heat and mass budgets).

We therefore recommend that a set of hydrographic sections be done during both deployment and retrieval of the moorings. In addition, if the mooring work is done during summer (cf. logistics section), then a separate hydrographic cruise should be conducted during late winter or early spring to map winter conditions. These sections should be located near the three mooring lines A - C, and they should extend past the inshore and offshore moorings by 3 - 5 km. In addition, it is desirable that the large gaps between the mooring" lines be filled with two additional hydrographic sections near 145*w and 150°W, i.e., near the two recommended additional profiling current meter installations. Finally, we urge that three short sections be done across Barrow Canyon and its northeastward extension, near 156"30' W, 155°30'W, and 154°30'W, to examine the upstream source of the water moving along the shelf. This is particularly important to the winter sections for purposes of examining brine drainage. The Barrow Canyon sections need not exceed 20 - 40 km in length, whereas the others will range from 50 - 100 km. These recommendations are denoted in Figure 3.



Depth contours in meters

Figure 3. Recommended Hydrographic Section Locations.

Distance between stations should be about 8 km in each section, which will require a maximum of 14 stations for a section. It is important that sampling be done to the bottom, i.e., within 1 - 2 m or less of the sea floor.

5. ACOUSTIC TOMOGRAPHY

Ocean acoustic tomography offers a possible approach for observations of the shelf circulation. The tomographic method consists of first measuring the travel time of an acoustic signal along a known ray path through the ocean. Fluctuations in travel time are then interpreted as fluctuations in the integrated temperature and current along the path. The travel time depends on the speed of sound and current velocity; and the speed of sound, in turn, depends on the temperature and the salinity by the following relationship:

$$\frac{\delta C}{C} = \alpha \delta T + \beta \delta S,$$

where $\alpha = 3.16 \times 10^{-3}\ {}^{\circ}C^{-1}$, $\beta = .96 \times 10^{-3}\ ({}^{0}/_{00})^{-1}$

In the Arctic Ocean at mid-depth, temperature fluctuations have an order of magnitude greater influence than those of salinity, since $\delta T \simeq .05$ and $\delta S \simeq .015$, so that changes in travel time along a ray path can be interpreted as an integrated temperature change from some base value, although salinity effects are not always negligible. Current effects are separated from those of temperature by reciprocal shooting, and then taking the sum and difference of travel time along the same ray path, but in opposite directions. The sum gives twice the temperature effect, while the difference gives twice the current effect.

The vertical resolution of tomography depends on the geometry of the eigenrays, i.e. , those paths which lie between a fixed source and receiver. In the Beaufort Sea the sound speed profile is upward refracting and sounds transmit by refracted-surface reflected (RSR) rays. Figure 4 illustrates a set of RSR eigenrays for 200 km range in the deep Beaufort Sea. The deepest penetrating ray makes seven bounces off the under ice surface, and apexes of the ray lobes penetrate to a depth of approximately 1,250 m. Rays that make additional bounces have shallower turning points in an orderly and predictable fashion. The resolution of the current and temperature profile depends on the ray geometries, which in turn depends on the mean sound-speed profile and to a lesser extent on the source-receiver placement. In general, the results of a tomographic inversion will give better resolution and accuracy in those areas which are sampled by the most rays. In the Arctic this is the near-surface areas, since all rays reflect from the ocean surface, whereas coverage is poorest in the deep regions where fewer rays penetrate.

The usual approach of measuring arrival times of signals traveling via identifiable eigenrays will not work in shallow water, since there is not enough vertical excursion for rays to develop large differences in travel time. Pulses arriving along all paths have nearly identical travel times and overlap in time at the receiver, so that it is not possible to distinguish and identify paths. On the Beaufort shelf the weak sound speed gradient results in rays traveling between source and receiver as surface reflected - bottom reflected types (SRBR). A set of such eigenrays is shown in Figure 5a for the sources and receivers mounted a few meters above the bottom at a range of 20 km. The total spread in arrival time for all paths is about 10 to 15 ms, so that the resulting received signal

