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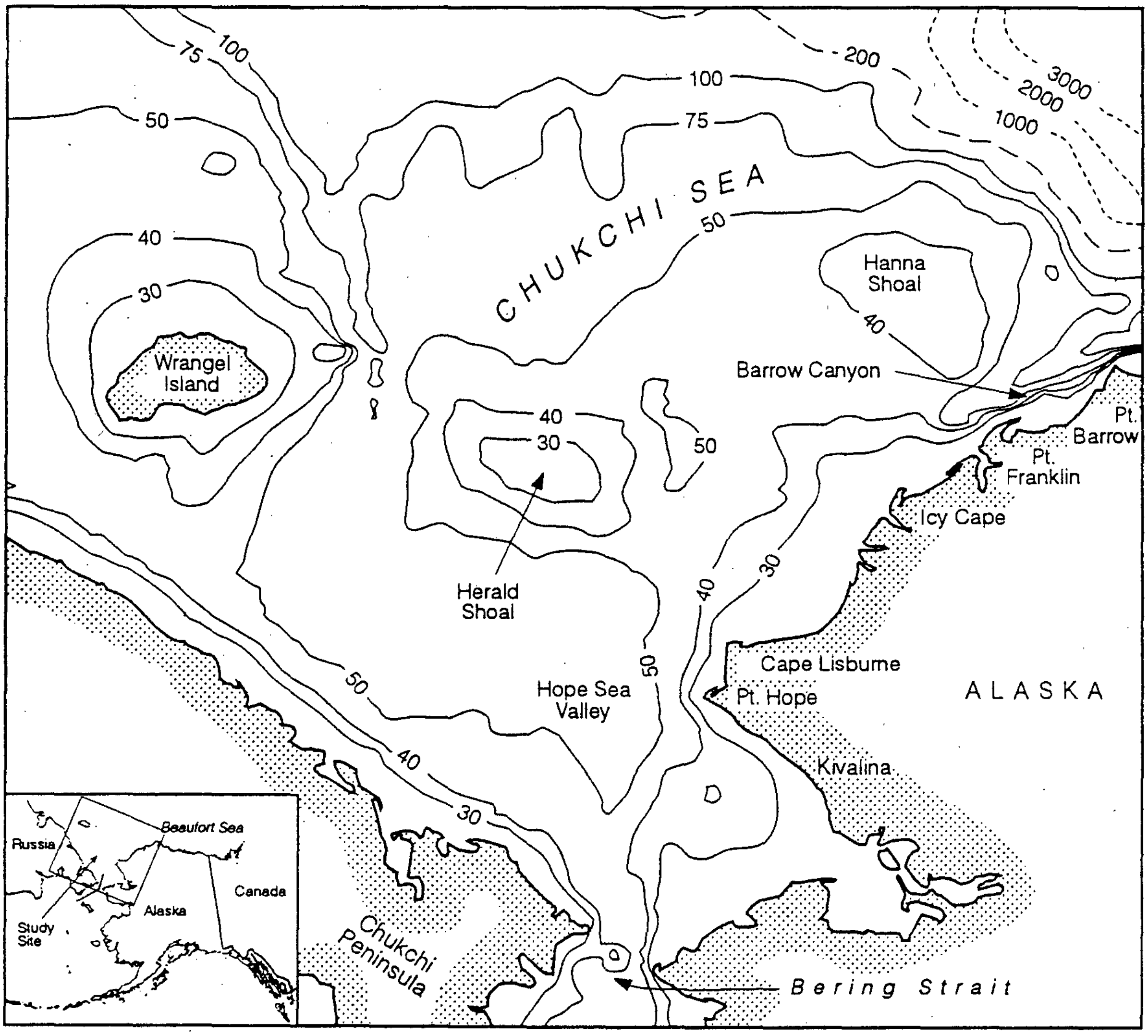
ALASKA OCS REGION

FISHERIES OCEANOGRAPHY OF THE NORTHEAST CHUKCHI SEA

FINAL REPORT



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FISHERIES OCEANOGRAPHY OF THE NORTHEAST CHUKCHI SEA

ERRATA

Page 2-17 and 2-18: Figures 10 and 11 are reversed.

Page 3-1: Bering shelf
should read Bering Sea

Page 3-1: conditions ensured
should read conditions ensued

Page 3-14: reversals effected
should read reversals affected

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FISHERIES OCEANOGRAPHY OF THE NORTHEAST CHUKCHI SEA

FINAL REPORT

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EXECUTIVE SUMMARY

THE NORTHEASTERN CHUKCHI SEA FISHERY OCEANOGRAPHY STUDY

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INTRODUCTION

The purpose of this study was to examine the distribution and abundance of fishes and invertebrates, biological aspects of the dominant species, and their relation to the physical environment. Here we provide a summary of the principal findings and integrate the biological results with the physical oceanography.

The data were derived from five summer and autumn cruises conducted between Cape Lisburne in the south to the ice-edge in the north between 1989 and 1992. Demersal fishes, mollusks, and snow crab abundance, biomass, and distribution were estimated with otter trawls whereas abundance of pelagic young-of-the-year (YOY) fishes were estimated with plankton nets and an Isaccs-Kidd midwater trawl. The hydrographic structure of the area was characterized with conductivity-temperature-depth (CTD) casts at trawl stations. Five current meter moorings were deployed in October 1991 and retrieved September 1992 to obtain time series measurements of currents, temperature, and salinity. Additional hydrographic data were also collected during the mooring recovery cruise.

The shelf waters of the northeast Chukchi Sea are primarily derived from the northern Bering Sea shelf waters and advected northward through Bering Strait. These waters are transported across the northeast Chukchi Sea shelf primarily by the Alaska Coastal Current (ACC). Variations in both winds and northward transport through Bering Strait significantly influence environmental conditions in the northeast Chukchi Sea. These physical oceanographic conditions in turn influence the distribution, abundance, and biomass of invertebrates and fishes which, in turn, determines animal associations and configurations of the associations.

PHYSICAL OCEANOGRAPHY

Two principal water masses, based on their temperature and salinity characteristics in summer and fall, flow northward through Bering Strait and spread across the northeast Chukchi Sea (Chapter 2). These water masses are the relatively warm and dilute Alaska Coastal Water (ACW) and the colder and more saline Bering Shelf Water (BSW). The BSW has higher nutrient concentrations than ACW and it carries a greater burden of the particulate organic carbon (POC) formed on the northern Bering and southern Chukchi shelves. This POC is easily assimilated by benthic organisms, in contrast, to the more refractive, terrestrially derived POC, characteristic of the ACW.

The ACC is the principal circulation feature on the northeast Chukchi shelf. This current originates on the Bering Sea shelf, flows northward through Bering Strait, and drains the Chukchi

Sea through Barrow Canyon - a distance of about 800 km. Between the Lisburne Peninsula and Barrow Canyon the main core of the ACC flows parallel to the bathymetry and is characterized, during the ice-free season (June through November) of most years, by a thermal front that intersects the bottom between the 30 and 40 m isobaths. The advection of ACW and BSW by this current is crucial to the seasonal flushing of the cold, saline waters (Resident Chukchi Water; RCW) formed in winter by freezing of the shelf waters (Chapter 3). Inshore of the bottom front, shelf waters consist mainly of ACW. North of this front and along the outer shelf, RCW comprises the bulk of summer/autumn shelf water mass, while to the west of the front Bering Shelf Water (BSW) is the dominant water mass. Consequently, the flow through Bering Strait and within the ACC effectively establishes the summer/autumn hydrographic regimes on the northeast shelf. As shown in following chapters and summarized in the following sections. These hydrographic regimes influence the distribution and abundances of benthic organisms and fish species in the study area.

From spring through autumn, flow within the ACC is remarkably continuous and steady (Chapter 3). As such, this current comprises an oceanographic corridor whereby plankton and fish from the northern Bering shelf can conceivably be carried or aid in their movement into the northeast Chukchi Sea during the ice-free season. On average, northward flow within the ACC and across the Chukchi shelf is maintained by the large-scale pressure gradient between the Pacific and Arctic oceans. Current variations about this mean flow are primarily forced by winds. On synoptic and longer time scales, these wind-forced circulation changes can alter the juxtaposition of water masses on the northeast shelf, thereby leading to changes in the distribution of fish species preferentially probing for "favorable" areas to inhabit. On seasonal and inter-annual time scales, wind-forced circulation changes affect the rate at which water is transported northward through Bering Strait (Chapter 2). These changes can be particularly important for temperature sensitive fish species which migrate into the Chukchi Sea and use this area in summer and autumn. For example, in years of stronger than normal southward winds the northward transport through Bering Strait is delayed and/or reduced. Such changes directly affect the time required to flush the cold RCW from the northeast Chukchi Sea and replace it with ACW and BSW. Year-to-year differences in the flushing rate could affect the migration patterns of fish into the northeast Chukchi Sea and explain the observed differences in abundance and biomass of Being flounder between 1990 and 1991 (Chapter 6).

Winds also play a crucial role in the annual retreat and advance of sea-ice. In years when summer and autumn winds are anomalously southward, ice retreat is delayed and the ice coverage is extensive, whereas in years of anomalously northward winds the ice-edge is displaced further northward. Such differences could markedly affect the location of ice-edge phytoplankton blooms and the distribution of larval fishes which feed on these blooms. Additionally, such vagaries in winds may lead to disruptions of phytoplankton and zooplankton patches which influences larval survival. This could be a mechanism explaining the missing age classes of Arctic staghorn sculpin (Chapter 5).

From a broad perspective, sediment distribution, as well as the organic carbon and nitrogen content of the sediments, roughly coincide with the circulation features. The study area consists of a broad mosaic of sediment types with a general trend of gravel inshore and more muddy-sandy sediments offshore (Feder *et al.* 1989). The along shore area consists of long narrow belts of gravel. Seaward of this area is dominated by sand but the further offshore regions are dominated by silts and clays with isolated patches of gravel (Sharma 1979). The Hanna Shoal area is dominated by gravel with various proportions of mud and sand. Roughly coinciding with distribution of sand-silt sediments is a zone of high organic carbon and nitrogen.

There is also a narrow band of sediments characterized by relatively high organic carbon (>7 mg/l) and nitrogen (>0.8 mg/l) which progresses northwestward from the Point Hope and Cape Lisburne area to offshore. Additionally, there is a wide band of sediments of high organic content emanating from the Point Franklin area northwestward offshore (Feder *et al.* 1989).

DISTRIBUTIONS AND ASSOCIATIONS OF BIOTA

In the three groups of organisms investigated, mollusks, snow crab, and fishes, there was a tendency for abundance and biomass to be greatest in the southern portion of the study area. Feder *et al.* (Chapter 10) found that abundance and biomass of epifaunal mollusks, primarily gastropods, was highest near the coast with particularly high values offshore of Lisburne Peninsula and between Icy Cape and Pt. Franklin. Snow crab abundance and biomass tended to be highest adjacent to the Lisburne Peninsula area and low elsewhere (Paul *et al.* Chapter 11). There were, however, occasional stations with high abundance and biomass of snow crab beyond the 40 m isobath offshore of Icy Cape. In contrast to these observations, abundance and biomass of total infaunal invertebrates and infaunal mollusks tended to be higher adjacent to and north and northwest of the 40 m isobath (Feder *et al.* 1989).

Patterns of fish abundance and biomass were similar to those of epifaunal mollusks. Additionally, there appears to be a cline of decreased species richness and biomass with increased latitude. In 1990 Barber *et al.* (Chapter 9) found abundance and biomass of fishes was generally greater offshore of the Lisburne Peninsula than at more northerly stations. Among the latter stations, abundance and biomass tended to decrease from inshore to offshore. Our observations are consistent with previous findings. For example, Fechhelm *et al.* (1985) found 29 species along shore and just north of Cape Lisburne with a decreasing catch/unit of effort from south to north. Sampling west of Pt. Barrow Frost and Lowry (1983) collected only 19 fish species. Wolotira *et al.* (1977) conducted surveys in the northern Bering Sea and the southeastern Chukchi Sea. Their biomass estimates for the 20 most abundant species were 351 kg/km^2 north of St. Lawrence Island, 639 kg/km^2 in Norton Sound, 320 kg/km^2 in Kotzebue Sound, and 158 kg/km^2 in the southeastern Chukchi Sea. These compare with our 1990 biomass estimates of an average of 951 kg/km^2 for a group of stations off Cape Lisburne and 103 kg/km^2 for a group northwest of Icy Cape (Barber *et al.* Chapter 9). It should be emphasized that, although Wolotira *et al.* sampled with an otter trawl similar to that used in our 1990 and 1991 sampling, their cod-end mesh size was twice as large as ours, 76 mm vs. 35 mm. Hence, Wolotira *et al.* undoubtedly underestimated biomass. If underestimated by a factor of two this would suggest there is a cline of decreasing abundance with increased latitude. They also found that biomass was higher nearshore than offshore.

Distinct associations of invertebrates and fishes were found in the northeast Chukchi Sea and there appears a qualitative similarity between the geographic configurations of those formed by mollusks and fishes. Feder *et al.* (1989) found two alongshore and two offshore macrofaunal associations and the former had higher diversity than the latter. When considering infaunal and epifaunal mollusks separately and independent of other invertebrates a mixed picture emerges. Feder *et al.* (Chapter 10) found that infaunal mollusks formed six associations, three alongshore and three offshore. The three offshore associations west and north of Icy Cape were more diverse than in the three alongshore and more southern associations. In contrast, epifaunal mollusks formed five associations with the highest diversity found in an alongshore and an offshore association. There was, however, no clear alongshore-offshore pattern of continuity;

both alongshore and offshore associations were disjointed. Additionally, the offshore associations were interspersed with areas characteristic of one alongshore association.

For fishes the number of species, species diversity (H), and evenness (V') formed similar patterns to abundance and biomass, i.e., greater offshore of the Lisburne Peninsula than over the northern shelf, and the northern shelf tended to be greater alongshore than offshore (Barber *et al.* Chapter 9). Additionally, cluster and discriminant analyses of the 1990 data also yielded three alongshore and three offshore associations of fishes in the northeastern Chukchi Sea (Barber *et al.* chapter 9). The northern offshore association had the fewest species, lowest diversity and evenness, and least abundance. The number of species, diversity, and evenness were highest in the Ledyard Bay association followed closely by the association off Cape Lisburne. Interestingly, the fish associations were configured somewhat similarly to those described by Feder *et al.* (Chapter 10) for epifaunal mollusks, i.e., there were three alongshore and three offshore associations. The results of the multivariate analyses in the fish study using environmental data resulted in 80% of the stations being classified the same as that for the cluster analyses using species and their abundance. Moreover, in the principal component analysis (PCA), bottom salinity was the primary factor influencing association configuration. [Bottom salinity and temperature varied in concert with a strong negative correlation ($r = -0.90$).] Bottom salinity and percent gravel accounted for 75% of the variation in station classification. There were also heavy loadings on depth as well as infauna and epifaunal abundance which suggested that these variables were important in station classification. These qualitative similarities in the distribution of invertebrate and fish associations suggest that there are common attributes influencing the organisms inhabiting the area.

Other investigators have found relationships between fishes and sediment type (Scott 1982), salinity and temperature (Jahn and Backus 1976; Mahon and Smith 1989), depth (Day and Pearcy 1968; Fargo and Tyler 1991), and organic matter (Oviatt and Nixon 1973). As an example, Fargo and Tyler (1991) found species associations related to depth and sediment type with sediment type differing for each species association. Species-associations and sediment type, however, did not exactly coincide; two sediment types were found in the same depth range of species-associations. They suggested that faunal similarities were maintained in regions of sediment transition and factors other than sediment type that governed distribution of associations. Pearcy (1978) similarly found a clear separation of the effects of depth but not sediment for two associations, one shallow and one deep. There was, however, an interaction between depth and sediment type where the shallow assemblage showed a high similarity between stations of different sediment types. Although Pearcy did not find a significant relationship between sediment type and total abundance, he did find a significant relationship for particular flatfish species. For example, higher catches of the slender sole (*Lyopsetta exilis*) occurred on clay/silt sediments and low catches on sandy sediments. In contrast the Pacific sandab (*Citharichthys sordidus*) showed the opposite relationship. This suggests that, even with multivariate techniques, it may be difficult to discriminate among the influences of the various, interacting factors.

Grebmeier *et al.* (1989) found higher invertebrate species diversity but lower invertebrate biomass associated with ACW than with Bering Shelf-Anadyr Water in the northern Bering Sea and BSW in the southeastern Chukchi Sea. They found species diversity was positively correlated with bottom temperatures, i.e., associated with ACW. In addition they found a significant positive correlation between species diversity and sorting coefficient of bottom sediments which suggests that sediment heterogeneity was a major factor influencing diversity. They also suggested that differences in food supply, in the form of POC and plankton import, was an important factor influencing diversity in areas with similar sediment types.

Temperature may also be an important variable influencing distribution in the northeast Chukchi Sea. We observed a large negative correlation between bottom temperature and salinity. Temperature is known to be one of the most important factors limiting the geographical range of coastal fishes (Norman and Greenwood 1975) and the consequences of changes in temperature on the distribution of fishes have been well documented by Cushing (1982) in the northeast Atlantic. Laevastu and Hayes (1981) also describe the changes in fish distribution associated with a thermal front on the continental shelf off North Carolina. Changes in the species structure of the fish community and individual species abundance were greatest immediately at a front. A more specific example for our area is the shift in distribution and abundance of yellowfin sole (*Limanda aspera*) with annual shifts in the bottom water temperature and the ice edge in the southern Bering Sea (Bakkala 1981).

BIOMASS OF BIOTA

Differences in food supply to the sediments underlying the BSW and the ACW have been invoked as the mechanism producing the underlying dissimilarities in biomass and abundance of invertebrates in the northern Bering and Chukchi seas. Grebmeier *et al.* (1988) found that, south of the Lisburne Peninsula, benthic biomass was substantially greater at stations influenced by the BSW than those within the ACW domain. Sediments underlying BSW had higher concentrations of total organic carbon and lower C/N ratios (indicating higher quality POC). These features were related to the high levels of primary production of the BSW which ultimately sinks to the bottom. Feder *et al.* (1989; Chapter 10) found high densities and biomass of total infaunal invertebrates and epifaunal mollusks, respectively, in the northern parts of the northeastern Chukchi Sea, particularly offshore of the bottom front separating BSW and RCW from ACW. These authors attributed the high density areas to the advection of BSW with its high concentration of nutrients, high quality POC, and ungrazed phytoplankton.

This argument, however, cannot be evoked to explain the higher fish and epifaunal mollusc biomass found inshore by Barber *et al.* (Chapter 9) and the higher biomass of epifaunal mollusks by Feder *et al.* (Chapter 10). Here, while the concentrations of phytoplankton might be low and the POC is of low quality (Grebmeier *et al.* 1989), the carbon flux could be substantial because of the swift inshore flow.

Based on these two mechanisms, flux to the bottom of high quality POC to the sediments vs. high flux of low quality POC, one would predict that deposit feeding organisms will dominate in areas where the former process is predominant and suspension feeders will prevail in areas where the latter predominates. Grebmeier *et al.* (1989) found that deposit-feeding polychaetes and/or bivalves dominated in silt and clay substrates which implies suspension feeders dominated in the coarser substrate areas. The importance of the transport of POC is indicated by Feder *et al.* (1989); they found associated with this inshore area a macrobenthos dominated by suspension feeders indicating suspended POC is important as a food source, and ultimately determining the high abundance and biomass of epifaunal organisms and fish in the area. It should be recalled, however, that sediment type varies in both the offshore and alongshore areas. Thus, carbon source and sediment type are varying together and the interaction and influence of the two can not be separated at this time.

INTERANNUAL VARIABILITY

It was implied in the previous section (Physical Oceanography) and in Chapters 2 and 3 that there is considerable interannual variability in the transport of waters through the Bering Strait. The interannual variation in the physical oceanographic conditions appear to impact the abundance and distribution of fishes in the northeast Chukchi Sea. Additionally, there is support for Pruter and Alverson's (1962) hypothesis that some species of fishes and invertebrates inhabiting the northeastern Chukchi Sea are maintained via continual recruitment of eggs and larvae transported northward from the southeastern Chukchi Sea or northeastern Bering Sea.

Biomass, abundance, and age structure of Arctic staghorn sculpin varied considerably between 1990 and 1991. Smith *et al.* (Chapter 5) found that mean biomass and abundance were significantly higher in 1990 than in 1991. For all 48 stations sampled in 1990 mean abundance was 716 ± 1345 fish/km^2 and mean biomass was 8.4 ± 13.5 kg/km^2. Mean abundance for the 16 stations sampled in 1991 was 429 ± 776 fish/km^2; mean biomass was 4.7 ± 7.8 kg/km^2. Comparison of abundance and biomass values for the two sample years indicated significantly higher values for 1990 ($p < 0.001$). In 1990 we found (Chapter 5) that 42% of the Arctic staghorn sculpin consisted of fish older than four years. In 1991 the number of fish in these age categories represented only 9% of the total. The oldest female observed was 9 years old; the oldest male was 8. The age structure changed dramatically from 1990 to 1991. In 1990 41.6% of the population consisted of fish ≥ 4 years old; 4.4% were ≥ 6 years old. In contrast, in 1991 only 8.9% of the population was ≥ 4 years old; only 1.4% was ≥ 6 years old. Three year old fish were very scarce in 1990 and 4 year old fish were scarce in 1991 suggesting that the 1987 class had very poor recruitment success. Because the stations from which fish were aged ranged from the extreme southern boundary of the study area to far to the northeast, this possible recruitment failure was widespread and could have resulted from a large-scale perturbation in the environment. Further, the marked difference in age distributions of Arctic staghorn sculpin in the two sample years suggests that variation in the physical environment may result in recruitment failures or mass mortality in this species.

Similar results were found for Bering flounder (Smith *et al.* Chapter 6). Both biomass and abundance were dramatically different in the two years of this study. Mean biomass declined significantly from 17.2 kg/km^2 in 1990 to 0.79 kg/km^2 in 1991. Mean abundance estimates for all stations sampled in 1990 and 1991 (995 and 429 fish/km^2, respectively) differed significantly ($U = 785$; $p < 0.001$). Similarly, 1990 and 1991 mean biomass estimates (17.2 and 0.79 kg/km^2, respectively) also differed significantly ($U = 825$; $p < 0.001$). Eight stations were sampled in both field seasons. Mean abundance and biomass at these stations in 1990 (207 fish/km^2; 7.6 kg/km^2, respectively) were significantly higher ($U = 85$; $p < 0.001$) than the estimates for 1991 (19.7 fish/km^2; 0.66 kg/km^2, respectively). This reduced abundance and biomass in 1991 was associated with significantly lower temperatures in 1991. Comparing the eight stations common to both years we found mean bottom temperatures of 5.4 and 0.9°C, respectively ($U = 54$; $p < 0.05$).

Age structure of Bering flounder was also very different between 1990 and 1991. In 1990 we found (Chapter 6) that ages ranged from 1 to 11 with age class 5 dominating. This differs considerably from Pruter and Alverson (1962) who found ages ranging from 6 to 13 with ages 7 through 9 making up 90% of the total number of fish. Additionally, in 1990 we found that 75% of the Bering flounder were ≥ 5 years old. This is evidence for dramatic shifts in population age structure over time as well as variability in abundance and that interannual differences in physical oceanographic conditions influence abundance of fishes in the area, possibly from the import from more southern waters.

Wyllie-Echeverria *et al.* (Chapter 4) concluded that populations of Bering flounder in the northeastern Chukchi Sea are maintained by the transport of larvae in the ACC. Sampling ichthyoplankton with a variety of mid-water gear from 1989 through 1991, Arctic cod dominated the catches and occurred throughout the northeastern Chukchi Sea; higher concentrations were found at northern stations during all three years. Arctic cod rarely occurred at southern stations when BSW was present. Bering flounder occurred primarily in areas dominated by the ACW as far north as 71°N. They did not occur where RCW was present.

The distribution of YOY Bering flounder and two other species reflected the distribution of the water masses (Wyllie-Echeverria *et al.* Chapter 4). Bering flounder were present during 1989 and 1990 in ACW and ACW/BSW but absent from ACW/RCW. In 1991 only one YOY Bering flounder was captured and it was in ACW. *Pleuronectes* spp., dominated by yellowfin sole (*P. asper*), and sandlance (*Ammodytes hexapterus*), followed the general pattern of Bering flounder distribution. These fish are primarily distributed in the Bering Sea and extend into the Chukchi Sea (Allen and Smith 1988). In 1989 and 1990 *Pleuronectes* spp. YOY occurred in ACW, and sandlance YOY were captured in ACW and ACW/RCW but were absent in 1991 samples. In 1990 the winds were primarily from the south and in 1991 from the north. The increased advection of BSW into the northeast Chukchi Sea would have increased the import of more southern species into the sampling area as compared to 1991. This suggests that YOY Bering flounder, and quite possibly yellowfin sole and sandlance, were advected into the northeastern Chukchi Sea with ACW.

To further test this hypothesis Wyllie-Echeverria *et al.* (Chapter 4) re-examined an earlier set of data obtained in September and October 1970 (Ingham *et al.* 1972). Using the data reported by Quast (1972) and the temperature and salinity profiles of Ingham and Rutland (1972) reported in this study, Wyllie-Echeverria *et al.* reconstructed the water masses present and YOY distribution for 1970. The ACW was present nearshore and to 71°N while RCW was not present south of 69°30'N. They found that Arctic cod were present at all stations but Bering flounder occurred only at stations south of 69°30'N and were associated with ACW. Water mass characteristics and distribution of pelagic juvenile fish species indicate that the conditions of 1970 were similar to those in 1989 and 1990. These authors concluded that while Bering flounder and others may be routinely advected into the northeastern Chukchi Sea by ACW, RCW may be a critical factor in delimiting their northern distribution.

CONCLUSIONS

The physical oceanographic conditions of the study area influence the distribution, abundance, and biomass of invertebrates and fishes which, in turn, determines associations of these organisms. Highest abundance and biomass of snow crab, epifaunal mollusks, and fishes tended to be in the south. Moreover, epifaunal mollusc abundance and biomass was highest nearer the coast. Infaunal mollusc biomass and abundance, however, was greatest adjacent to, and north and northwest of a bottom thermal front separating the Bering Shelf Water (BSW) and Resident Chukchi Water (RCW) masses from the Alaska Coastal Water (ACW). The mollusks, epifauna and infauna, and fishes formed inshore and offshore associations. These associations were affiliated with bottom type, salinity, and bottom temperature. The observed differences in abundance of YOY, missing year classes, and dramatic differences in abundance and biomass of specific fish species appear to be related to interannual differences in wind and transport.

In view of the findings, the northeastern Chukchi Sea appears to be a transition zone between the northern Bering Sea and the Arctic Ocean. The observed differences in distributions, abundance, biomass, and the resulting fish and invertebrate associations involve sediment type, the area's hydrography, import of particulate organic carbon (POC), and flux of plankton from the water column to the benthos. This shelf area may thus be considered the "downstream link" in the flow of water between the Bering Sea and the Arctic Ocean. Therefore, processes operating "upstream" in the Bering Sea have considerable influence on the physical and biological characteristics of the northeastern Chukchi Sea.

CHAPTER 1

INTRODUCTION, BACKGROUND, AND METHODS

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INTRODUCTION

In the absence of commercially-exploited populations, there has been, historically, little emphasis placed on acquisition of data on the organisms and the habitats they occupy or interrelationships between the two. If little information exists on how organisms interact with their habitat and associated fauna, it will be difficult or impossible to conceptualize or predict how fishery organisms might respond to natural or artificial perturbations. Informed management decisions depend on information and predictive capability. In the northeastern Chukchi Sea, exploitation has been extremely low since the end of commercial whaling. Very little pertinent information existed until very recently in spite of the fact that the area is important for subsistence fisheries and is an important migration corridor and habitat for whales, walruses and anadromous fishes.

There has been considerable interest and effort in developing information for this area over the past six years because of potential oil exploration and extraction. Much remains to be understood about exploitable species and their relation to the environment. The Outer Continental Shelf Environmental Assessment Program has recognized the need for this information.

This project is a result of the efforts of the Minerals Management Service (MMS) of the U.S. Department of Interior to oversee oil exploration in the study area in a manner consistent with protection of marine and coastal environments. Our environmental studies will help delineate the oceanographic environment and some basic life history characteristics of the more abundant fish and invertebrates present. We hope our studies have clarified what Arctic resources may be at risk from potential oil and gas activities and have helped assess the possible effects on these resources.

The overall goal of this project was to develop a data base that will allow characterization of the area and, in a general way, prediction of possible outcomes of environmental perturbations, whether natural or resulting from human activity. An underlying assumption is that the basic life history and biological characteristics of the dominant fish and shellfish species in the northeastern Chukchi are similar to those observed in other parts of their range or for similar species and may be used to interpret biological processes in the Chukchi Sea. The study evolved from a single year survey to a multi-year study which involved the University of Alaska's vessel the *Alpha Helix* and a chartered trawler. It also involved ships of opportunity, launches being operated from a tender supporting drilling operations and the University of Hokkaido's research vessel the *Oshoro Maru*. The general locations sampled during the four field seasons are shown in Figure 1.

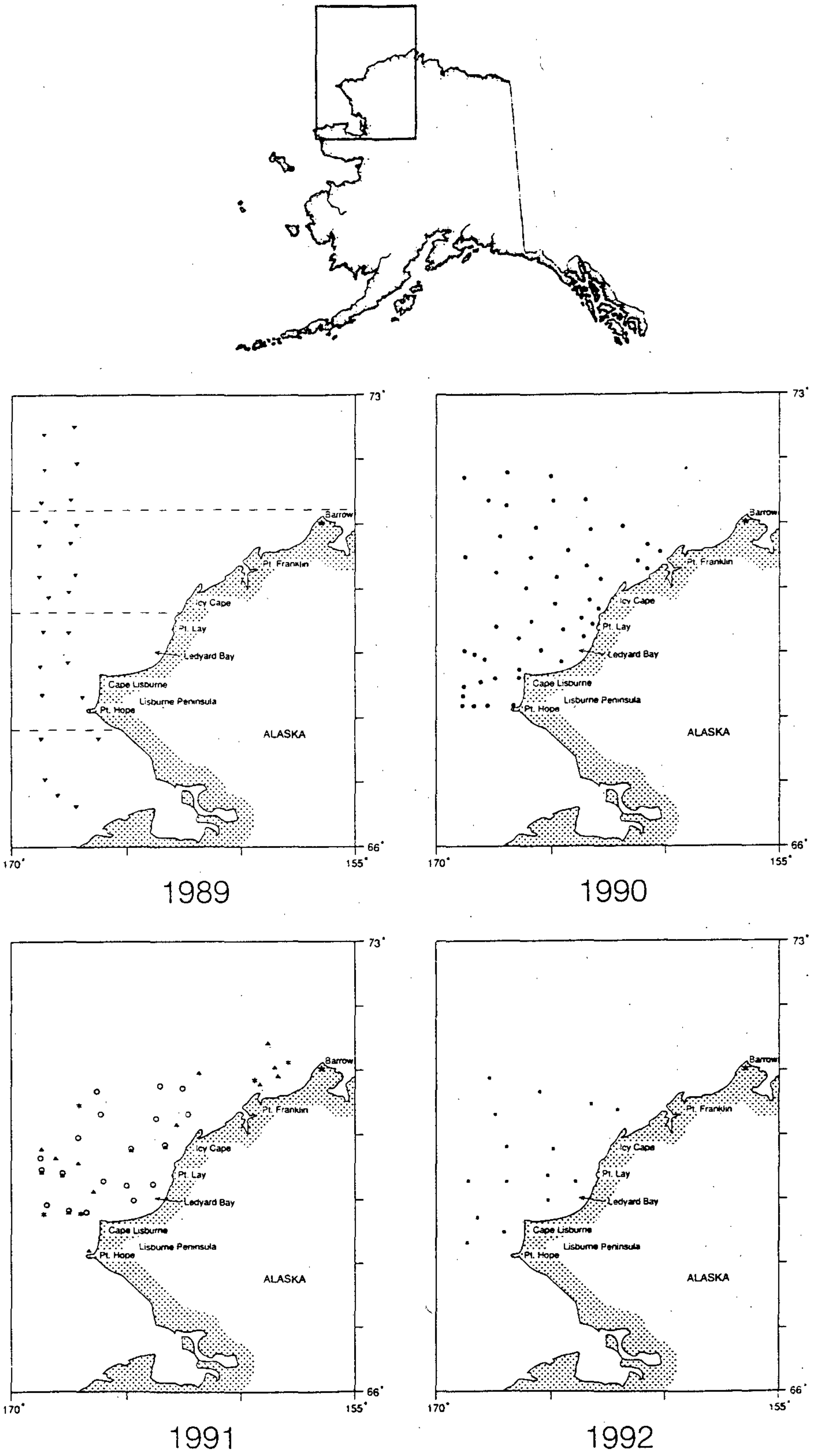

Figure 1. General sampling locations where fishes and invertebrates were sampled and current meter moorings established during the four years of study in the northeastern Chukchi Sea.

To guide our initial thinking and data collection we formed several hypotheses. First, we hypothesized that the physical attributes of the environment and the life history characteristics of the species are variable both temporally and spatially. Second, we hypothesized that there would be differences in abundance and/or biomass of the major species occupying the different water masses in the area. Third, we hypothesized that the fish communities relate to infaunal and eipfaunal invertebrate communities previously identified.

Objectives to address these hypotheses were:

1) Determine the distribution of water masses in the northeastern Chukchi Sea;

2) Develop basic biological information for dominant fish and shellfish species for important life stages;

3) Determine relationship between hydrographic conditions and fish species abundance, biomass and/or behavior;

4) Determine the community structure of the fish and shellfish with emphasis on ichthyofauna in the northeastern Chukchi Sea;

5) Compare community structure of fish and shellfish with previously identified infaunal invertebrate communities of the area.