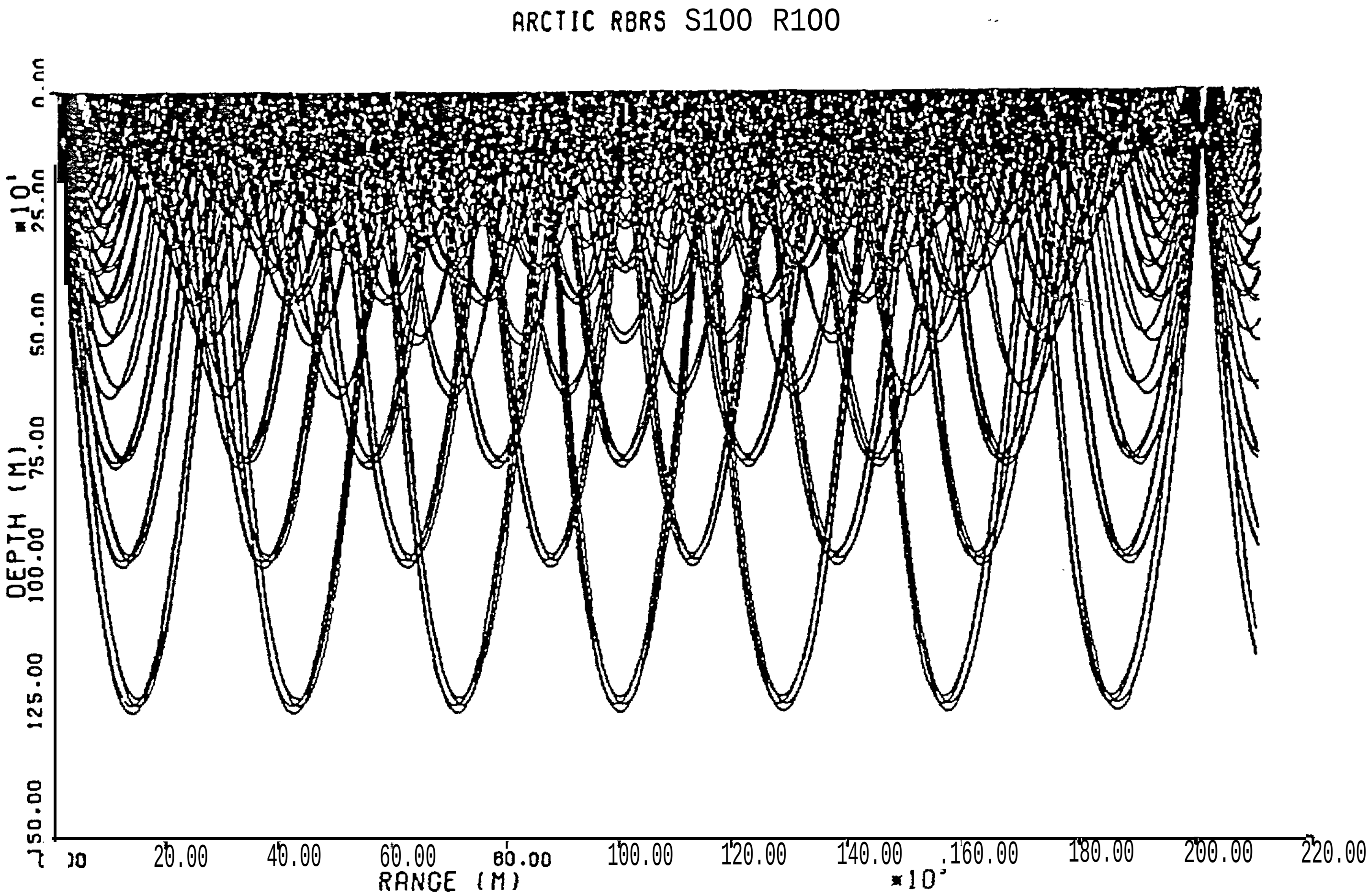


Figure 4a

Fig. 4a. Paths of eigenrays computed for the Beaufort Sea with source and receiver located at 100 m depth. The upward refracting sound-speed profile results in rays that make multiple bounces off the under ice or ocean surface.

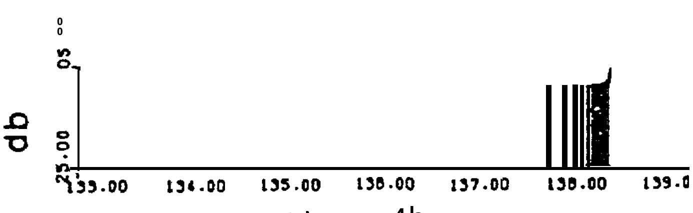


Figure 4b

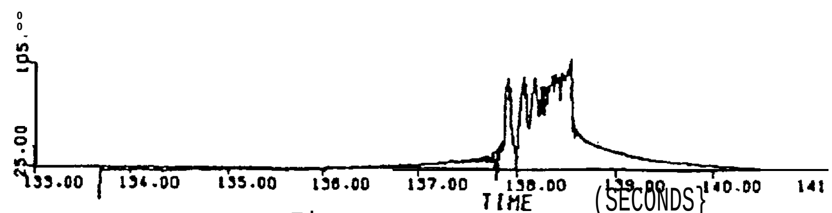


Figure 4c

Fig. 4b. Intensity versus arrival time for the eigenrays of Figure a. Rays that travel deep in the channel arrive first in groups of fours associating with combinations of up-and-down launch and receive angles. Arrival time is nearly proportional to the depth of the ray apexes.

Fig. 4c. Predicted pulse response for a typical tomographic probe signal. The first arriving 5 paths can be separated in time.

(Fig. 5c) is a single broadened pulse, and individual arrivals are not separable in time. All rays sample the entire water column, and it is therefore impossible to measure current and temperature profiles. However, by measuring the average arrival time of the broadened pulses, the range and depth averages of the temperature perturbations of the channel are observed. With reciprocal transmission, the range and depth average of current gives transport.

The principle advantage of tomography in this application is that it provides horizontal and vertical averages. By comparing a single tomographic measurement, say, one that averages over 20 km, with a current meter point measurement, it also becomes possible to estimate coherence length.

Four tomographic experiments have been considered, two in the deep offshore area and two on the shelf. Briefly, they are described as follows.

Offshore Triangular Array

A three-point reciprocal transmission moored array approximately 200 km on the side, situated offshore but adjacent to the shelf area, would provide monitoring of the vertical profile of the temperature, current speed and direction, and vorticity. This would therefore monitor the offshore oceanic forcing on the shelf. Each array element would consist of a single transceiver package moored at a depth of 50 m below the surface, which would both transmit and receive at 12-hour intervals for a period of one year. The system would be entirely self-contained and battery powered. Problems associated with precision of clocks and mooring motions are well understood, and several transceiver packages that could be used for this experiment already exist within the research community. The path of eigenrays,