To guide the reader, this report is organized in the following manner. First, in this introductory chapter, we review the literature which formed the basis of our approach and thinking at the beginning of the study. We also present the general methods used and areas sampled during the study. Second, because we felt strongly that the knowledge gained in this project should be disseminated as widely as possible, the remaining chapters are based on manuscripts submitted (or in final preparation) to refereed scientific journals or a symposium on the ecology of arctic fishes. Chapter 2 reviews what was known about the oceanography of the study area with additional information gained from oceanographic observations at stations occupied primarily for biological sampling. Chapter 3 presents new information on the physical oceanography from hydrographic and five current meter stations established in the study area. Chapter 4 presents information on the relationship of young-of-the-year fishes to the water masses of the area. Chapters 5, 6, and 7 presents new information on the distribution, abundance, and biology of three dominant species which occupy the area, the Arctic staghorn sculpin (*Gymnocanthus tricuspis*), the Bering flounder (*Hippoglossoides robustus*), and the Arctic cod (*Boreogadus saida*). Chapter 8 presents information on the food habits of these three species and saffron cod (*Eleginus gracilis*). Chapter 9 concerns the fish community of the area and its relationship to the physical oceanography. Chapter 10 presents information on the distribution, abundance, biomass, and community structure of infaunal and epifaunal mollusks of the area. Chapter 11 presents new information on the distribution, abundance, biomass, and reproductive biology of the snow crab (*Chionoecetes opilio)*. Chapter 12 is a synthesis of existing new information obtained in this study. When appropriate, the information obtained from ships of opportunity has been integrated in these chapters. The majority of the data from ships of opportunity, however, was not appropriate for publication and therefore is presented in the appendix.

BACKGROUND

Oceanographic

Geological.—Reviews of the shelf's geological characteristics may be found in Sharma (1979), Morris (1981), and Feder *et al.* (1989). The northeastern Chukchi Sea shelf is wide and shallow, averaging less than 50 m in depth, and has gentle slopes leading out from shore. It is relatively featureless with the Barrow Canyon, Herald Shoal, and Hanna Shoal being the primary exceptions (Sharma 1979).

Sediments of the shelf form a large general pattern of: gravel occurring as long narrow belts along the shore and a few isolated patches in offshore regions; sands predominating in near-shore areas, and silts and clays dominating offshore areas (Sharma 1979). More specifically, the proposed study area is formed of a broad mosaic of sediment types (Feder *et al.* 1989). The inner shelf and Hanna Shoal consist of relatively coarse material dominated by gravel with various proportions of mud and sand. Bisecting these two areas is a zone dominated by gravelly sand mixed with large areas consisting of gravel. Lastly, the more offshore areas are dominated by mud mixed with sand and gravel. At about 70°N, however, the dominant muddy sediments are bisected by an area of gravelly sand, much of which emanates from Herald Shoals. Interestingly, the percent of organic carbon and nitrogen in surficial sediments is somewhat related to sediment distribution. Transecting the different sediment types, however, is a narrow band of relatively high organic carbon (>7 mg/g) and nitrogen (>0.8 mg/g) progressing northwestward from the Point Hope and Cape Lisburne area, and a wide band emanating northwestward from the Point Franklin area (Feder *et al.* 1989).

Physical.—The physical oceanography of the northeastern Chukchi Sea is affected by inflow from the Bering Sea, coastal freshwater discharge, sea-ice ablation and accretion, and winds. Their influence was first discussed in the monograph by Coachman *et al.* (1975). Since then, there have been a number of physical oceanographic investigations of the Chukchi Sea (see reviews by Hachmeister and Vinelli 1985; Aagaard 1988; Coachman and Aagaard 1981; Lewbel and Gallaway 1984) which largely confirmed many of the tentative conclusions reached by Coachman *et al.* (1975). The most striking aspect of the Chukchi Sea, which makes it unique among all arctic shelves, is that its circulation and water mass properties are profoundly influenced by the northward flow of Pacific Ocean waters through Bering Strait. This flow determines the rate at which waters are flushed from the shelf and provides significant contributions to this shelf's heat, salt, nutrient, and carbon budgets. Moreover, Bering Strait serves as an important migratory path for marine mammals, fish, and planktonic life forms. The transport through the strait varies in response to the regional winds. Northward transport is maximum in summer when winds are weak and variable and minimum in winter when northerly winds are strong. There are also significant interannual and longer period transport variations which have been tied to interannual differences in the regional wind field (Coachman and Aagaard 1988).

In summer, three major water mass modes are found in the northeast Chukchi Sea; Bering Shelf Water (BSW), Alaska Coastal Water (ACW), and Resident Chukchi Water (RCW). The BSW is formed by a mixture of cold Bering Sea water and a salty and nutrient-rich fraction crossing onto the northern Bering shelf through the Gulf of Anadyr. The ACW is warmer and more dilute than BSW and consists of Bering Sea water diluted by inflow from the many rivers draining western Alaska, of which the Yukon is the largest. A distinct thermohaline front, extending from the northern Bering Sea and over much of the Chukchi shelf, separates the BSW (which lies to the west and/or offshore of this front) from the nearshore ACW. The RCW occupies the shelf from winter through spring and is gradually displaced northward in summer when the shelf is flooded by BSW and ACW. The RCW is, in fact, a product of these two water masses and develops its cold, salty properties with the onset of fall cooling and freezing (the latter process increases shelf salinities due to salt rejection from growing sea-ice).

North of Bering Strait and in the vicinity of the Lisburne Peninsula, ACW and BSW diverge; most of the BSW veers to the northwest within the Hope Sea Valley and enters the Arctic Ocean through Herald Canyon. The ACW flows northeast within the Alaska Coastal Current and enters the Arctic Ocean through Barrow Canyon. The Alaska Coastal Current (ACC) lies shoreward of and parallel to a bottom thermal front usually observed along the 30-40 m isobath. Mean speeds within the ACC are about 0.1 m/s but the strength of both the flow and the bottom front vary substantially along the current's path in conjunction with the bottom slope. At smaller length scales, flow separation in the lee of coastal landforms such as Cape Lisburne, Icy Cape, and Pt. Franklin generates eddies (Hachmeister and Vinelli 1985; Lewbel and Gallaway 1984; Sharma 1979) which may act as traps for fish larvae advected within the ACC. Variability within the ACC is also significantly affected by the regional winds, and on occasion, these are sufficiently strong to force the flow to reverse for periods as long as one month. Flow along the outer shelf is also influenced by forcing from the deep ocean. This forcing is apparently due to the passage of eastward propagating shelf waves (Aagaard and Roach 1990) which result in the cross-shelf advection of waters overlying the continental slope. Within Barrow Canyon, these events can upwell water from within the Atlantic layer of the Arctic Ocean (i.e., from as great as 250 m depth).

The volumes of ACW and BSW occupying the northeast Chukchi Sea appear to vary from year-to-year. For example, in the fall of 1981, no ACW was observed north of Pt. Lay (Aagaard 1988); instead the shelf north of this point was occupied by RCW. In contrast, observations from 1993 indicate that much of the RCW had been flushed from the shelf and replaced with ACW and mixtures of ACW and BSW. These interannual differences in shelf water mass composition appear to be related to interannual differences in the transport through Bering Strait which determines the rate at which winter water is flushed from the shelf.

Biological.—Although considerable research has been conducted in the southeastern Chukchi Sea which may shed some light on how the northeastern portion functions, little benthic ecological work had been done until recently by Feder *et al.* (1989). As previously pointed out, Johnson (1989) found that the ACW intersected the coast near Point Franklin. Feder *et al.* (1989) demonstrated that benthic biomass and production estimates outside the frontal zone delineating the two water masses were significantly higher than inside the zone (Figure 2a and 2b). Additionally, they found that there were four identifiable assemblages of macrofaunal benthic species (Figure 3). Grebmeier *et al.* (1988, 1989) have found in the southeastern Chukchi Sea assemblages of benthic organisms associated with the frontal zone between the BSW and ACW. These authors suggest that there is a coupling between the benthic habitat and production of organic matter which leads to a higher biomass beneath these two water masses. In this case the communities underlying the BSW receive more and constant marine derived food supply.

This is in contrast to those communities underlying the ACW which received a variable, lower quality food supply which is derived from both terrigenous and marine origin. Recently, Parrish (1987) estimated primary production to be from 25-150 g C/m^2/day with values highest north and west of Cape Lisburne and lowest north and west of Barrow. He also constructed production contours which showed highest production in the Bering Sea Water zone. This suggests that the fishery organisms in the proposed study area will be of higher biomass in those areas, influenced by the BSW.

Fishery Organisms

Previous Surveys.—Walters (1955) summarized information on the arctic Alaskan marine fish fauna, primarily in terms of taxonomy and zoogeography. Since then, the fish fauna of the Chukchi Sea has been sampled and cataloged in several biological baseline surveys. Alverson and Wilimovsky (1966) sampled 74 stations in the Chukchi Sea; six of these were located north of Cape Lisburne and involved sampling with an otter trawl and a biological dredge. They reported a total of 43 marine fish species and recognized the ten dominant marine forms both in terms of numerical abundance and frequency of occurrence. Quast (1972) reported a preliminary list of 26 fish species captured in a Coast Guard survey of the eastern Chukchi Sea from Point Hope to Point Barrow. The Coast Guard study employed the Isaacs-Kidd midwater trawl at 19 stations and a try net at one station. Quast (1974) examined the abundance and distribution of Arctic cod caught in the Coast Guard survey and attempted to link those features to depth, fish response to light and vertical water movements. Wolotira *et al.* (1977) surveyed the demersal fish fauna of the southeastern Chukchi Sea and the northern Bering Sea. They provided a list of the 20 most abundant species in the southeastern Chukchi Sea and included biological information on these taxa. Frost and Lowry (1983) trawled in the northeastern Chukchi and western Beaufort seas, collecting 19 fish species. Frost and Lowry included biological observations on Arctic cod (the most abundant species caught) and seven other species.

Fishes of the area indicate it is a transition zone between the Bering and Beaufort seas but with a very strong resemblance to the western Beaufort Sea fauna (Morris 1981; Craig 1984). Additionally, evidence indicates that the fish fauna differ as one proceeds from the coast to offshore and from south to north (Alverson and Wilimovsky 1966; Frost and Lowry 1983; Fechhelm *et al.* 1985). For example, in the lagoons and exposed coastline near Point Lay, gillnet and fyke catches consisted of anadromous and marine fishes with Arctic cod, capelin (*Mallotus villosus*), Arctic flounder (*Liopsetta glacialis*), and fourhorn sculpin (*Myoxocephalus quadricornis*) dominating (Fechhelm *et al.* 1985). From trawling, only marine species were found with Arctic staghorn sculpin, Arctic cod, shorthorn sculpin (*M. scorpius*), hamecon (*Artediellus scaber*), and saffron cod dominating. In the southern part of the northeastern Chukchi Sea Arctic cod, capelin, and Bering flounder dominate (Alverson and Wilimovsky 1966) whereas in the northern part Arctic cod, Canadian eelpout (*Lycodes polaris*), twohorn sculpin (*Icelus bicornis*), and hamecon dominate (Frost and Lowry 1983). Lastly, it is suggested that some of the marine fishes and invertebrates inhabiting the area maintain their populations only through continual recruitment of eggs and larvae transported north from the Bering Sea by the currents (Pruter and Alverson 1962; Feder et al. 1989).

The Fish Fauna.—The fishes comprising the fauna of the study area consist of about 41 species, five of which are primarily Bering Sea in their distribution. The total list includes a lamprey, herring, three salmonids, two smelts, a lanternfish, five cods, seven eelpouts, sandlance, ten sculpins, two poachers, two snailfishes, four pricklebacks and five flatfishes.
(Frost and Lowry 1983). The Arctic cod is a demersal species with adults associating with a substratum. The substratum may be the sea floor or the undersurface of sea ice. However, larval and postlarval Arctic cod are caught in the water column, indicating that the first year of life is pelagic. The first year of life begins with eggs in January and February. Larvae occur from May through July and juveniles in August. Thus, much of the first year in the study area is spent under the ice where weak currents prevail. In addition, there is evidence that juvenile Arctic cod

avoid sunlight and that their depth distribution may be influenced by vertical water movement (Quast 1974). Foods of Arctic cod in offshore waters consist primarily of copepods and a gammarid amphipod. In nearshore waters (behind barrier islands) mysids are the dominant prey (Bendock, 1979). The availability of prey may depend to an extent on bottom type in the study area. Gammarid amphipods and other benthic invertebrates as prey may be sensitive to disturbance of the substratum.

The most abundant and consistently present fish in several surveys was the Arctic coddT flatfishes in the study area are few in number of species, fewer than in the southeastern Chukchi Sea based on a comparison of Alverson and Wilimovsky's (1966)and Quast's (1972) reports. Of the five species found, four are much more abundant to the south in the Bering Sea (Bering flounder, yellowfin sole, Alaska plaice, starry flounder). The fifth, *Liopsetta glacialis*, inhabits the entire Arctic coastline. The first four species are likely drifted into the study area as pelagic eggs and larvae by surface currents from the south. Both *Liopsetta* and *Platichthys* are relatively tolerant of fresh water.

Eelpouts (Zoarcidae) are benthic, negatively buoyant, and feed primarily on benthic invertebrates including gammarids, polychaetes, cumaceans and caprellids (Frost and Lowry, 1983). These fish tend to develop very large eggs (2.7 - 4.5 mm in *Lycodes polaris*) in the larger females. The large embryos that result from these eggs are probably released in fall or early winter. The size suggests that these fishes may be relatively independent of the plankton as a food supply or able to reach an advanced state of development before feeding.

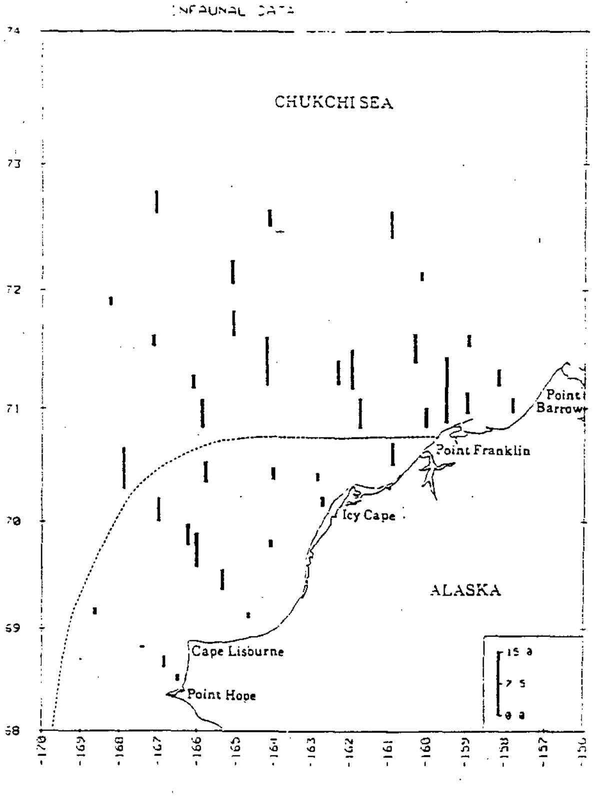

Figure 2a. Distribution of biomass (gC/m^2) in the northeastern Chukchi sea, August-September 1986. The frontal zone (shown by the dashed line) presumably separates the mixed Bering shelf/Anadyr Water in the west and north from the Alaska Coastal water (Figure 68 from Feder *et al.* 1989).

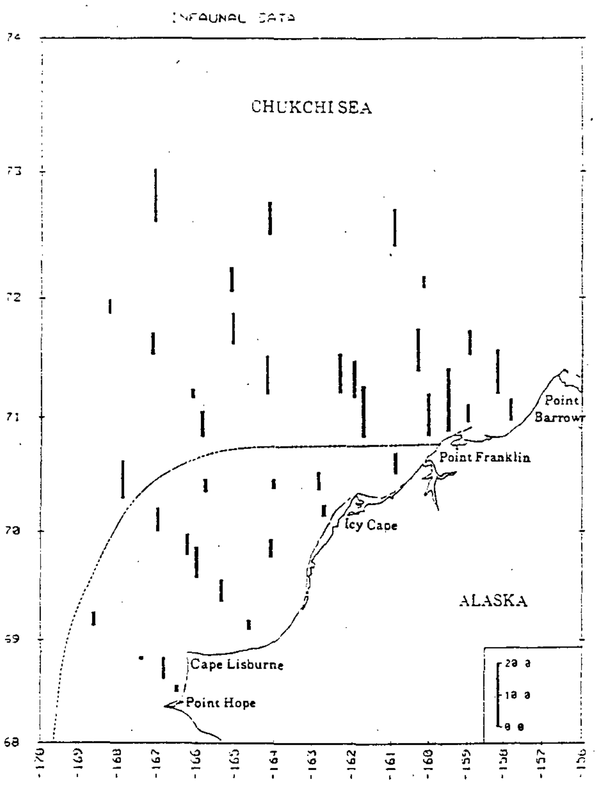

Figure 2b. Carbon production estimates (gC/m^2 yr^{-1}) for the 37 stations occupied in the northeastern Chukchi Sea, August-September 1986. The frontal zone (shown by the dashed line) presumably separates the mixed Bering Shelf/Anadyr Water in the west and north from the Alaska Shelf/Anadyr Water in the west and north from the Alaska Coastal Water (Figure 69 from Feder *et al.* 1989).