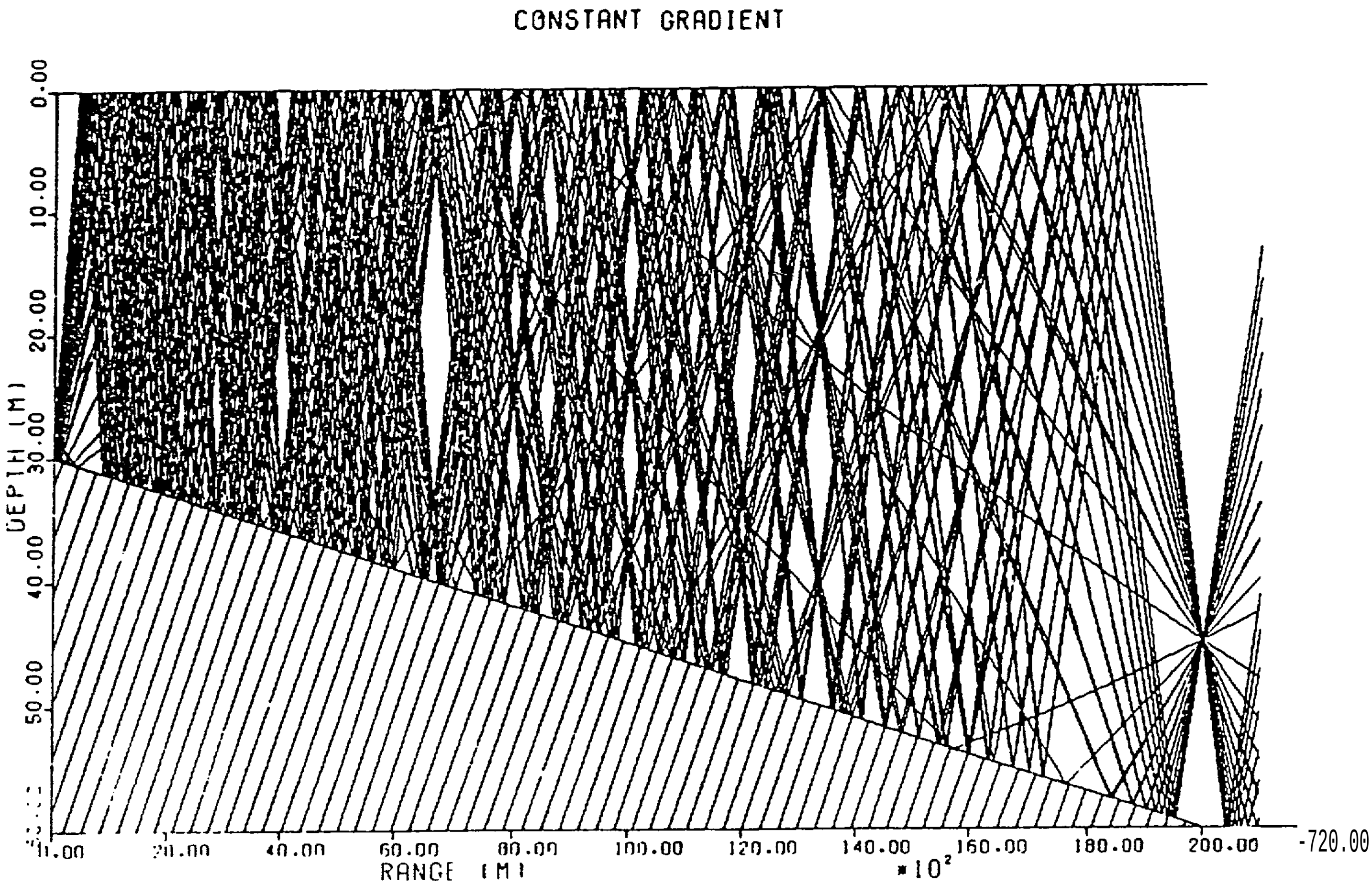


Figure 5a

Fig. 5a . **Eigenrays** for the **Beaufort** shelf area. Source and receiver are spaced by 20 km. The weak sound-speed gradient results in rays that travel by surface reflected-bottom reflected **(SRBR)** paths between source and receiver.

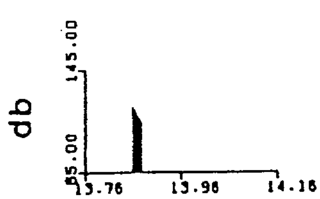


Figure 5b

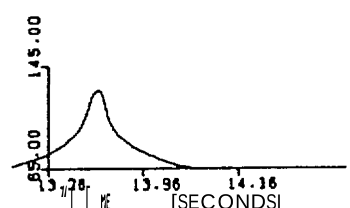


Figure 5c

Fig. 5b. Intensity versus arrival time. All paths have nearly identical arrival times.

Fig. 5c. Pulse response of the channel for a typical tomographic probe signal. All of the received signals overlap in time and individual paths cannot be separated.

the arrival time patterns, and the pulse response of the channel for a typical tomographic signal are shown in Figure 4 A-C. The arrivals from various paths are spread out in time and easily identifiable and resolved with temporal processing. Precision of travel time measurements for a particular path should be within 1 ms, for which Table 2 shows a typical current and temperature resolution. Vertical resolution of the current and temperature profile should be quite good. The last arrivals are associated with rays that have turning points near the depth of the receiver. The arrival time of the last rays is used to estimate the average current and temperature in the upper 50 m. From 50 to 500 m depth, inversion will estimate currents in steps of 10 - 20 m and then from 50 - 200 m increments for the lower depths. The resulting current profiles are for horizontal range averaged currents over approximately 200 km.

Table 2. Acoustic Tomography Resolution.

Travel Time	Temperature	Current
Deep Array		
1 ms	.0002°C	.2 cm/sec
Shallow Array		
.2 ms	.002°C	2 cm/sec

Offshore Line Array

A three-element line array along a slope contour line allows for a redundant measure of the longshore velocity component, together with an estimate of the divergence. The transceiver 'would be located on the 1000 m contour.

Shelf Triangular Array

A triangular array on a shelf area of perhaps 20 km on the side would resolve onshore and alongshore current component and vorticity. Fluctuations with length scales less than 10 km would be strongly filtered.

Shelf Line Array

An unevenly spaced line array of four transceivers would permit a measure of the longshore component of current for six different horizontal length averages. The length scale of the fluctuations could then be deduced and used to extrapolate and interpret results from the point sensors used in the core program. Similarly, a line array oriented perpendicular to the shore would provide estimates of the magnitude and correlation length of cross-shelf fluxes.

Of these experiments, a modification of the shelf line and shelf triangular arrays is suggested. The proposed location of the transceivers is shown in Figure 6. Components of vertically averaged transport for each receiver pair would be measured, thus providing up to four separate estimates of the cross-shelf transport over the extent of the grid (in addition to longshore flow estimates). This is therefore a means of measuring cross-shelf fluxes in the face of possible strong longshore variations of small scale.

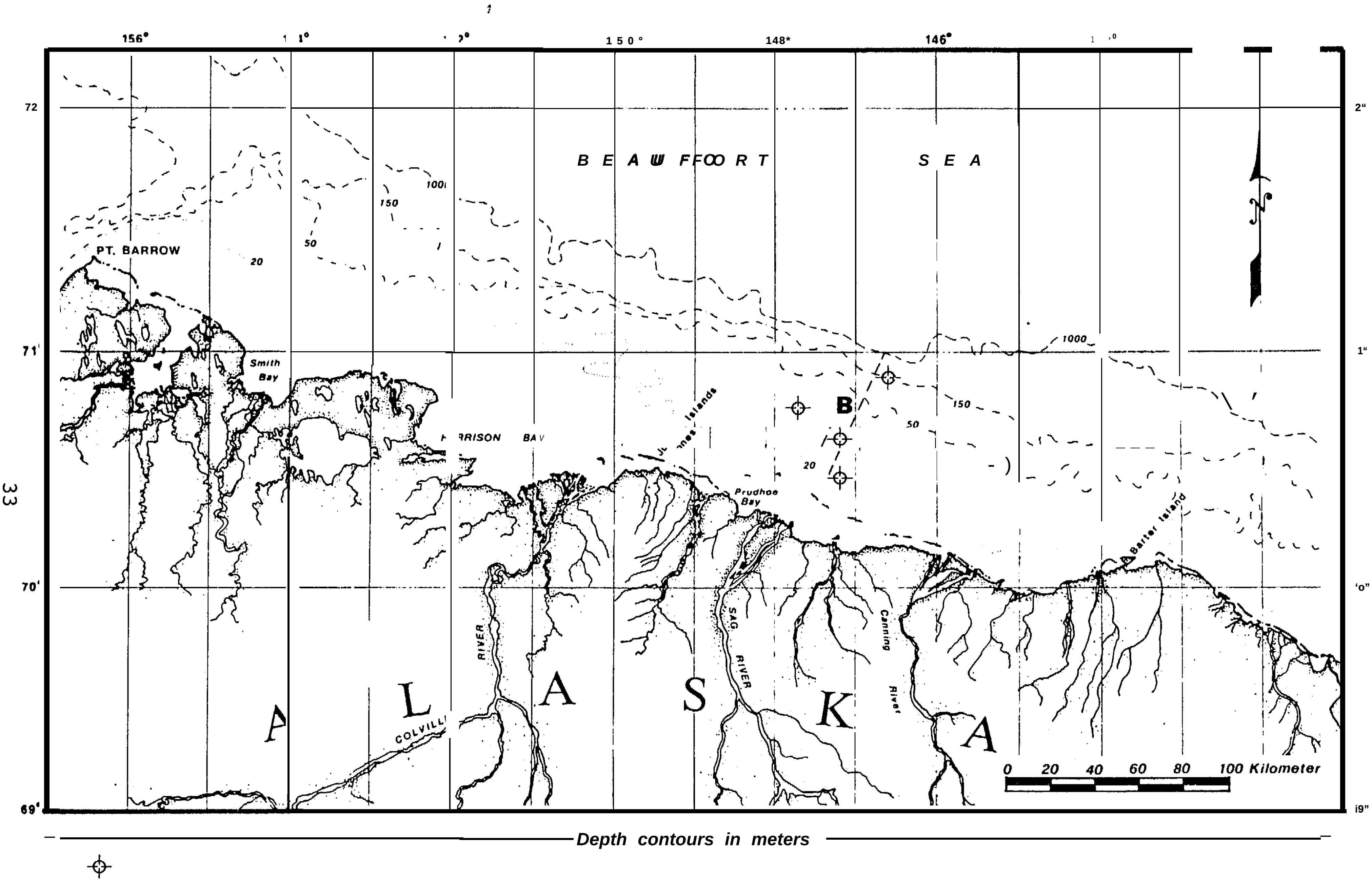


Figure 6. Transceiver locations for possible shelf tomography experiment.

There are, however, a number of technical difficulties which make tomography very much experimental. For example, the precision of travel time measurements for ray paths making multiple interactions with the under ice surface is not well understood.and has never been measured. When signals reflect from the ocean wave surface, without the presence of ice, there is a strong nonsecular component which is Doppler-shifted by the ocean wave motion. Coherent signal processing techniques are essentially narrow band filters which remove the Doppler-shifted components and retain the specular unshifted signals. It is these signals which can be used for precise travel time measurements. For under-ice reflection there will be both specular and non-secular components, but the nonsecular components are not significantly Doppler-shifted and cannot be readily discriminated against with coherent processing techniques. In fact, the scattered energy will continue to transmit with multiple reflections to the receiver, producing a coherent reverberation background which will both interfere with and broaden the signal arriving along the eigenray paths. The temporal resolution of the previous deep ocean tomography experiments with reflected-refracted paths will therefore be difficult to duplicate in the Arctic.

The reflection loss associated with ice is also poorly understood and quantified from experimental data. Losses could be as much as 3 to 6 dB per bounce, further complicating the precision of travel time measurements.

Overall, therefore, tomography must be regarded as highly experimental methodology, rather than an established oceanographic technique. Yet there are advantages that could help balance the risks. For example, the horizontal averaging capability of tomography could be a key to understanding the spatial scales of the circulation. Furthermore, a vertically integrated measurement including upper water column properites is obtained, thus yielding total transport within the grid.

6. METEOROLOGICAL MEASUREMENTS

Figure 7 shows the recommended network of permanent manned land (▲), unmanned satellite transmitting land (o), and unmanned on-ice satellite transmitting (+) weather stations necessary to define the wind field on the inner-and outer shelf. The probable seaward limit of orographic effects is shown by the dashed arc. Also, there are usually two drifting atmospheric pressure and position buoys 150 km north of this proposed array. They are part of the ongoing Arctic Basin Buoy Program (National Science Foundation, U.S. Navy) which will continue for the next four years. The zones seaward of Smith Bay (l), Stefansson Sound (2) and Camden Bay (3) (coastal segments numbered in Fig. 7) are the study areas of major concern. Sites A and E are the permanent NWS stations at Barrow and Barter Island respectively; sites H (Franklin Bluffs), G (Jago River site), and F (Narwhal Island) would be unmanned satellite transmitting weather stations on land; and sites B, C, and D would be unmanned satellite transmitting weather stations installed by helicopter on the ice 100 km north of the coastline.

The information transmitted from the land weather stations would be temperature pressure, wind speed and wind direction relative to a fixed azimuth. The on-ice stations would transmit the same parameters plus magnetic compass readings (for azimuth determination), together with the oceanographic parameters listed in the instrumentation section.

The geometrical center of networks A-B-F (outer shelf), A-B-H (inner shelf) and A-F-H (near shore) can be used to define the geostrophic wind velocities (Vg), from which the suface wind stress can be estimated for the zones seaward of