METHODS

1989 and 1990.— In the following sections we describe the general techniques and gear type used during the research program. The number of samplings made with each gear type throughout the study is summarized in Table 1. Based on the distribution of water masses and surficial sediments, stratified sampling was used in 1989 and a modified stratified sampling in 1990. For the 1989 sampling program the study area was divided into three strata. The southern stratum was north of 68°03'N latitude and south of 69°38'N whereas the northern stratum was north of 71°20'N (Figure 1). In both of these strata the surficial sediments are dominated by muds (Sharma 1979; Feder *et al.* 1989). From the literature we assumed, however, these strata would be dominated by different water masses; we assumed ACW and BSW would dominate the southern stratum whereas RCW water mass in the northern stratum. We also assumed that the central stratum, between the northern and southern strata, would undoubtedly be dominated by gravels or sand emanating from Herald Shoal and the water masses may consist of BSW and RCW. In 1989 the prescribed sampling area was completed early, and additional stations were occupied in the southeastern Chukchi Sea. This area was designated stratum 4 (Figure 1). Sampling for this portion of the study was conducted on 3 to 9 September 1989. The data from the otter trawl (see next section) from this portion of the study were not appropriate for publication and the results are reported in Appendix 1. The data from midwater sampling forms part of Chapter 4.

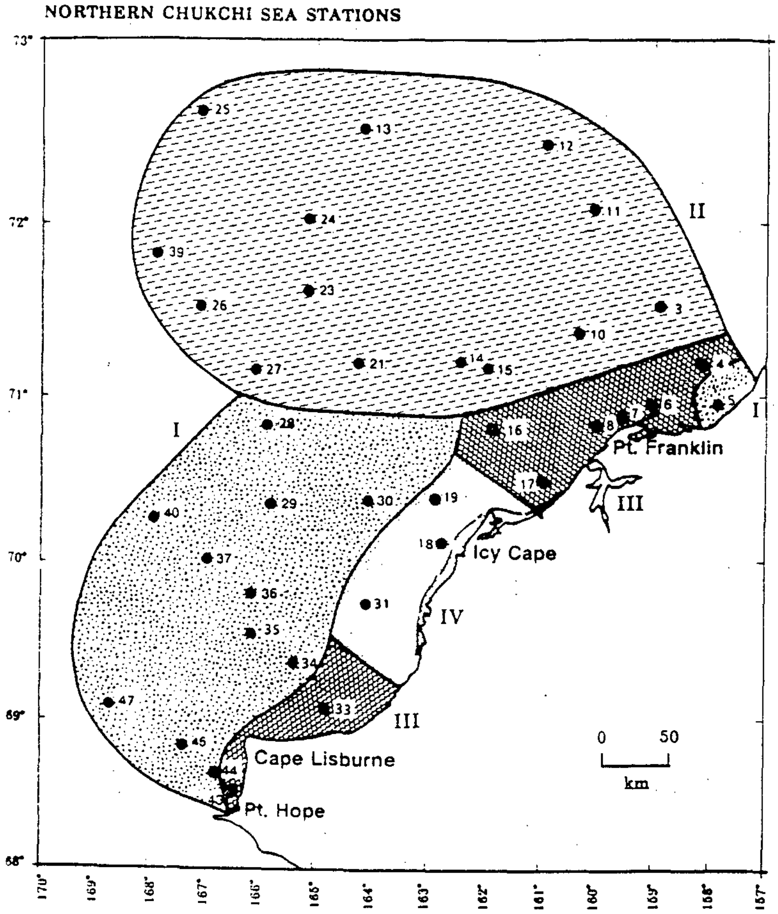

Figure 3. Distribution of macrofaunal communities in the northeastern Chukchi Sea based on cluster and principal coordinate analyses of abundance data collected August-September 1986 (Figure 69 from Feder *et al.* 1989).

To meet the 1990 objectives, we designated 61 stations in 11 transects perpendicular to the coast to be occupied. To ensure that stations were located in inshore and offshore areas as well as northern and southern areas, nearshore stations were established closer to one another than the offshore stations. Additionally, the more southern transects were in closer proximity than the northern transects. It was assumed the distribution of the several water masses and surficial sediments previously discussed would influence fish distribution over the entire area.

Table 1.—Number of samplings conducted in the northeast Chukchi Sea from 1989 to 1992.

				Trawl		
Ship	**Year**	**Otter**	**IKMT**	**Beam**	**Plankton**	**Bongo**
Alpha Helix	1989	50	25	0	9	0

Table 1. continued

Ship	Year	Trawl Otter	IKMT	Beam	Plankton	Bongo
Ocean Hope III	1990	96	94	0	0	48
Ocean Hope III	1991	28	3	0	0	14
Oshoro Maru	1991	18	0	17	0	0
Oshoro Maru	1992	17	0	0	0	0
Responder Barge	1992	20	6	0	0	18

Table 1. continued

Ship	Year	Hydrographic CTD	CMM Deployed	CMM Recovered
Alpha Helix	1989	25	0	0
Ocean Hope III	1990	48	0	0
Ocean Hope III	1991	14	0	0
Surveyor	1991	*	5	0
Alpha Helix	1992	108	4	5
Oshoro Maru	1991	18	0	0
Oshoro Maru	1992	17	0	0
Responder Barge	1992	20	0	0

*	- Data on file with Pacific Marine Environmental Laboratory, NOAA, Seattle, WA.
CMM	- Current Meter Mooring.
Bongo	- Bongo plankton net twin 0.6 m diameter nets of 0.6 mm mesh .
IKMT	- Isaccs-Kidd midwater trawl. 2.65 m^2 area, 5 mm net with 1 mm codend.
Otter	- Otter trawl. Trawls used were a 6.1 meter headrope try-net from the *Alpha Helix*, NMFS's standard 83-112 survey trawl with a 25.2 m headrope from the *Ocean Hope III*, an otter trawl with a 43.3 m headrope from the *Oshoro Maru*, and a 4.9 m try-net from a launch, the *Responder*.
Beam	- University of Hokaido's standard 2 x 2.5 m trawl with 1 mm mesh lining.
Plankton	- 1 m diameter with 1 mm mesh.
CTD	- Conductivity-Temperature-Depth Sensor.
Otter	- Trawls used were: *Alpha Helix* - 6.1 m head rope, mm mesh; *Ocean Hope III* - 25.2 m head rope, 33 mm mesh; *Oshoro Maru* - 43.3 m headrope, 90 mm mesh;

Responder - 4.9 m headrope, 5 mm mesh

This would result in fish associations differing along north to south and onshore to offshore axes. Because of the inclement weather, however, only 48 stations were occupied between 16 August and 16 September 1990 (Figure 1). Weather conditions dictated the general areas in which we could sample and stations were numbered to reflect the sampling sequence. The data from the 1990 sampling formed the core information for many chapters in this report.

Biological.—At each station demersal and midwater trawling, as well as zooplankton and Global Positioning System (GPS); LORAN C could not be used for navigation due to radio propagation characteristics and the placement of the master and slave stations (Johnson 1989). In 1989 demersal fish were sampled from the University of Alaska's research vessel with a 6.1 m headrope otter trawl with 35 mm stretch meshed codend. At each station two one-half-hour otter trawls were conducted at speeds of approximately 2.5 kts. Fish were sorted to lowest taxonomic category possible and counted. Young-of-the-year (YOY) fishes and larvae were sampled with and Isaccs-Kidd midwater trawl (IKMT) and bongo net (see following for description). Physical oceanographic sampling were conducted. Each station location was determined with a

In 1990 otter trawling was conducted from a chartered fishing vessel with the National Marine Fisheries Service's (NMFS) standard 83-112 survey trawl; it had a 25.2 m head rope and 34.1 m footrope set back 7.1 cm from a tickler chain. Fish density and biomass/km^2 were determined by the area swept method; we noted the boat's location when the net reached bottom and when the trawl left the bottom upon its retrieval. Additionally, the width of the wings and height of the headrope above the footrope were determined with a Scanmar mensuration unit. Upon the net's retrieval the entire catch was weighed in the net with an electronic load cell (4,536 kg capacity), fish were sorted to the lowest taxonomic category possible, counted, placed in baskets, and weighed with a mechanical platform scale (81.6 kg capacity). Total length measurements and otoliths were obtained from subsamples of Arctic cod, Bering flounder, *Myoxocephalus cf. verrucosa*, and *Lycodes raridens*. Total lengths were determined with a measuring board to the nearest centimeter, and both sagittal otoliths excised and stored in vials containing a solution of 50:50 glycerin:water containing thymol (Chilton and Beamish, 1982). Subsamples of Arctic staghorn sculpin were frozen and returned to the laboratory where standard and total lengths were determined to the nearest millimeter with dividers and weight determined to the nearest 0.01 g on an electric pan balance. They were then sexed, ovaries weighed and preserved in vials containing Gilson's solution (Bagenal and Braum, 1978), otoliths obtained and stored as previously described, and stomachs stored in vials of 70% ethanol. Weights were obtained to the nearest 0.01 gram. Trawl-caught invertebrates were also identified to the lowest taxonomic categories possible and weighed. Certain species, for example snow crab and *Neptunia* spp., were also counted and weighed.

Midwater fishes were sampled with an IKMT having a 1.8 m head bar (sampling a 2.65 m^2 area), 5 mm mesh net, and a collecting bucket with a 1 mm mesh screen. In the net's mouth a flowmeter was attached to determine water volume sampled. The IKMT was towed obliquely, the wire let out until it was estimated to be several meters above the bottom and then pulled in at about 1 m/sec as the boat traveled at approximately 2-2.5 kts. Ichthyoplankton was sampled with a bongo net having 60 cm diameter openings (110 cm^2 area) and 1 mm mesh netting in which a flow meter was suspended. The bucket screens were also of 1 mm mesh netting. Samples were preserved in 5% formaldehyde solution, returned to the laboratory, and sorted. Juveniles and larvae were separated from both the IKMT and bongo net samples, and stored in a buffered 5% formaldehyde solution. Juveniles were identified following Baxter (unpublished manuscript, *Annotated Key to the Fishes of Alaska*), and counted. With the aid of a dissecting microscope, ichthyoplankton were identified following Matarese *et al.* (1989), and counted. Abundance was expressed as numbers/1000 m^3. The volume sampled was determined from the area of the IKMT and bongo nets openings and the revolutions of the flow meters (calibrated as to the revolutions/distance traveled).

Ages were estimated by examination of the external surface of otoliths and burnt otolith sections (Barber and McFarlane, 1987). Surface aging was done by placing each whole, unground otolith in a watchglass of glycerin:water solution and examining each under reflected light with a dark background through a dissecting microscope. A number of otoliths for each species were examined and criteria for annuli developed prior to aging each fish. Age estimates were obtained twice, followed by a third examination for those which did not agree. After ages were estimated from the surface, for those which were large enough, one otolith from each fish was randomly chosen and broken as near as possible through the nucleus and burned in an alcohol flame. Under a dissecting microscope the burned surface was brushed lightly with vegetable oil and examined under reflected light. Again, criteria for an annulus were developed prior to aging the fish. A true age validation study has not been conducted on any of the species involved in this study and will be very difficult to do so. Alternatively we collected fins from a subsample of Arctic cod and Arctic staghorn sculpin and attempted to obtain age information from these structures. The finrays proved to be to small and inappropriate for aging.

A hierarchical cluster analysis of fish collected at each station sampled in the 1990 and 1991 sampling was performed following Feder *et al.* (1989). In this case, the mean number of each species collected from the two trawls at each station was used to calculate the Czekanowski coefficient and used to calculate the similarity matrices for the stations. The results of these analyses are presented in Chapter 9.

Physical.—Vertical profiles of temperature and salinity were made at each station with a Seabird SBE 19 internally recording CTD (conductivity-temperature-depth) instrument. Because of a malfunction in the internal memory of the CTD, however, data from only 45 of the 52 CTD casts were recovered. At most stations calibration samples were collected for salinity and temperature with a Niskin bottle equipped with a reversing thermometer. The salinity samples were analyzed after the cruise with an Autosal laboratory salinometer. The results of the 1989 cruise are reported in Appendix 1 and data from the 1990 and 1991 ichthyofauna sampling is supporting information for Chapters 2, 4, 7, and 9.

1991 and 1992

Biological.—In 1991 biological sampling was again conducted from a chartered fishing vessel. Additionally, "Ships of opportunity" were also utilized. The University of Hokkaido's research vessel *Oshoro Maru* was used to collect information on snow crab and ichthyoplankton. Additionally, a pilot program was initiated where sampling with the bongo net, IKMT, and a try net was attempted from a launch offloaded from a barge used as a support vessel for the oil drill ship.

Because all stations were not occupied in 1990, additional sampling was conducted from 14 - 25 September 1991 from a chartered trawler. Eight stations established in 1990 were reoccupied in 1991 and an additional eight stations were established and sampled (Figure 1; locations are listed in Table 2 of Chapter 5). Techniques used in sampling during 1991 were identical to those previously described. The purpose was to gain wider coverage, estimate interannual variability of abundance, biomass, and species, and to collect reproductive data on snow crab (Chapter 11).

Sampling was conducted from *Oshoro Maru* on 25 July to 31 August 1991 (Figure 1) and 1992. In 1991 fishes and snow crab, for reproductive information, were collected with an otter trawl having a 43.3 m headrope and 48.6 m footrope fitted with rollers, and a 90 mm codend mesh. YOY and larval fishes were sampled with the University of Hokkaido's standard beam trawl with a 2 x 2.5 m square mouth and a net 17 m long with mesh grading from 6.5 mm to a 4 mm; the codend had a 1 mm lining. In 1992 sampling was conducted as in the previous year; however, the otter trawl had a 45 mm mesh liner in the cod-end. Information on snow crab obtained during the cruise will be found in Chapter 11 and on ichthyoplankton in Chapter 4, and fishes collected listed in Appendix 4.

A pilot program was initiated in 1991 where sampling was conducted in the vicinity of the drill ship (located at 71°20'N 165°25.8'W) from a 10.9 m launch deployed from the barge *Responder* (a drill ship support vessel). Sampling was conducted on 24-27 July, 13 - 18 August, and 28 September 1991. The launch was equipped with a detachable A-frame and diesel powered winch system to deploy and retrieve sampling gear. Sampling gears used were the IKMT, the bongo net, and a 4.9 m otter trawl of 5 mm mesh netting. Additionally, CTD casts were made as previously described. Data from these cruises may be found in Appendix 6. Some of the information on YOY fishes and ichthyoplankton was used in Chapter 4.

The CTD data set was supplemented by year-long measurements, at hourly intervals, of ocean currents, temperature, and salinity from five current meter moorings. The moorings were deployed in collaboration with researchers from NOAA's Pacific Marine Environmental Laboratory during a cruise aboard the NOAA vessel *Surveyor* conducted from 22 September to 11 October 1991. The original deployment plan called for moorings to be deployed in Barrow Canyon (within the Alaska Coastal Current) and in the north central Chukchi Sea (between Herald and Hanna Shoals). The Barrow Canyon moorings were designed to: 1) gauge flow and water mass property variations within the Alaska Coastal Current, 2) determine the frequency and on-shelf extent of water upwelled along the continental slope, and 3) build upon previous observations which indicated large interannual variations in winter production of extremely saline water formed on the northeast shelf. The area between Hanna and Herald Shoal was chosen for investigation because it had been the focus of recent oil exploration activities and the prevailing circulation pattern was unknown. However, heavy ice conditions prevented the vessel from reaching two of the three planned sites in the north central Chukchi Sea. Instead, these two moorings were deployed offshore of Cape Lisburne essentially bracketing the front between ACW and BSW. In the end, this turned out to be a fortuitous choice as the circulation in the winter of 1991/92 turned out to differ significantly from previous conceptions and the data from these moorings proved crucial in determining the reasons for this circulation change.

The moorings were recovered in collaboration with researchers from Japan's Marine Science and Technology Center (JAMSTEC) from a cruise aboard the University of Alaska's *Alpha Helix* conducted from 14 September to 9 October 1992. An extensive grid of CTD stations, covering the entire Chukchi Sea was also occupied on this cruise and the results are presented in Chapter 3.

CHAPTER 2

OCEANOGRAPHY OF THE NORTHEAST CHUKCHI SEA: A REVIEW[1]

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Abstract.—This paper reviews the physical oceanography of the ice-free season (July-October) of the northeast Chukchi Sea. This shelf sea is unique among those adjoining the Arctic Ocean because its physical and biological characteristics are profoundly influenced by the northward transport of Pacific Ocean waters through Bering Strait. A portion of this inflow, the Alaska Coastal Water, is warmed and diluted in summer by solar heating and river runoff and flows across the northeast Chukchi shelf within the Alaska Coastal Current (ACC). The dynamics of this current are governed by the large-scale pressure gradient between the Pacific and Arctic oceans, the density contrast between shelf water masses, and the local wind field. The core of the ACC parallels the bathymetry and coincides with a bottom temperature front. Current speed and frontal strength vary in proportion to the topographic relief. Surface fronts are also observed but they are more variable and not necessarily collocated with the bottom front. The regional oceanography is also affected by upwelling along the shelfbreak and mixing and circulation along the seasonally varying ice-edge. Accumulating evidence reveals very large interannual variability in winds, sea-ice extent, and the northward transport through Bering Strait; all of which contribute to the environmental variability of the Chukchi Sea.

INTRODUCTION

The Chukchi Sea lies at the northeastern end of the enormous Eurasian continental shelf system of the Arctic Ocean. These shelf seas (Barents, Kara, Laptev, East Siberian, and Chukchi Seas) comprise 12% of the continental shelf area of the globe (2.6 x 10^7 km^2, Walsh [1988]) and 22% of the total area of the Arctic Ocean (17 x 10^6 km^2, Carmack [1990]). The Chukchi Sea is unique among arctic shelf seas in that waters of Pacific Ocean origin flow across it and exert a profound influence on its circulation, the sea-ice, and water properties.