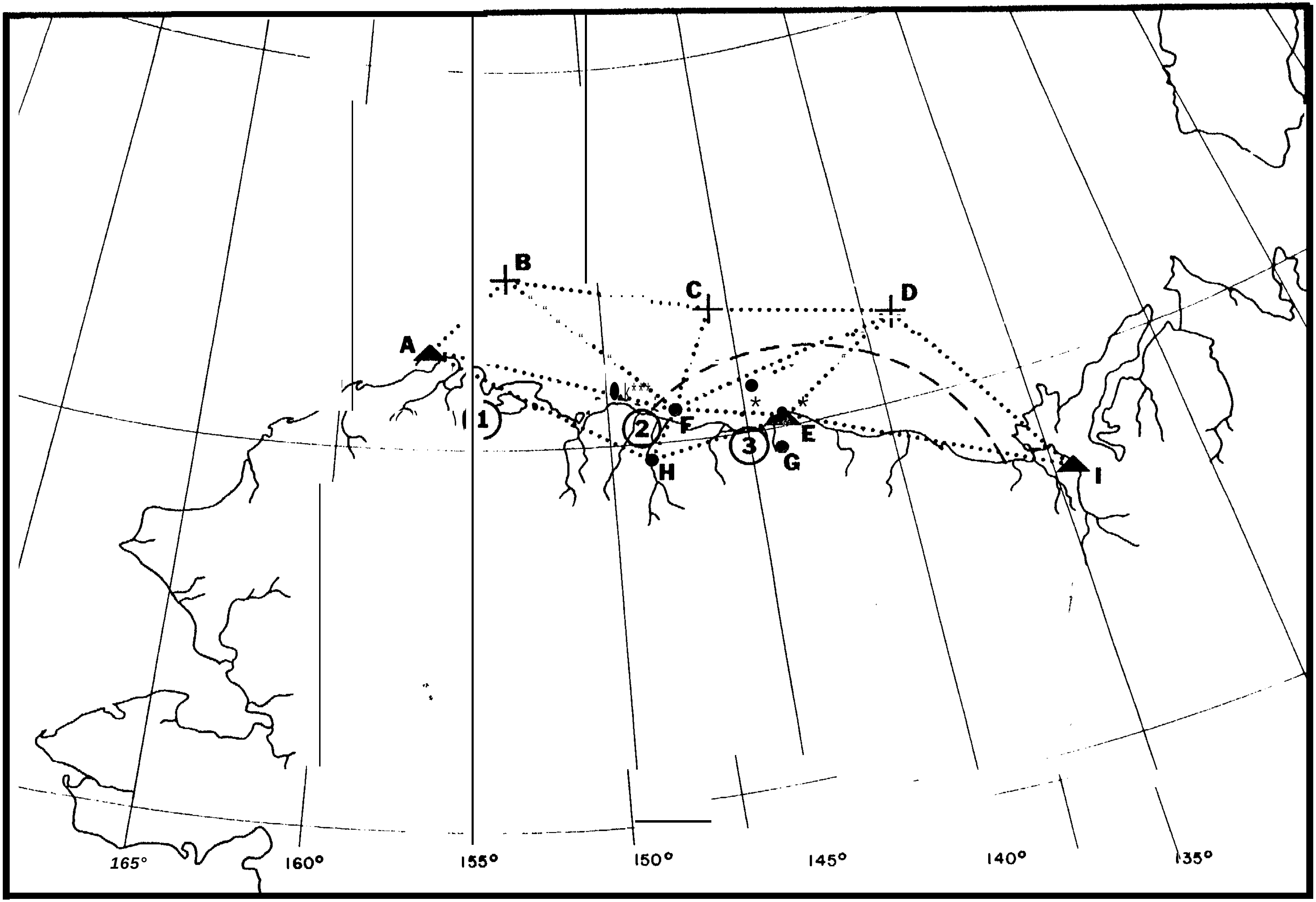


Figure 7 . Possible weather station networks for deriving a high resolution geostrophic wind on the inner and outer shelves. The dashed line-is the probable maximum extent of orographic effects.

Smith Bay; that of networks F- C-D (outer shelf), H-C-E (inner shelf) and H-F-E (near shore) can be used to define Vg for the zones seaward of Stefansson Sound; and that of networks C-D-E (outer shelf), F-D-E (inner shelf) and H-F-E (near shore) can be used to define Vg for the zones seaward of Camden Bay.

Only the inner and outer shelf geostrophic winds are required to resolve the wind field within the defined study area west of Camden Bay. However, the nearshore winds in this region would probably be useful in examining exchange mechanisms between the nearshore and inner shelf regions. Furthermore , the nearshore winds can be obtained by the addition of a single station at Franklin Bluffs. This unmanned land station is relatively inexpensive compared to the on-ice stations, with much easier logistics, and we therefore recommend it as a cost-effective and worthwhile option.

The Camden Bay area will be highly susceptible to orographic effects due to the presence of the Brooks Range (Dickey, 1961; Kozo, 1984a). The pressure difference E-G can be used to determine if the orographic condition known as mountain barrier baroclinity (MBB) is present (Kozo, 1984b). This is caused by northeasterly winds piling up cold air against the Brooks Range, inducing a higher pressure at G than E. The result is a perplexing westerly wind on the inner shelf, while synoptic weather maps indicate easterly winds (Kozo, 1980, 1984a). Under these conditions, when the pressure at Barter Island (E) drops below that at Jago (G), offshore winds from the west will be present on the inner shelf, causing ice and water movement to the east (Kozo, 1984b) despite large scale weather map evidence of winds from the opposite direction. This effect usually disappears in the summer open water season.

The second orographic phenomenon present in the area offshore from Camden Bay is the corner effect (Dickey, 1961; Kozo 1984a). It can occur throughout the year. Stable atmospheric boundary layers, typical of the arctic regions, lead to deflection of large-scale horizontal flows around topographic barriers (Brooks Range) with ensuing speed changes. Dickey (1961) successfully modeled air flow on land around the Brooks Range by using the 600 m elevation contour (approximately cylindrical in shape) as an upper boundary to horizontal wind flow. Kozo and Robe (1984) also successfully predicted offshore buoy drift in this shelf area using Dickey's technique in a modified form. The velocity field around a cylinder of specified radius in steady horizontal irrotational, frictionless flow is well known (e.g., Batchelor, 1967). Therefore taking a wind velocity calculated from network D-F-E pressure data for the area inside the dashed curve (Fig. 7) and modifying it for the corner effect, will give a new speed and direction at any distance offshore from the specified elevation contour (Kozo and Robe, 1984). For example, a geostrophic wind speed U and direction 285" might be changed to 1.62 U (62% speed increase) from 269° (16° change in direction) at E due to the presence of the Brooks Range.

The calculation of the geostrophic wind field itself is straight forward (Kozo, 1982). For example, using triangle CBF in Fig. 7 and noting that pressure can be represented as a function of latitude (y) and longitude (x) on a plane surface, the following set of equations:

$$P_C\ (x,y) = ax_C + by_C + C$$

$$P_B\ (x,y) = ax_B + by_B + C$$

$$P_F\ (x,y) = ax_F + by_F + C$$

are generated, where the subscripts C, B and F denote respective station positions. Pressure (P) data are broadcast by each station, and relative positions of each station are known on a x, y grid; a two-dimensional least squares technique or Cramer's rule can be applied to solve for unknowns a, b and c. Since $\partial P/\partial x = a$ and $\partial P/\partial y = b$, the pressure gradient ∇P can be computed, and therefore also the geostrophic velocity.

INSTRUMENTATION

1. CURRENT METERS

A total of 27 conventional current meters and five Doppler profilers are required for the recommended program, including the three redundant moorings, the two optional profiler installations, and the Barrow Canyon mooring. Current meters of proven capability with both temperature and conductivity sensors are readily available, and they have been used in both polar regions over many years by a number of investigators.

Doppler profilers are a relatively new development, but they have recently been successfully deployed in the offshore Beaufort Sea in a downward-looking mode from a drifting ice station as part of the 1984 AIWEX program. The range for a 300 KHz instrument readily exceeded 300 m, so that the amount of back scattering to be expected in these waters is more than adequate for their deployment on the shelf. Bottom-mounted versions with tilt and directional sensors logging into the recording data stream are also available, and these have been successfully deployed both on the northern California continental shelf and in the Gulf of Maine (Pettigrew and Irish, 1984) as well as on industrial oil platform applications. A real-time current monitoring installation on the New York coast has also used a bottom-mounted Doppler system (Appell, 1984).

Approximate cost of suitable conventional current meters is in the $6000-$8000 range for each instrument. Doppler profiler instruments are approximately $75,000 each.

With the current meters, as with all the instrumentation for the program (e.g., pressure gauges, CTD, etc.), careful attention must be paid to proper calibration procedures.

2. PRESSURE GAUGES

Nine pressure gauges are required (six under the suggested option). The most stringent accuracy requirements probably come from determining the fluctuations in the longshore pressure gradient. Work on other shelves (e.g., Hickey, 1984) suggests that fluctuations of order 10^{-4} cm see-2 need to be resolved. For 200 km separation, this corresponds to sea level differences of about 2 cm, which is easily resolved by available stable sensors. These have a resolution at typical shelf depths of a fraction of a millimeter and a repeatability of a fraction of a centimeter (Wearn and Larson, 1980), and they have been used successfully in both the Arctic and the Antarctic during the last decade, including deployments on the Alaskan shelf. Suitable pressure measuring instruments cost approximately $5000-$6000 each.