This paper reviews the physical oceanographic characteristics of the northeast Chukchi Sea. The open water season (mid-July through October) is emphasized because it is of primary concern to fisheries biologists and relatively little data have been collected during the ice-covered seasons. The northeast shelf is highlighted because it has been the focus of recent research spurred by concerns related to oil exploration activities. Moreover, due to limited access to the western Chukchi Sea, little information has been published on this region since the monograph by Coachman *et al.* (1975). More, detailed information on the oceanography of the Bering Strait and southern Chukchi Sea are found in Coachman *et al.* (1975) and Walsh *et al.* (1989).

The plan of the paper is as follows. The next section describes the bathymetry of the

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[1] Submitted for publication in Fish Ecology in Arctic North America.

region and this is followed by a description of the seasonal variation in the wind field. Both the bathymetry and the winds strongly influence the mean flow field of which the gross features are described in the section entitled "Chukchi Sea Circulation". The various water masses of the Chukchi Sea, which are mainly of advective origin rather than a consequence of *in-situ* formation, are then presented. With these four sections as background, the section entitled "Hydrography and Circulation of the northeast Chukchi Sea" provides specific examples of both and shows how they are interrelated. Aspects of shelfbreak upwelling and its implications for the Chukchi Sea are discussed in the "Upwelling" section. The "Sea-ice" section describes the seasonal distribution of sea-ice and aspects of ice-edge oceanography. Accumulating evidence indicates that the Chukchi Sea is subject to large interannual variations and examples of this variability are described in the "Interannual Variability" section. The final section of the paper concludes with a summary. Figure 1 illustrates the bathymetry and provides a reference map for the place names used throughout the text.

BATHYMETRY

The Chukchi Sea is bounded to the north by the shelfbreak (~200 m isobath) of the Arctic Ocean and to the south by Bering Strait - a distance of more than 800 km (Figure 1). Its lateral extent varies from a minimum of about 85 km in Bering Strait to a maximum of about 900 km between Long Strait in the west and Pt. Barrow in the east.

The basin has a relatively flat bottom, with depths deepening gradually from 30 m in the east to 55 m in the west. There are, however, several important bathymetric features which steer the currents and influence sea-ice and water property distributions: 1) Hope Sea Valley, a broad 55 m deep depression, extending northwest from the southern Chukchi Sea to Herald Sea Valley, 2) Herald Shoal in the center of the basin and, 3) Hanna Shoal in the northeast. The latter two have minimum depths of about 25 m.

Two shelfbreak bathymetric features facilitate cross-shelf exchange of water by steering currents and by channeling upwelled water onto the shelf: 1) Herald Sea Valley, east of Wrangel Island, is a relatively gentle, 50 km wide depression which terminates on the shelf at about 150 m depth, and 2) Barrow Canyon, a steep-sided canyon originating offshore of Pt. Franklin, cuts across the continental slope, and terminates at depths greater than 3000 m. Both canyons are the main conduits through which shelf water enters the Arctic Ocean (Coachman *et al.* 1975). Shelfbreak isobaths diverge from east to west such that bottom slopes decrease from 10 m/km in the northeast to 1 m/km in the northwest Chukchi Sea. This bathymetric change might have implications for the exchange of shelf waters with those of the Arctic Ocean (see Upwelling).

WINDS

Wind stress acting directly on the surface of the ocean or coupled to the ocean via a floating ice pack accelerates ocean currents. For shallow seas, such as the Chukchi, winds are important because they can induce rapid changes in the current structure over the whole water column and, consequently, redistribute water mass properties.

Winds over the Chukchi and northern Bering seas are strongly influenced by a polar high pressure cell centered at about 79°N, 170°W (Pease 1987). On average, this pressure system drives easterly winds over the northern Chukchi Sea and northeasterly winds over the southern Chukchi and northern Bering Seas. North of Point Lay (~69.5°N), the monthly mean winds vary little throughout the year and the variance about these monthly means is constant from February through July but increases in fall. South of Pt. Lay both the mean monthly winds and their variance vary seasonally. For example, mean July winds at Tin City (Figure 1) are from south southeast and 55% of all recorded winds blow from southerly quadrants during this month. In February mean winds are from the north and 78% of all recorded winds blow from the northerly quadrants (Brower *et al.* 1988).

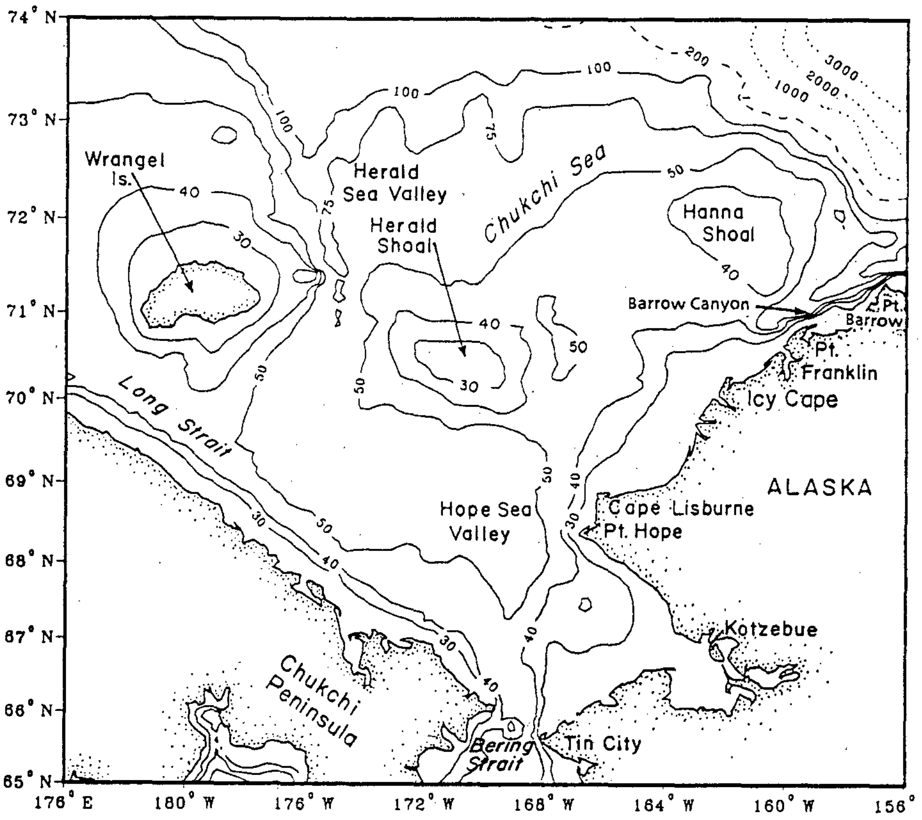

Figure 1. Bathymetry and place names of the northern Bering and Chukchi Seas.

Temporal and spatial variations in wind stress are a consequence of low pressure systems migrating eastward across the Bering Sea. In winter, storms propagate mainly across the southern Bering Sea and into the Gulf of Alaska, while in summer and fall, the frequency of storms propagating northeastward into the southern Chukchi Sea increases (Overland and Pease 1982, Brower *et al.* 1988, Aagaard *et al.* 1990). The storm track patterns and the complexity of the coastal topography result in relatively low correlations in wind stress fluctuations between coastal stations in the southern and the northern Chukchi Sea (Aagaard *et al.* 1990). Their correlations were computed using wind data sampled at 6-hourly intervals over record lengths of 12 or more months. Given the seasonal changes in storm tracks it is possible that these correlations also vary seasonally such that the spatial correlation of the winds is greater in winter than in the summer and fall. Spatial heterogeneity of the wind field in autumn influences the current structure of the northeast Chukchi Sea; south winds in the southern Chukchi Sea accelerate coastal currents northward whereas north winds in the northeast Chukchi Sea accelerate coastal currents southward. Differential advection of distinct water masses by these currents could establish strong horizontal gradients (fronts) in temperature and salinity.

CHUKCHI SEA CIRCULATION

The most important circulation feature of the Chukchi Sea is the northward flow through Bering Strait which has a mean annual transport of 0.8 Sv (Coachman and Aagaard 1988; 1 Sverdrup = 10^6 m^3/s). This transport is driven by the 0.5 meter drop in sea level between the Pacific Ocean and the Arctic Ocean (Overland and Roach 1987). Approximately 85% of this inflow originates in the deep Bering Sea and the Gulf of Anadyr (Kinder *et al.* 1986) with the remainder derived from the northeast Bering shelf. Transport fluctuations, at time scales which range from days to weeks, are of the same magnitude as the mean and are correlated with the north-south winds (Coachman and Aagaard 1988). Northward transport is minimum in winter when north winds prevail and is maximum in summer when south winds occur more frequently.

The Bering Strait throughflow bifurcates offshore of Lisburne Peninsula; one branch continues along the northeast coast as the Alaska Coastal Current (ACC) and the remainder flows to the northwest. Both of these flows are sustained, in part, by the sea-level difference between the Bering Sea and Arctic Ocean. The northwestward current consists of a diffuse, slowly drifting transport through the Hope and Herald Sea valleys (Coachman *et al.* 1975). In contrast, the ACC is a swift (0.2 m/s) coastal current whose main axis is found within 20 - 50 km of the Alaskan coast and which flows into the Arctic Ocean through Barrow Canyon. There is also a southeastward flow, the Siberian Coastal Current, which enters the Chukchi Sea through Long Strait and flows along the Chukotsk Peninsula before commingling with the Bering Strait inflow.

Relatively little is known about the circulation over the shelfbreak of the northern Chukchi Sea. However, hydrography (reviewed by Carmack 1990) and trajectories of buoys deployed in sea-ice (Colony 1984) indicate that, on average, currents in the upper 50 m flow westward and comprise the southern limb of the wind-driven anticyclonic (clockwise) gyre of the Arctic Ocean (Coachman and Aagaard 1974). Beneath this surface layer and extending to at least 2500 m depth, hydrography and moored current meter observations collected along the continental slope of the Alaskan Beaufort Sea (Aagaard 1984, Aagaard *et al.* 1990) reveal a well-defined eastward flow, the Beaufort Undercurrent, which flows opposite to the prevailing east winds. This current has a width of about 70 km and appears to be a persistent feature of the Arctic Ocean's circulation. Between 60 and 100 m depth mean speeds are about .05 m/s but fluctuations up to 1 m/s are common. Above 250 m depth, its source waters originate in the Bering Sea and drainage from Eurasian shelves. Beneath 250 m depth, undercurrent waters originate in the Atlantic Ocean which enter the eastern Arctic Ocean through Fram Strait in the Greenland Sea. Presumably the undercurrent is weaker to the west of the Chukchi Sea because of the decrease in shelfbreak slope (cf. Bathymetry) and because its volume increases after the Bering Strait inflow has joined it. While the dynamics of this undercurrent await theoretical study, they must be related, in part, to these inflows. Insofar as the undercurrent flows in a direction opposite to that of the wind, with shallow water to its right, it bears a strong similarity to the poleward flowing undercurrents along the eastern boundaries of mid-latitude oceans and it is probable that these undercurrents share similar dynamics.

WATER MASSES OF THE CHUKCHI SEA

Based upon this mean circulation scenario, the various Chukchi Sea water masses, and their origins, can be better appreciated. The temperature-salinity characteristics of these waters are shown in Figure 2 which was constructed from data collected between Bering Strait and Barrow within the past decade. The water mass nomenclature of Coachman *et al.* (1975) is adopted in this discussion.

The northward flow issuing from Bering Strait consists of Alaska Coastal Water (ACW) and Bering Shelf Water (BSW). A well-defined front, extending northward from Bering Strait to the Lisburne Peninsula, separates ACW, on the east side of the front, from BSW (Coachman *et al.* 1975; Walsh 1989). The ACW properties vary broadly, with temperatures ranging from 2 - 13°C and salinities less than 32.2 practical salinity units (psu). The low salinities are due to the influx of freshwater from river discharge (primarily the Yukon) along the Alaskan coast. Since the ACW is less dense than more saline waters, it is confined to the surface layer and is warmed by solar radiation. Bering Shelf Water is colder (0 - 3°C) and more saline (32.5 - 33 psu) than ACW. It is a blend of Bering Sea shelf water formed in winter and water flowing onto the shelf from the deep Bering Sea through the Gulf of Anadyr (Coachman *et al.* 1975). Bering Shelf Water also has much higher concentrations of dissolved nutrients and chlorophyll than ACW (Walsh *et al.* 1989).

Four additional water masses are observed on the northeast Chukchi shelf. The first derives from melting sea-ice and is characterized by low salinities and temperatures. The second, Resident Chukchi Water (RCW), is advected onto the shelf from the upper layers of the Arctic Ocean or is shelf water remnant from the previous winter. Its low temperatures (< 1°C) and relatively high salinities (32 - 33 psu) reflect the effects of freezing and brine drainage from growing sea-ice. The third water mass, Atlantic Water (so named because of its origin) has very high salinities (~34.5 psu) and moderate temperatures (0.5°C) and is generally found at depths greater than 250 m along the continental slope of the Chukchi and Beaufort Seas. Atlantic Water is observed in Barrow Canyon (Garrison and Paquette 1982) especially during upwelling events (Mountain *et al.* 1976; Aagaard and Roach 1990) but it is not clear how frequently these waters are advected into the shallower reaches of the shelf. Bourke and Paquette (1976) reported sporadic observations of warm, saline water, extending as far south as 70°N, along the bottom of the northeast Chukchi Sea. They hypothesized that these derived from Atlantic Water upwelled through Barrow Canyon. The fourth and final water mass is indicated by the freezing point curve in Figure 2. Winter waters on the Chukchi shelf are generally only a few tenths of a degree warmer than the freezing point.

HYDROGRAPHY AND CIRCULATION OF THE NORTHEAST CHUKCHI SHELF

The observations reported by Johnson (1989) are a useful introduction to several of the more important oceanographic features of the region. His data were collected during a cruise from late August to early September, 1986, which began near Barrow and concluded off Pt. Hope. During the first few days of the cruise, the winds blew from the northeast and then reversed and blew from the southeast and southwest. The ice-edge was located between 72.5 and 73°N during this survey.

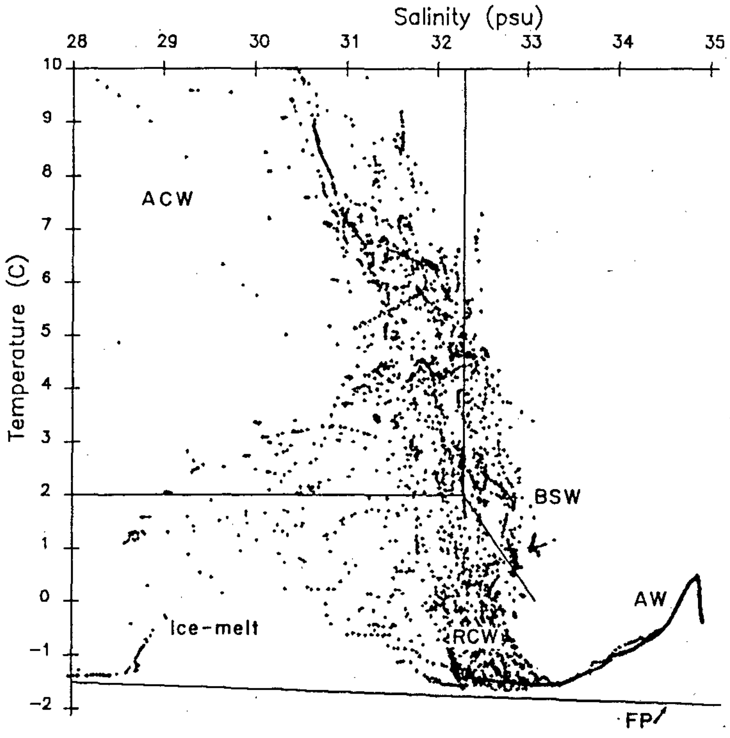

Figure 2. Temperature-salinity diagram of major water masses of the Chukchi Sea. Acronyms are as follows: ACW (Alaska Coastal Water), BSW (Bering Shelf Water), RCW (Resident Chukchi Water), AW (Atlantic Water), and FB indicates the freezing point temperature of seawater for a given salinity.

Figure 3 shows the near-surface velocity vectors obtained throughout the cruise from a shipboard Acoustic Doppler Current Profiler. At the beginning of the survey, vigorous southwestward flow (~.75 m/s) was observed offshore of Barrow. (Simultaneous current meter data from the same area showed that these currents reversed along with the wind and flowed toward the northeast for the duration of the survey.) The trajectory of the ACC is apparent in the vectors which trace out a swift northeastward and northward current to the west and northwest of the Lisburne Peninsula. The vectors veer eastward between 70.5 and 71.5°N and then northeastward on approaching the coast. In the shallow (<25 m depth) embayment, to the north of the Lisburne Peninsula, the flow is weak and the vector pattern suggests a clockwise circulation cell. Coachman *et al.* (1975) inferred a similar circulation pattern here and the observations are consistent with laboratory results showing the formation of eddies and stagnation points in the lee of capes protruding into a coastal flow (Boyer *et al.* 1987). Finally, the influence of Hanna Shoal is indicated by the meridional divergence of the flow at 72°N, 165°W and eastward flow to the north of this shoal region.

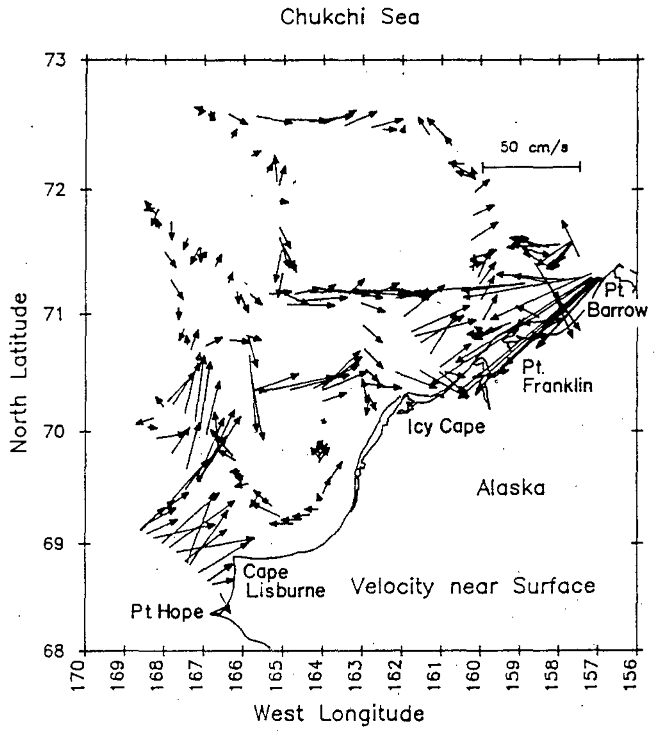

Figure 3. Near-surface velocity vectors in August-September 1986 as measured with a vessel-mounted Acoustic Doppler Current Profiler (from Johnson 1989).

The hydrography from this cruise is presented in the form of maps showing contours of the surface and bottom isotherms and isohalines (Figures 4a - 4d). The surface maps (Figures 4a and 4b) indicate that ACW extends over the whole region south of about 71°N. The tongue of cold, low salinity, ice meltwater projecting southwest from Barrow is consistent with the observed surface flow at the beginning of the survey. These two water masses are separated by a surface front (delineated by the 3 - 6°C isotherms and the 31.5 psu isohaline), between 70.5 and 71 °N, which extends offshore to the west-southwest for about 200 km. The front weakens at the point where the 32 psu isohaline attains its easternmost position and then bends to the southwest.

Along the bottom (Figures 4c and 4d), ACW is observed inshore and to the south of the 32.5 psu and 3°C isopleths. A sharp thermal front (parallel to, but much stronger than, the surface thermal front) separates the ACW from the rest of the sampled domain which consists of RCW and mixtures of ACW and RCW. This bottom front parallels the 30 and 40 m isobaths and is strongest north of Icy Cape where these isobaths converge (Figure 1). Moreover, the velocity vectors (Figure 3) are roughly parallel to the isobaths (and the front) and they are oriented such that warmer and less saline water is found to the right of the direction of flow. Both of these observations are consistent with the dynamics of density-driven, coastal geostrophic flows over a sloping bottom (e.g., Csanady 1982). Geostrophic motion implies an equilibrium flow in which the pressure gradient is balanced by the Coriolis acceleration. For the case just discussed, the pressure gradient is perpendicular to the local orientation of the front and the isobaths and arises due to the density contrast between warm, dilute and cold, salty water.

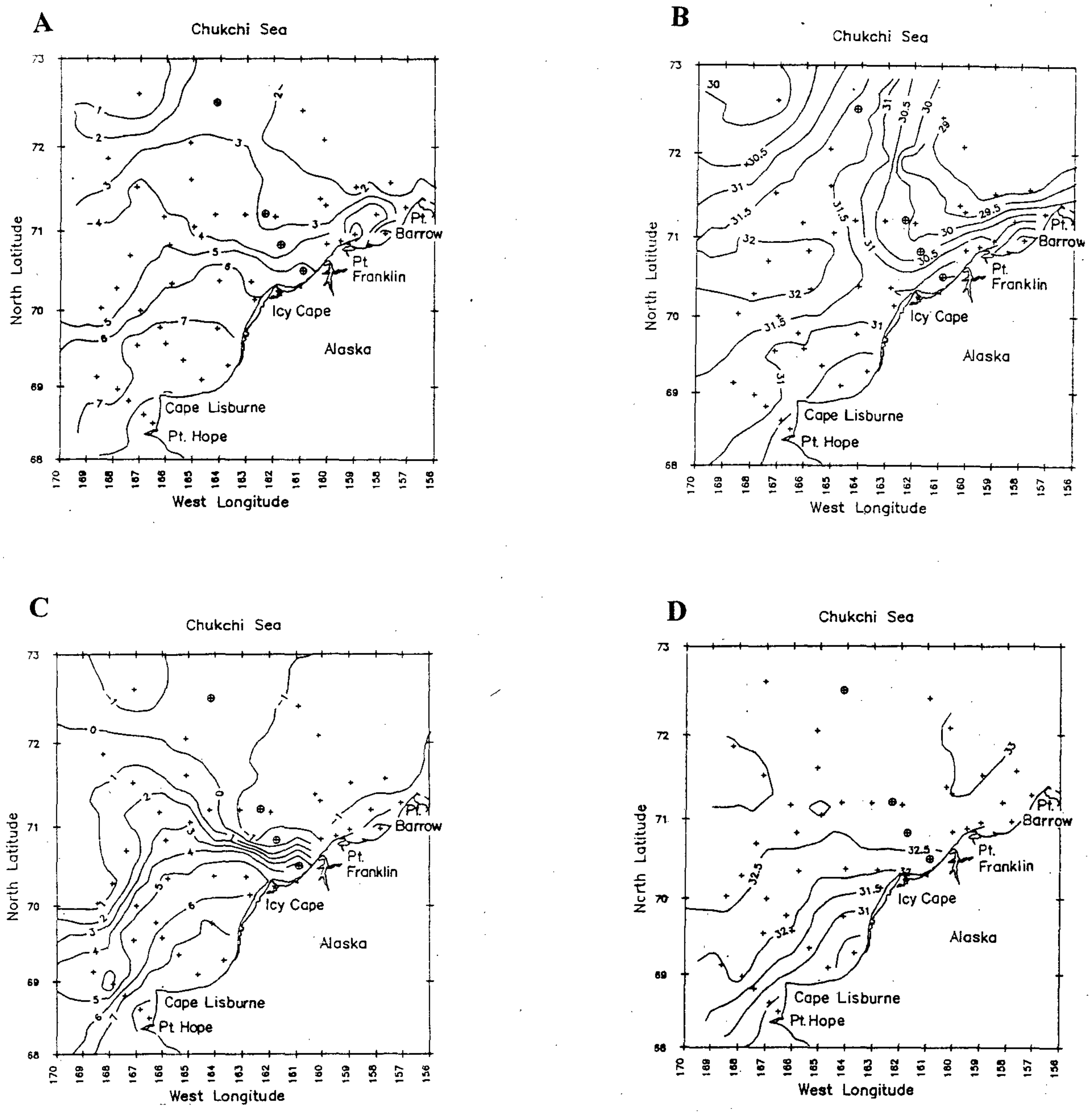

Figure 4. Contour maps of (a) surface temperature (°C), (b) surface salinity (psu), (c) bottom temperature (°C), and (d) bottom salinity (psu) in August-September, 1986 (from Johnson 1989).

By way of comparison, surface and bottom temperature (Figures 5a and 5c) and salinity (Figures 5b and 5d) maps are shown from data I collected in late August through mid-September 1990. Throughout August and most of September winds at Barrow blew steadily and strongly from the east while winds at Kotzebue, although more variable, were primarily from the southwest and west. The ice-edge in September, 1990 was at about 74°N. The ACW was observed at the surface at all locations and temperatures were higher and salinities lower relative to the 1986 survey. While a strong front is observed extending westward from the coast midway between Cape Lisburne and Pt. Lay there is no indication of a front intersecting the coast between Icy Cape and Pt. Franklin.

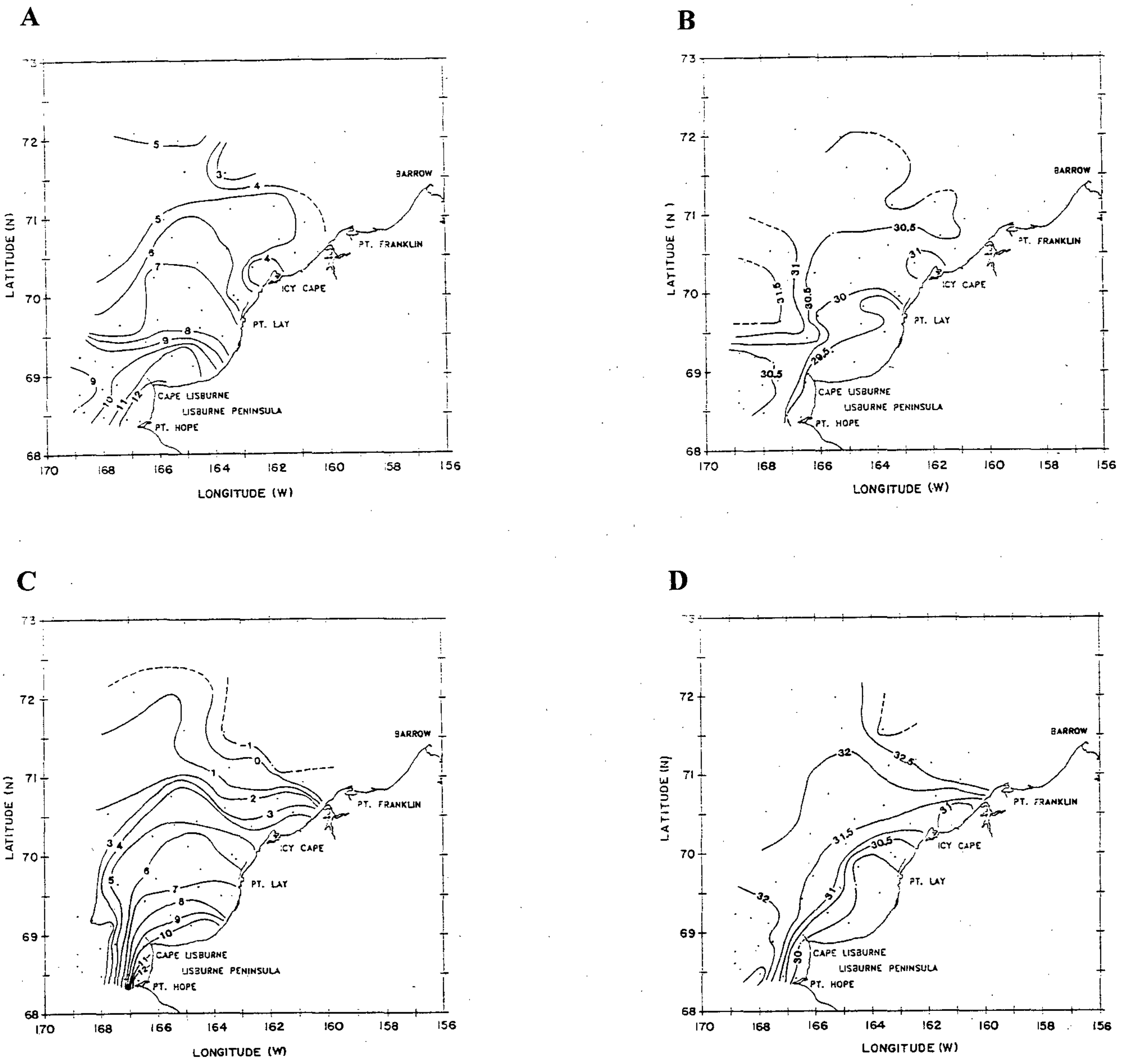

Figure 5. Contour maps of (a) surface temperature (°C), (b) surface salinity (psu), (c) bottom temperature (°C), and (d) bottom salinity (psu) in September 1990.

Alaska Coastal Water extends over a broad area of the bottom and is found everywhere inshore of the 32 psu isohaline (Figures 5c and d). The ACW is also bounded by a weaker thermal front in a similar location and orientation as that observed in 1986. Resident Chukchi Water lies north of this front while west of Pt. Hope the bottom waters seaward of the front are characteristic of the colder, saltier BSW.

The relatively coarse station spacing of the 1986 and 1990 surveys permit mapping large-scale hydrographic features but they do not resolve adequately the strength of these fronts. However, Aagaard's (1988) cross-section profiles of temperature and salinity collected in late August 1982 from transects running northwestward from the coast off Pt. Lay and Pt. Franklin (Figure 6) illustrate their intensity. The Pt. Lay section consists wholly of ACW and shows a well-mixed, 20 m deep, surface layer, of uniform temperature (7°C) and salinity (~30 psu), extending over the entire transect. The surface layer is separated from the colder and saltier bottom waters by a 5 m thick thermocline across which the temperature decreases from 6 to 2°C. Approximately 40 km offshore, the thermocline intersects the bottom forming a front along the 35 m isobath. Bottom temperatures decrease by 4°C over the 25 km width of the front.

The Pt. Franklin transect is more complex. Alaska Coastal Water is confined to a band within 20 km of the coast and is separated from offshore waters by an intense surface to bottom temperature front. Seaward of the front, waters in the uppermost 20 m derive from ice melt, while those at greater depths are RCW. Moreover, there is neither a well-mixed surface layer or a thermocline. Rather, the surface layer is strongly stratified due to the salinity difference between the meltwater and RCW. The most striking aspect of this transect, however, is the intensity of the thermal front across which the temperature changes by 6°C within 5 km.

Taken together, these results, plus others shown by Fleming and Heggarty (1966) and Coachman *et al.* (1975), suggest that the bottom front between the 25 and 40 m isobaths is a frequent feature of the ice-free season of the northeast Chukchi Sea. (However, Aagaard's [1988] data from September 1981 show no evidence of this front and reasons for its absence in that year are discussed in Interannual Variability.) In examining the surface temperature distributions it is evident that surface and bottom fronts are not always collocated. In fact, the presence and the location of surface thermal fronts appear to be much more variable and this variability is probably a consequence of the greater influence of wind forcing in the near-surface layer as well as the location of the ice-edge. Paquette and Bourke (1981) have also noted that the positions of the surface and bottom fronts associated with the marginal ice zone of the Chukchi Sea do not often coincide. Although satellite thermal imagery is often useful in delineating the circulation on the Chukchi shelf (Walsh *et al.* 1989), one consequence of these results is that analysts cannot draw inferences on the absence, presence, or location of bottom fronts based solely upon this imagery.

Although the bottom front can be displaced in response to wind-induced current fluctuations (Johnson 1989) its mean position is most likely established where the bottom depth is equal to the mean depth of the mixed layer. In the Chukchi Sea tidal velocities are small (~0.05 m/s) and the most important energy sources for mixing are cooling at the ocean surface and the winds. The mixed layer depth represents an equilibrium depth over which mixing processes are balanced by stabilizing processes (atmospheric heating, freshwater influx from rivers, and melting sea-ice). Hence, variability in these parameters should also be reflected in the position of the bottom front.

While the body of physical oceanographic data from the northeast Chukchi Sea is small, further support for the contention that this bottom front is an annually recurring hydrographic feature is apparent in biological data. Feder *et al.* (1990; in press) show large increases in abundance and biomass of benthic communities within the vicinity and north of the front. Grebmeier *et al.* (1988) show similar changes in benthic community structure crossing the front south of the Lisburne Peninsula.

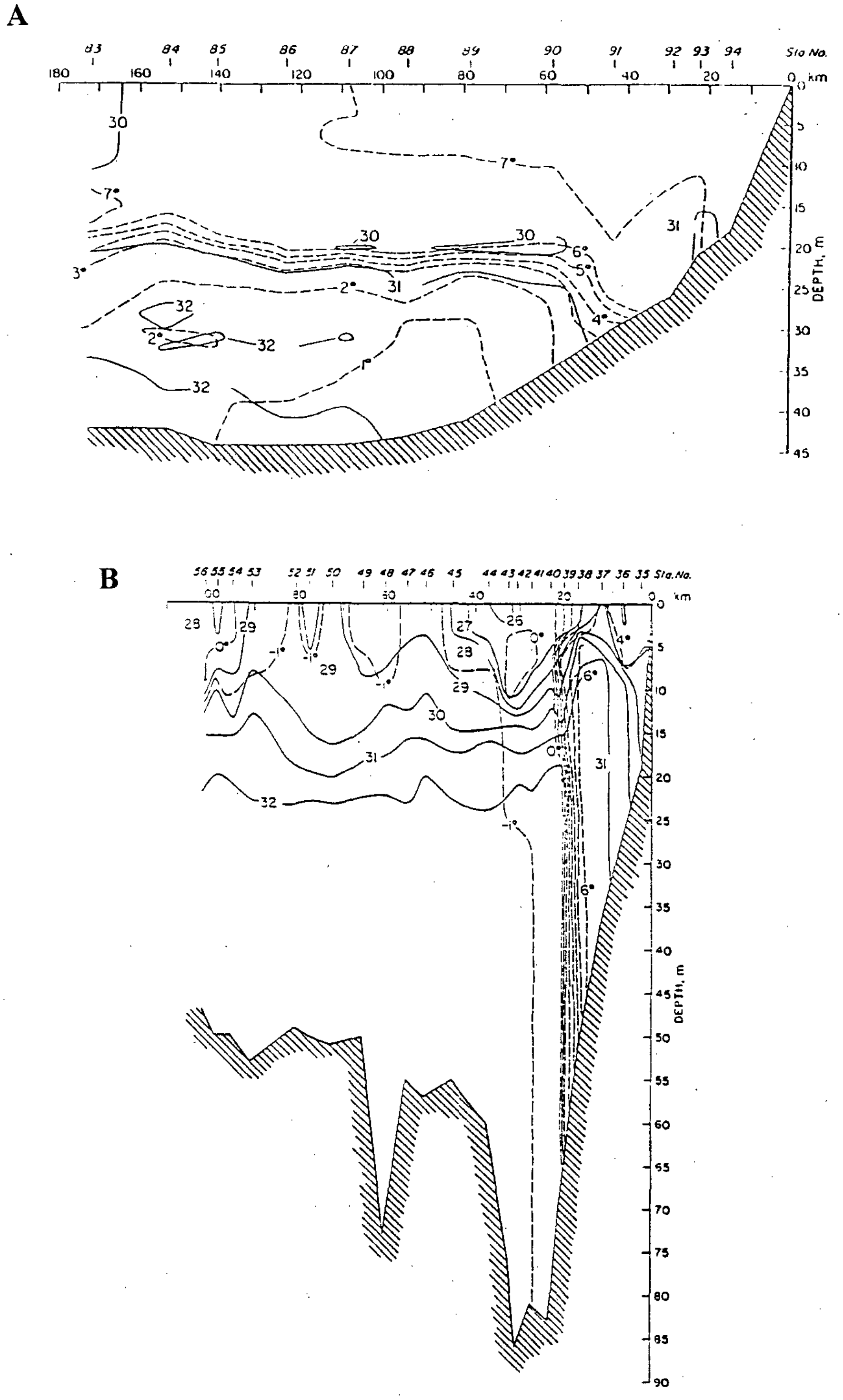

Figure 6. Cross-section profiles of temperature and salinity (psu) from transects extending northwestward from a) Pt. Lay and b)Pt. Franklin August-September 1982 (from Aagaard 1984).