3. TEMPERATURE AND CONDUCTIVITY SENSORS

Three temperature/conductivity chains are recommended for the moored arrays and an additional one to be installed in conjunction with each drifting meteorological station. The most stable sensors available today for these applications have an accuracy over a year of about 0.01 - 0.02°C and 0.03 millimho cm^{-1} which is amply adequate for the intended purpose. While complete systems are not now available off-the-shelf, integration of the sensor signals into data loggers is not a formidable task. With respect to the chains suspended from the drifting meteorological stations, these should include two current sensors, and their integration into the data stream will also have to be customized. Again, conventional current sensors are suitable and their use in this mode is routine. T/C chains and recorders can cost up to $18,000 each.

4. TOMOGRAPHIC INSTRUMENTATION

Transceiver units for reciprocal shooting have been available only in the research community (Government laboratories and universities) until recently, and such units might be obtained from these sources. However, several research groups have agreed on design standards and commercial units are now available. Cost per unit is about $85,000, including technician services for installation at sea. Typical standard specifications (Worcester et al., 1984; 1985) are as follows:

Carrier Frequency	400 Hz
Band Width	80-100 Hz
Endurance	18 months or 50 hours of transmission
Operating Depth	2000 m (6000 m optional)
Batteries	Alkaline
Weight	500 Kg

5. METEOROLOGICAL INSTRUMENTS

Drifting Meteorological Stations

Three offshore drifting meteorological stations are recommended, with additional stations to be emplaced as previous ones move out of the study area with the drifting pack ice. Stations would include sensors for wind speed and direction, barometric pressure, air temperature, compass heading, internal temperature (used as a correction on the pressure sensor output), and oceanographic sensors. The oceanographic sensors would include current speed and direction, temperature, and conductivity at 20 m and 40 m below the surface. The latter measurements provide estimates of shear and other gradients in the upper ocean.

For reasons of helicopter transport and rapid installation, the wind sensor could be mounted on a 3m mast above the ice surface. Battery power by lithium units is preferable to alkaline. Wind speed and direction data should be vector-averaged over 15 minute periods, taking a series of instantaneous values every 10 seconds (90 values). The data could be transmitted via either the ARGOS or GOES system.

Average cost for these drifting stations would be approximately $40,000 with oceanographic current, temperature, and conductivity sensors attached. Alternately, the minimum meteorological requirements would be met by measuring only barometric pressure (and internal temperature). Together with the satellite positioning capability, this would still provide a vital data base at a substantially reduced cost, and we suggest it as an option.

Prior to individual deployment, the meteorological station pressure sensors (land and on-ice) should be calibrated simultaneously to obtain relative offset through use of a pressure standard. This same standard should be matched to the station pressures at Barrow and Barter Island also.

Land Meteorological Stations

Three on-land meteorological stations are proposed in addition to those already operated by the National Weather Service. Stations would include sensors for wind speed and direction, barometric pressure, air temperature, and internal temperature for pressure sensor correction.

The wind sensor height above ground would be 10m (standard meteorological elevation). The Narwhal Island (F') and Franklin Bluffs (H) sites have precise elevation measurements available to correct their actual elevation pressures down to sea level pressures (hypsometric equation). The Jago (G) site inland from Barter Island (see Fig. 7) should be at a known elevation, less than 250 m elevation but ∿50km (south) from Barter Island.

The average price for the basic meteorological station with an ARGOS or GOES transmitting antenna and self-contained data processing is about $18,000 each. Alternatively, internal recording and manual retrieval of the data could be considered in order to reduce costs.

6. MOORINGS

The necessary mooring technology has been available for a number of years and is well proven for ice-covered waters (Aagaard et al., 1978; Aagaard, 1981). These techniques essentially involve placing-moorings through the ice and onto the bottom. Acoustic pingers are used for relocation in conjunction with conventional navigation. Acoustic releases are used to bring the moorings up under the ice (or sometimes into a lead). Divers are used to finally locate and retrieve the mooring, after cutting a hole. The techniques are somewhat different than in open water and require particular attention to the acoustics required for mooring relocation.

7. SYNOPTIC SECTIONS

We recommend that the synoptic sections be done with a high-accuracy CTD system supplemented with bottle samples for salt and nutrients. We do not recommend the use of expendable probes since these are expensive and of lesser accuracy. If the sections are done using helicopter logistics (cf. logistics section), then special care need be taken to prevent freezing in the sampling bottles. This is not a trivial problem, but neither is it unsurmountable, and considerable experience in this regard has been accumulated in arctic operations. Obtaining current profiles by lowering an instrument at each hydrographic station is a routine procedure. The use of XCP's at each section is also possible, but would be much more expensive than a high quality profiling current meter.

LOGISTICS

1. GENERAL CONSIDERATIONS

Based upon the scientific rationale and instrumentation requirements_ for the oceanographic program, an operation and logistics plan was formulated. Preliminary analysis involved examining the choice of working platforms (i.e. ice-breakers, conventional ships or boats, helicopters, fixed-wing airplanes, and submarines) that have been successfully used in the Beaufort Sea region in the past. A number of these were eliminated as unavailable or unsuitable. A more detailed analysis was then carried out for the remaining platforms where capabilities, limitations, availability? and cost estimates were closely examined. For the purpose of cost estimates, availability, and comparisons, only commercially run platforms were examined, although government owned and operated facilities may be available for the program, such as icebreakers or helicopters.

Submarines, conventional ships and boats, and fixed-wing airplanes were eliminated from further consideration as work platforms during the preliminary analysis. Suitable submarines are not commercially available, would be too costly, and are completely inappropriate for the planned mooring operations. Whereas conventional ships and boats have been used extensively in the nearshore regions of the Beaufort Sea during the open water period, the 20 m isobath is near the limit of their capability before ice reinforcing becomes necessary. Since the oceanographic program requires getting out to the 1000 m depth contour which is 80-120 kilometers offshore, ice breaking capability is required for ship support. Fixed-wing support was eliminated from consideration since landing near predetermined mooring sites would be very limited out on the pack ice, as a result of the numerous pressure ridges and rubble fields. However, airplanes may be useful in shuttling heavy mooring supplies from the base of operations to remote locations closer to the study site (e.g., transporting buoys, chain, anchors etc. from Prudhoe Bay to Barter Island).

The choices that were left following the initial analysis were either icebreakers or helicopters. Both of these methods have their advantages and disadvantages which are discussed in detail in the subsequent sections, followed by recommendations and conclusions.

Two separate trips will be required to deploy and recover oceanographic equipment, assuming an initial one year deployment of instrumentation. The exact timing of the deployment and recovery of oceanographic moorings will depend on the final selection of the logistics method to be used. Additional trips will be required for hydrography, the number and timing again depending on the logistics selected. For example, if mooring deployment and recover is by ship during summer, then a helicopter cruise will be desirable in the late winter or early spring. In addition, a number of intermediate trips will have to be made to deploy offshore meteorological stations. The general drift of ice should be slowly westward at approximately 1 km/day during the solid ice period from December to the first week in May. Met station B may drift out of the study area, requiring that an additional station be deployed to the east as stations C and D drift westward. The Camden Bay Zone will probably need a station implanted every three months. It will also be important to visit the shore stations during the spring melt period (late May-Early June) and fall freeze-up period (entire month of September) when anenometers can ice up.

2. SHIPS

The Beaufort Sea shelf region is completely ice covered for most of the year, with only a two or three month period in the summer during which boats can operate. Usually by mid- to late-July, a shore lead has opened up along the Beaufort coast with a 75 percent probability of encountering the ice edge near the shoreline (Webster, 1982). Due to the prevailing winds (east to northeast), the ice is pushed further from shore, but upon a shift to westerlies the ice moves rapidly back in toward the coast. Maximum retreat of the ice edge occurs in mid- to late September (Webster, 1982). During an average year ice concentrations range from 5/10-8/10 during August and September and from 7/10-10/10 during July and October in the study region (LaBelle et al., 1983). The five-tenths ice concentration boundary usually is used to signify the ice concentration above which ice-breaking vessels are needed for navigation. Based on these observations and the experience of numerous investigations along the Beaufort coast, icebreaking capability will be required to get to the shelf break which lies 80-100 kilometers offshore, with the optimum months being August and September.

Icebreakers are usually classified by the amount of ice that they can travel through. Since the majority of the icebreakers working in the arctic are of Canadian origin, the Canadian classification will be used in this report. For example, a vessel which has been designed to Arctic Ice Class I specifications is able to proceed continuously through at least one foot of solid ice at three knots. We deem that a Class I - Class II icebreaker with an experienced crew could negotiate the ice conditions that are likely to be encountered in the August-September time window. Typically these ships are 150 feet in length or longer. A smaller ship could conceivably be used if the ship had a flexible schedule in terms of when certain stations were occupied.

Time estimates were made to carry out the scientific program based on the number and location of moorings and meteorological stations to be deployed and retrieved, and hydrographic profiles to be performed (refer to Figures 2 and 3 for locations). It was estimated that the specified program would take from 16-18 days to carry out from dock "- to dock, assuming certain minimum vessel requirements which are listed below:

- Arctic Ice Class I - II icebreaker.
- Minimum length of 150 feet.
- 24 hour per day operations.
- Accommodations for 6-8 people in the scientific party.
- Boom, A-frame, crane, or davit with hydraulics for deploying and retrieving heavy instrument packages.
- Capable of 1000 nm range and 30 days at sea (not critical since ship could resupply at Prudhoe Bay).
- Satellite and/or GPS navigation system.
- Ample deck space to stow mooring hardware and still have space to safely deploy and retrieve moorings.
- Accurate echo sounder capable of 1000-m depths for the outer shelf and slope work.
- Hydrographic winch.

Some of the above requirements are not critical since winches, navigation equipment, echo sounders, etc. , could be installed for the job.

In preparing costs and estimating time, it has been assumed that the staging area for the field operations would be in Prudhoe Bay. Loading of mooring hardware, anchors, equipment, and project personnel would probably take place from the West Dock Causeway. Since the deepest draft vessel that this facility can accommodate is 2.5-3.0 meters, and no other loading facility is available along the U.S. Beaufort Coast, equipment would have to be ferried out to the icebreaker by a smaller tug or supply boat.

No commercial icebreakers are currently registered in the United States. The majority of the available icebreakers are registered in either Canada or one of the Scandinavian countries, with most of the Canadian icebreakers based out of Tuktoyaktuk in the Canadian Beaufort Sea. To avoid having to ferry equipment and supplies out to a deep draft vessel in Prudhoe Bay, the icebreaker could be loaded in Canada except for the added problem of getting equipment through customs. Transit time to Prudhoe Bay for a vessel originating in Tuktoyaktuk is one to two days depending on the ship, with another two to three days of mobilization\demobilization in Prudhoe Bay. Therefore, the entire vessel lease period would be approximately 30 days each time, along with a 2-3 day charter of a small tug or supply boat.

We investigated a number of suitable vessels for the program so that various choices and alternatives could be considered. In general, vessels originating in Tuktoyaktuk were found to be more expensive due to their higher operating costs and shorter operating season than those found on the east coast of Canada or in Europe. However, ships originating on the east coast or in Europe would have a much longer transit time having to come through the Northwest Passage or down through the Panama Canal and up along the West Coast.

Table 3 gives a brief description of the vessels which have been identified as suitable to perform the required work. All listed vessels were available for the 1986 and 1987 open water season at the time of this report. In some cases the vessel was 'partially committed, so that the client would have to be flexible in terms of when the lease period would begin.

U.S. Coast Guard icebreakers would, of course, be suitable but would have to be committed to the program over the necessary time period to ensure success of the scientific program. The availability of U.S. Coast Guard icebreakers was not ascertained, as this could most easily be done by NOAA directly.

3. AIRCRAFT

The other alternative for conducting an oceanographic investigation in the offshore areas of the Beaufort Sea is to base the logistics on helicopter support. Pressure ridge frequency data presented by LaBelle et al. (1983) show 12 pressure ridges per nautical mile at 25 and 60 nautical miles from shore along the Beaufort Coast. Based on these observations and personal experience of the principal investigators of this report, fixed-wing support was ruled out for use other than for transporting equipment from the base of operations to remote locations closer to the study site.

In order to conduct the sampling program safely from helicopters, ice-covered conditions must exist. In addition to sufficient ice, other environmental constraints are air temperature and adequate daylight and visibility for flying

Table 3. Commercial Vessel Descriptions

Owner/Vessel	Length m	Main Engines BHP	Ice class	Fuel Capacity m3	Desk Space m^2	Crew (24-hour Operating)	Total Accommo-dations	Lease Fees $/Day*
Beaudril/Ikaluk	78.9	14,900	4	1596m^3	452	19	34	$85,000.00
Beaudril/Miscaroo	78.9	14,900	4	1482m^3	452	19	34	85,000.00
Badudril/Kalvik	88.0	23,200	4	1919m^3	442	19	34	90,000.00
Beaudril/Terry Fox	88.0	23,200	4	1919m^3	442	19	34	90,000.00
ATL/Arctic Ivik	67.4	7,200	2	830m3	397	12	29	30,000.00
Canmar/Kigoriak	90.7	16,800	3	1329m3	—	19	34	90,000.00
Canmar/Robert Lemeur	82.8	9,600	3	2060m3	—	16	26	90,000.00
Canmar Suppliers I-IV	62.5	7,200	2	471m^3	—	13	16	30,000.00
Canmar/Supplier VII	56.2	5,280	1	274m^3	—	13	19	25,000.00
Carino/Polar Circle	50.3	2,500	1	370m3	—	12	33	** 8,200.00

* Includes estimate of fuel consumption

** Minimum charter of 70 days to come from East Coast and working. The air temperature below which helicopters will no longer operate is usually taken to be -40°C. Brewer et al. (1977) gives the average minimum, mean, and maximum air temperatures based on the 1, 50, and 99 percentile for the region to be: February (-42°C, -30°C, -8°C); March (-40° C, -26° C, -6°C); April (-32°C, -20°C, -2°C); May (-20″ C, -8*C, +2° C). A minimum of 9-10 hours of daylight is considered necessary in order to have sufficient time for sampling, which precludes any mid-winter work. As seen in Figure 8, the first time nine hours of daylight is exceeded during the year is March 1 at 71″N latitude. Thus, based on air temperatures, ice conditions and daylight, the field work could begin in early March and extend through until early May. Visibility begins to deteriorate at this time as a result of frequently occurring fog and low-level stratus clouds making flying impossible. This gives roughly a two-month window for winter sampling from a helicopter.