In summary, the mean flow in the ACC arises in response to the large scale pressure gradient between the Pacific and Arctic Oceans and horizontal pressure gradients established by the density contrasts between water masses on the shelf. The former varies on millennial time scales while the latter varies seasonally and in response to synoptic atmospheric pressure patterns. The main axis of this current is parallel to a bottom front oriented along the bathymetry. Along the current's axis, speeds vary in conjunction with the strength of the front and the magnitude of the bottom slope. The latter point is illustrated by the mean and maximum current speeds reported by Aagaard (1988) from year-long current meter records obtained offshore of Pt. Franklin (large bottom slope) and Cape Lisburne (smaller bottom slope). Mean and maximum speeds from the Pt. Franklin moorings were 0.2 m/s and 1.1 m/s, respectively. The corresponding values for the Cape Lisburne moorings were 0.05 m/s and 0.62 m/s.

Johnson's (1989) and Aagaard's (1988) results show that superposed on the mean flow of the ACC are large temporal variations, which occur on time scales of days to weeks, and which are correlated with the north-south wind component. (Northward winds accelerate the along-isobath flow component, i.e., in the same direction as the mean flow. Southward winds decelerate this flow component and sufficiently strong southward winds can lead to current reversals.) This current variability might play an important role in transporting shelf water into the interior of the western Arctic Ocean given D'Asaro's (1988) hypothesis that, at the mouth of Barrow Canyon, these fluctuations generate the long-lived eddies observed throughout the interior of the western Arctic Ocean. Aagaard's (1988) results show that along-isobath current fluctuations at the Pt. Franklin moorings were also correlated with those at Cape Lisburne implying that the velocity field of the northeast Chukchi Sea is coherent over alongshore distances as large as 350 km. The current response to fluctuations in the wind field occurs rapidly (<1 day) and, within the vicinity of the front, is accompanied by dramatic temperature and salinity changes (Johnson 1989). Such effects can complicate the interpretation of hydrographic data collected over a large area during a two to three week cruise and indicate the need to consider the wind history of this region in analyzing such data.

UPWELLING

The deeper (~100 m depth) waters offshore of the shelfbreak of the northern Chukchi Sea provide a potentially important source of nutrient rich water for this shelf. At still greater depths (~250 m), waters upwelled from the Atlantic layer could exert a substantial change in the temperature-salinity structure of the northern Chukchi Sea as well as provide nutrients. Shelfbreak upwelling provides a mechanism for the flux of these waters onto the shelf. Episodic upwelling in Barrow Canyon and along the shelfbreak of the Beaufort Sea is a frequent phenomenon which has been inferred from hydrographic data (Garrison and Paquette 1982; Bourke and Paquette 1976; Hufford 1974) and observed in current meter records (Mountain *et al.* 1976 and Aagaard and Roach 1990) from the same area. Aagaard and Roach's (1990) results show that upwelling, from depths as great as 300 m, occurred along the Alaskan Beaufort Sea shelfbreak in the form of eastward propagating events of about five days duration. While these upwellings were not well-correlated with local winds they were most common in fall and early winter when winds were most variable. They suggest that these episodes are a response of the shelfbreak circulation to large-scale stochastic wind forcing and theoretical support for this hypothesis is implied by the numerical model results of Philander and Yoon (1982).

Once upwelled the deeper waters will influence the shelf if they can be advected shoreward. Data from Aagaard and Roach's (1990) mooring anchored on the 150 m isobath within Barrow Canyon suggest that average upcanyon (onshore) velocities during upwelling episodes were about .25 m/s. Over the five-day duration of such an event, water parcels would be displaced 125 km upcanyon or as far inshore as the 60 m isobath. In contrast, their current records from the Beaufort Sea shelfbreak show that upwelling-related onshore velocities were much smaller than those observed in Barrow Canyon. This is not unexpected given that onshore flow is weaker over regions of large bottom slope (i.e., the Beaufort shelfbreak) than over regions of gentle bottom slope (Johnson and Rockliff 1986). Hence, the westward decrease in slope along the Chukchi Sea shelfbreak suggests that the onshore excursion of upwelled water here might be greater than in the Beaufort Sea. This hypothesis remains untested because, to date, no long-term measurements have been made on this part of the shelfbreak.

SEA-ICE

The Chukchi Sea is generally ice-covered from November through June. North of Bering Strait, the seasonal retreat of sea-ice begins in June and, in the mean, attains its farthest north position along about 72.5°N in mid-September (Naval Oceanography Command Detachment 1986). In comparison to the Beaufort and East Siberian Seas, ice-retreat begins earlier and ice-advance occurs later on the Chukchi shelf due to the influence of warm water advected northward through Bering Strait. However, interannual differences in the seasonal retreat, advance, and position of the ice-edge are related to the winds (Muench *et al.* 1991; e.g., north winds advect the ice-edge southward and vice-versa).

The northward retreat of the ice-edge during the summer months does not proceed uniformly along its length. Figure 7 (from Muench 1990) shows that the ice-edge between Wrangel Island and Pt. Barrow is markedly indented by three "meltback embayments" whose relative positions vary little from year-to-year. Two of these embayments overlie Herald Sea Valley and Barrow Canyon and the third is observed between Herald and Hanna shoals. All are related to bathymetric steering of the northward flow of warm waters. (The data of Paquette and Bourke [1981] clearly show the northward advection of warm water between Herald and Hanna shoals and this flow is also suggested by spreading of the bottom isotherms at about 71°N, 165°W in Figures 4c and 5c.) These "meltback embayments" might have biological significance because there are marked differences between the wind-forced circulation along a straight ice-edge and a meandering ice-edge. The model of Roed and O'Brien (1983) shows that for a straight ice-edge, zonally oriented such that open water lies to the south of the ice, winds from the east result in upwelling along the ice-edge and winds from the west result in downwelling. Hakkinen's (1986) model results show that if an ice-edge has meanders (i.e., embayments) upwelling occurs on the windward side of the meander and downwelling on the lee side. High rates of primary production are often associated with ice-edges (Niebauer 1991) and ice-edge upwelling of nutrients would enhance this productivity. In the northern Chukchi Sea, where mean winds are from the east and vary primarily in the zonal direction, these embayments could be significant sites for carbon fixation. Hakkinen's (1986) model results further imply that biological production along the ice-edge of the Chukchi Sea could vary dramatically in both time and space and that field programs must be suitably designed to address this issue.

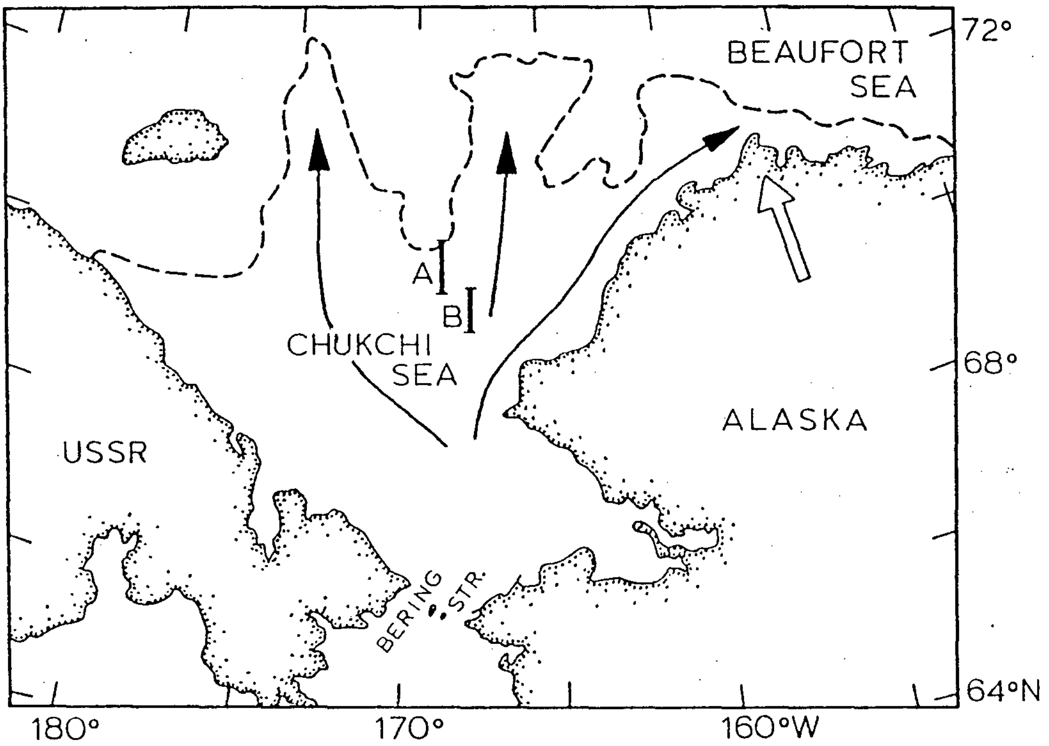

Figure 7. Schematic of the Chukchi Sea ice-edge illustrating location of "meltwater embayments" in summer (from Muench 1990). Transects A and B correspond to the cross-section profiles shown in Figure 8a and 8b.

Ice-edge zones are characterized by large spatial gradients in water (and air) mass properties, currents, winds, ice concentration, and the ocean wave field. All of these variables are interrelated through complicated feedback processes which are rarely in equilibrium. (A non-technical overview of these processes is given by Muench [1989]. More technical aspects of these processes are found in the June 1987 "Marginal Ice Zone Research" Special Issue of the Journal of Geophysical Research.) An illustration of some of the complexities of these regions in the Chukchi Sea are given in Figures 8a and 8b (from Paquette and Bourke 1981) which show two cross-section profiles of temperature and salinity along the transects A and B shown in Figure 7. Figure 8a (transect A; July 1978) shows that the ice-edge frontal system consists of an upper-layer front established by meltwater and a lower-layer front established by the temperature contrasts between RCW and the northward flowing ACW and BSW. (As mentioned in section 6 these upper and lower-layer fronts do not always coincide as is evident in other transects shown by Paquette and Bourke (1981)). The hydrographic structure suggests a horizontally and vertically sheared, westward flow confined to the surface front. In contrast Figure 8b (transect B; July 1974) shows strong vertical salinity gradients, but weak horizontal gradients and the whole transect is characterized by finescale (1 - 5 m thick) temperature intrusions and weak currents. According to Paquette and Bourke, the differences between these two sections is related to the orientation of the ice-edge with respect to the prevailing background circulation at the time of the sampling. In Transect A, warm water from the south was flowing northward and perpendicular to the ice-edge whereas in Transect B, flow was northeastward and approximately parallel to the ice-edge. The temperature fine-structure reflects the influence of lateral mixing along the current's path.

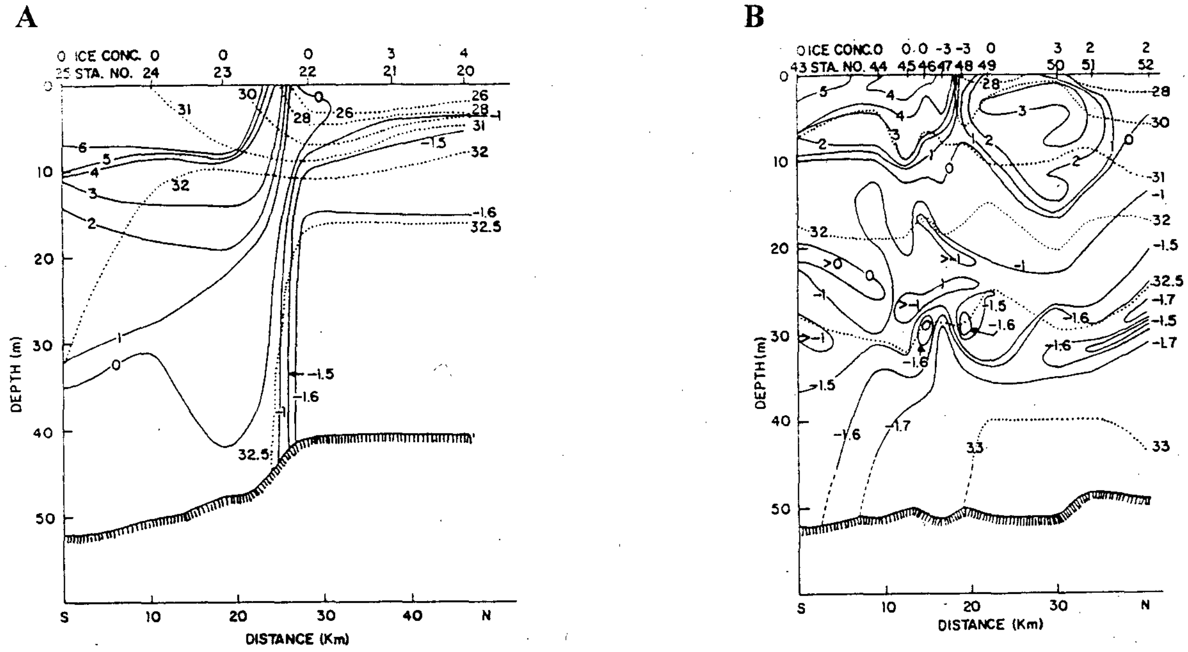

Figure 8. Cross-section profiles of temperature and salinity along two transects normal to the summer ice-edge. Figure 8a (from July 1978) illustrates the case where well-defined upper- and lower-layer fronts coincide. Figure 8b (from July 1974) shows complex temperature fine-structure associated with strong vertical salinity gradients. For each figure the topmost line of numbers corresponds to the ice-concentration in eighths. Ice concentrations preceded by a minus sign indicate concentrations in negative powers of ten; positive numbers represent ice concentrations in eights (From Paquette and Bourke 1981).

INTERANNUAL VARIABILITY

The relative brevity of research programs seldom affords opportunities to appreciate variability on time scales exceeding the seasonal and this is especially true for high-latitude oceans where sampling is costly and complicated by harsh environmental conditions. However, accumulating evidence points to large interannual variations in the oceanographic conditions of the Chukchi Sea. A major step forward in understanding this variability was made by Coachman and Aagaard (1988) who related transport variations in Bering Strait to north-south winds. Their results (Figure 9) show that the mean annual transport varied by a factor of 2 over the period from 1946-1985. In addition to interannual differences, a large secular decrease in transport began in the late 1960s. Prior to 1969, 70% of the estimated mean annual transports exceeded the 40-year mean, whereas, from 1969 to 1985, 76% of the transports were less than this mean.

Such variations should have important consequences for the Chukchi Sea because of the implied variation in the northward flux of heat, salt, and nutrients, but few data exist upon which conclusions regarding the effect of this variability can be made. However, in the section on upwelling it was noted that Aagaard's (1988) data from September 1981 showed no indication of the bottom front which was argued to be a frequent feature of the northeast Chukchi Sea. The absence of this front in 1981 is seen in the cross-section profiles of temperature and salinity along the Pt. Lay transect shown in Figure 10 (the corresponding transect for 1982 was shown in Figure 6a). Moreover, no ACW is present along this transect which consists of very cold (~-1°C) RCW along the bottom and within 80 km of the coast and meltwater elsewhere. Differences between the 1981 hydrography and the years discussed previously could be associated with differences in winds. Figure 11 shows time series of the monthly anomaly of the north-south surface wind component at 67.5°N, 167.5°W for the period 1981 to 1991. (The monthly anomalies are the deviates from the mean wind for that month. The wind components are estimated from synoptic atmospheric pressure grids following Aagaard *et al.* [1990].) Time series of this variable to the south and north of this location are quite similar. The data show persistent, north wind anomalies from July through November 1981. In 1986 and 1990 south wind anomalies prevailed during these months while in 1982 both north and south anomalies were observed. The magnitude and persistence of the 1981 wind anomalies would have resulted in: 1) reduced northward transport through Bering Strait thereby increasing the time required to flush winter water from the Chukchi shelf, and 2) westward displacement of ACW from the northeast Chukchi Sea.