Time estimates for helicopter-based operations are 45 working days of charter for both mooring work and hydrography. Using two helicopters reduces the time required. No travel time or mobilization/demobilization would be necessary. Helicopters are readily available in Prudhoe Bay, Barter Island, and in Barrow, and equipment to be used would be loaded or unloaded daily. The study, however, could take slightly longer than the estimated time due to weather days and the time involved in switching the base of operations from Prudhoe to Barrow for the western portion of the study. The eastern portion of the study could be run from either Barter Island, or from Prudhoe Bay if fuel caches were left at some intermediate site.

A minimum endurance of three hours flight time was considered necessary in order to sample the offshore

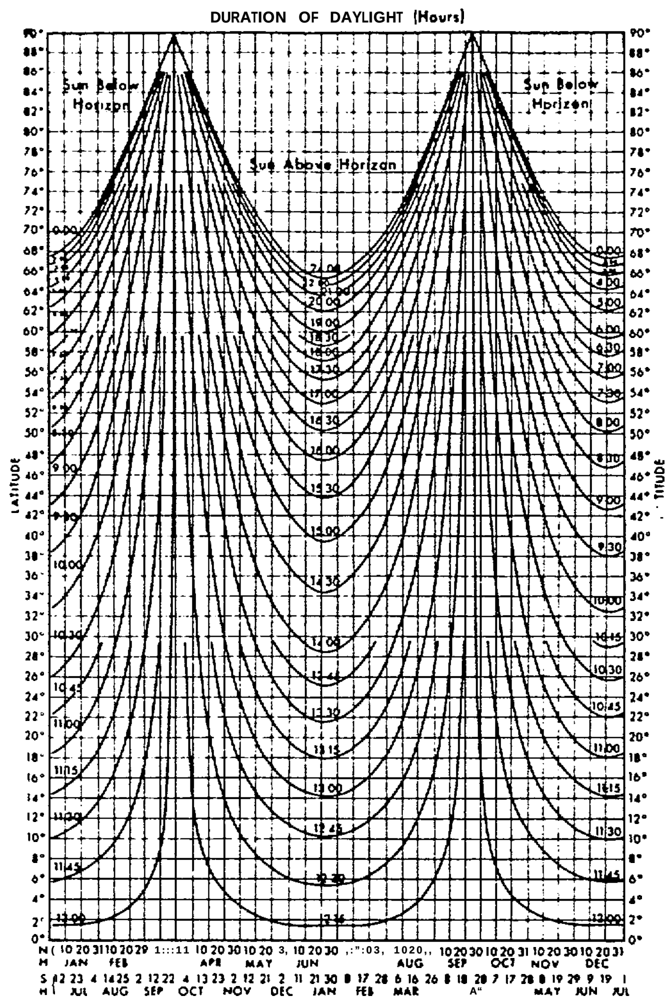


Figure 8. Duration of Daylight.

locations. Based on endurance and on payload and interior volume considerations, a minimum of a Bell 205 helicopter would be necessary. A Bell 212 would be preferable with its twin engines, added safety and slightly longer endurance. Payloads for the Bell 205 and 212 are about the same at 2500 lbs. These helicopters are capable of carrying a pilot, co-pilot/mechanic, and three passengers with 1800 lbs of equipment for 150 km with enough fuel for a safe return. Suitable helicopters also exist within NOAA and have been used on previous OCSEAP studies.

Assuming three hours of flight time per day, the cost of a Bell 205 and a Bell 212 would be approximately $4200 and $5100 respectively per day including fuel. These prices were obtained for commercially available aircraft in Prudhoe Bay.

In addition to the narrow operating window, other disadvantages of helicopter-based logistics include: limited space for equipment, special equipment needed to get through ice, and diving operations necessary for mooring recoveries. A detailed description of equipment and techniques for deploying and recovering instrumentation in permanently ice-covered waters is given in Aagaard et al. (1978).

Other costs which would be incurred for helicopter operations would be room and board costs for the duration of the field effort for scientific personnel. Rental of a truck would also be necessary in both Prudhoe Bay and in Barrow. Room and board typically runs from $90-100/day per person with truck rental being $100/day or $2200/month for a l/2-ton pickup. Even though the field effort may take up to twice as long compared to using an icebreaker, only half the number of scientific personnel (3-4 people) would be required. Since the operating window is fairly narrow, these time constraints could be overcome by utilizing two field teams to conduct field operations out of Prudhoe Bay and Barrow at the same time or in tandem from the same base of operations. For example, it might be desirable to conduct the mooring operations with one aircraft and hydrography with a second.

4. CONCLUSIONS

In order to compare costs between helicopters operations during ice-covered conditions and icebreaker support during the open water season, a number of assumptions were made. It has been assumed that the study would last for a minimum of a one year period with only an initial deployment and a final recovery of oceanographic instrumentation planned. The deployment and recovery dates of the moorings would depend on the logistic method decided upon. Hydrographic work would be conducted at the same time, but would also require one or more additional cruises for coverage during other seasons. Deployment of the meteorological stations would probably be by helicopter, so did not enter into the cost comparison. A summary of costs per trip is given below for both methods.

Helicopter: 4S day helicopter charter* @ $5100/day
15 weather days - no helicopter charge
200 man day per diem @ $100/day
40 days of truck rental @ $2200/month

TOTAL COSTS $252,400

Icebreaker: 30 day vessel charter* @ $30,000/day
3 day supply vessel charter* @ $5000/day
210 man days per diem @ $30/day

TOTAL COSTS $921,300

* Charter lease rates include fuel.

Again, these total costs reflect the amount estimated for each of the two trips involving both mooring ahd hydrographic work. Items which would be the same regardless of the logistic method used, such as mobilization time, were not taken into account in the cost comparison. Therefore these costs should not be taken as complete.

Even though there are certain disadvantages to performing helicopter based operations, it is felt that the cost advantages, mobility, and closer control over logistics outweigh the disadvantages. Depending on the timing of the study, a combination of these two methods may eventually be decided upon.

In the event that government operated ships or helicopters are available and cost is not the critical element, either method would be suitable for the job. The recommended scientific plan and methodologies could be carried out from either ship or helicopter based logistics, with little or no basis for scientific preference. The question then becomes one of availability and agency preference.

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