Coachman and Shigaev (1992) have also documented temperature and salinity (and, by implication, other constituents) differences in the source waters feeding into Bering Strait. They show that these waters were most saline in the late 1960's and least saline in the mid-1970's. Temperatures and salinities of southeastern Bering Shelf water also show considerable interannual variations and these are associated with interannual variability in ice cover over the Bering Sea shelf such that cold, dilute bottom waters in summer follow extensive winter ice cover, and vice versa.

Summer-fall sea-ice extent in the Chukchi Sea also varies enormously from year-to-year. For example, the Naval Oceanography Command Detachment (1986) atlas shows that the mid-September ice-edge position in the northern Chukchi Sea ranges from 70 to 75°N - a distance of over 500 km. Mysak *et al.* (1990) analyzed variations in sea-ice extent over the Chukchi and Beaufort Seas for the period 1953 to 1985 and show that interannual differences can amount to nearly 300% and that these differences can persist for from three to six years. They argue that the variability is related to variations in regional winds and coastal freshwater discharge induced by hemispheric-scale atmospheric fluctuations.

SUMMARY

The preceding sections have shown that the bathymetry, meteorology, sea-ice distribution, and northward advection of waters through Bering Strait profoundly influence the oceanography of the northeast Chukchi Sea. One of the more important hydrographic features observed during the open water season is the frequent occurrence of a bottom thermal front which parallels the bathymetry and the core of the Alaska Coastal Current. Biologically, the front appears to be an important feeding area for marine mammals preying on benthic organisms and a "boundary" across which benthic and fish community structure change markedly (Feder *et al.* 1990; Feder *et al.* in press; Wylie-Echeverria *et al.* in this volume; Smith *et al.* in this volume).

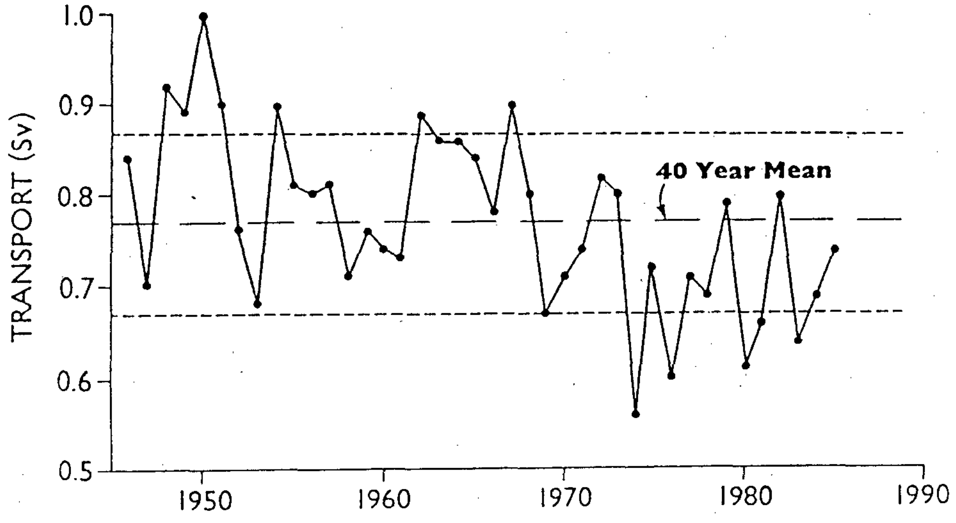

Figure 9. Mean annual northward transport through Bering Strait from 1946-1985 (from Coachman and Aagaard 1988).

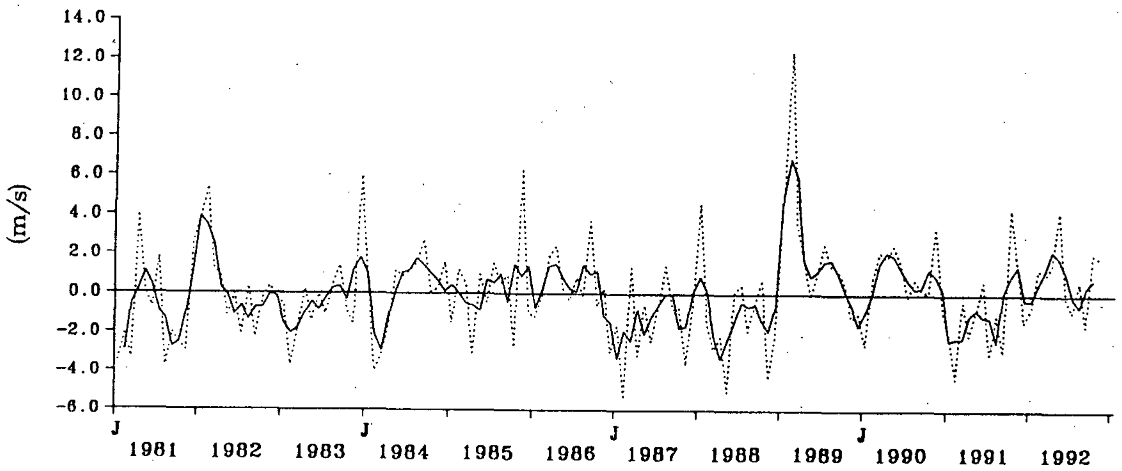

Figure 10. Time series of the monthly (solid line) and three-month running mean (dashed line) of the north-south component of surface wind component 67.5°N, 167.5°W for the period 1981 to 1991. Positive values: south winds stronger than normal or north winds weaker than normal. Negative values: south winds weaker than normal or north winds stronger than normal. Salinity in psu.

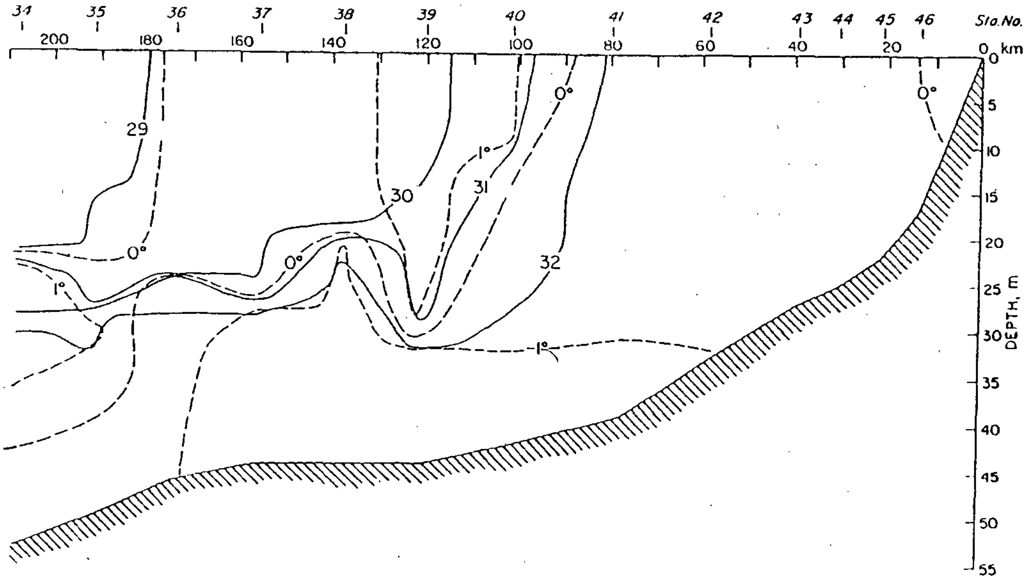

Figure 11. Cross-section profiles of temperature and salinity along a transect extending northwest from Pt. Lay in September 1981. The corresponding transect for August 1982 is shown in Figure 6a (from Aagaard 1988).

The oceanographic regime of the southern Chukchi Sea supports some of the highest primary production rates observed in the global ocean and some of this production is exported to the northern Chukchi Sea and Arctic Ocean (Walsh *et al.* 1989). Biologically, little is known about the northern Chukchi Sea but the effects of the ice-edge and shelfbreak upwelling might have important biological implications for this region of the Chukchi shelf.

The review has indicated the enormous, but poorly documented, interannual variability in the physical environment of the Chukchi Sea. To what extent the variability affects this ecosystem remains to be studied. However, in order to discriminate between natural biological changes and those induced by the activities of man requires an interdisciplinary effort directed toward understanding this variability and its effects.

ACKNOWLEDGEMENTS

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APPENDIX I. CHAPTER 2.

Results from the Fall 1992 Hydrographic Survey

Fall Hydrography.—The current meters, described in the body of this report were recovered in fall 1992 from the *R/V Alpha Helix*. This cruise, conducted in collaboration with oceanographers from the Japan Marine Science and Technology Center (JAMSTEC) and largely funded by JAMSTEC, provided an opportunity for occupying an extensive Conductivity-Temperature-Depth (CTD) hydrographic grid throughout the Chukchi Sea. The cruise took place from September 21 through October 4, 1992 and the sampling transects are shown in Figure 1. Measurements included vertical profiles of temperature, salinity, and fluorescence. The latter provides a relative measure of the chlorophyll concentration in seawater and may be considered a proxy variable for the particulate organic carbon fraction associated with phytoplankton. Ancillary sampling included collection of dissolved nutrients, oxygen isotopes, and barium for analysis by scientists funded by other agencies. These data are presently being analyzed by other investigators. In addition, Japanese oceanographers measured dissolved oxygen concentrations and their results are still being analyzed.

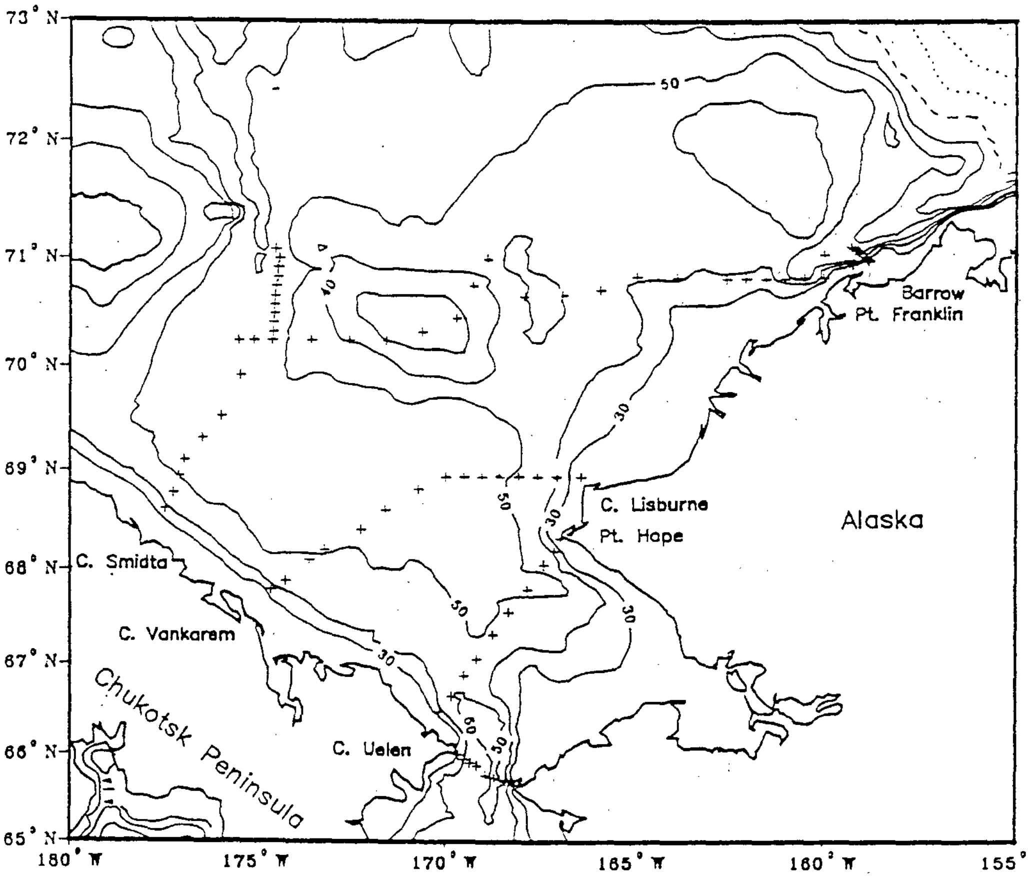

Figure 1. Hydrographic stations (+ signs) occupied in fall 1992.

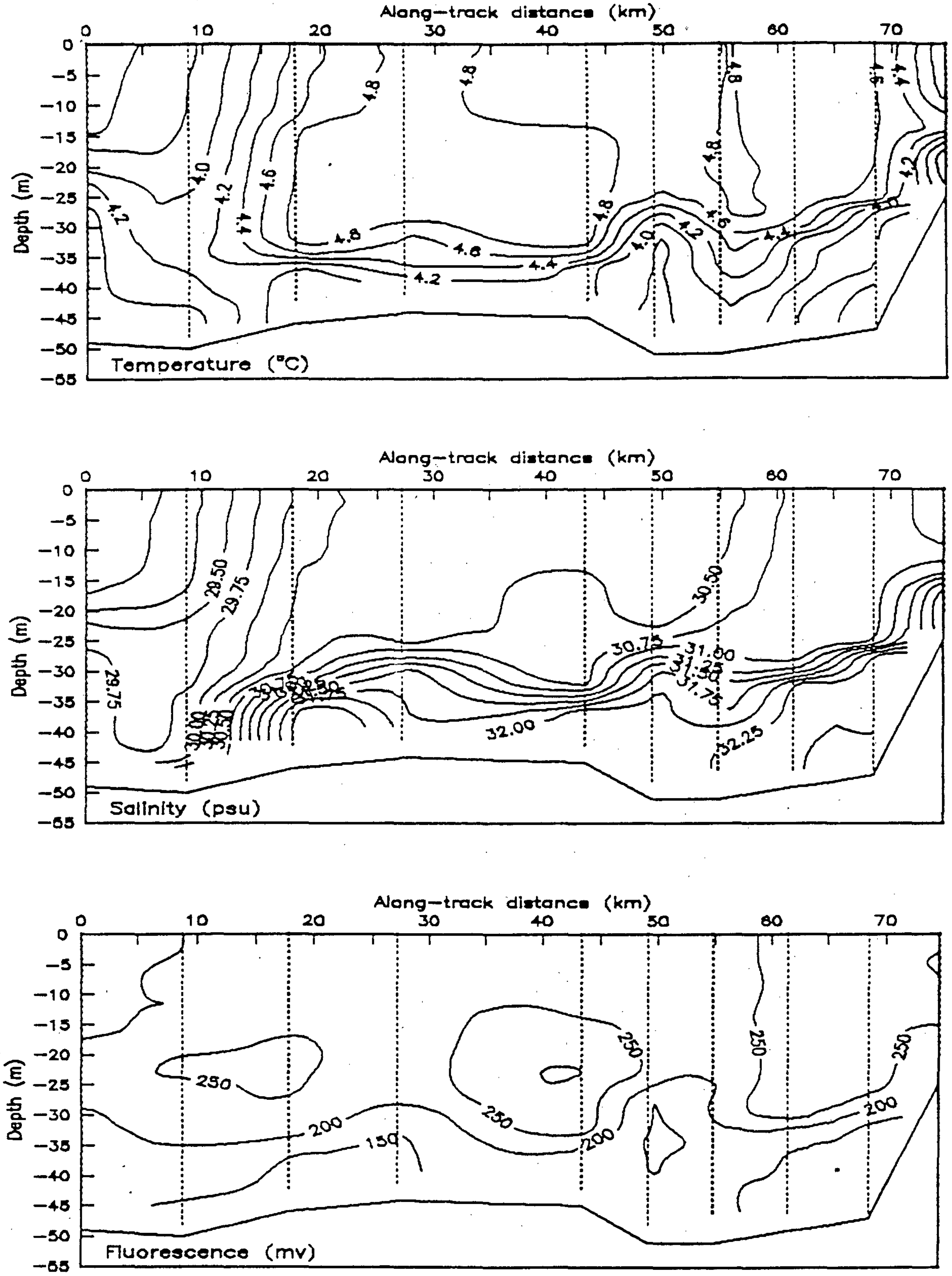

Figure 2. Contours of temperature (top), salinity (middle), and fluorescence (bottom) from west to east in Bering Strait, 21 September 1992.

The temperature and salinity observations stand in sharp contrast to results previously reported for Bering Strait. For example, Coachman *et al.* (1975) and Walsh *et al.* (1989) find that the warmest and most dilute waters (Alaska Coastal Water, or ACW) lie at the surface on the eastern side of the strait and that the coldest and most saline waters (Anadyr Water, according to Coachman *et al.* 1975) are found near the bottom on the western side of the strait. Typically there is a strong front separating these two water masses. Our interpretation of the water mass distribution on 9/21 is as follows. The cool, low-salinity waters on the western side of the strait represent a southward extension of the Siberian Coastal Current (SCC). This current flows southeastward along the north coast of the Chukotsk Peninsula, but is believed to mix with waters flowing northward through Bering Strait and then to recirculate throughout the Chukchi Sea (Coachman *et al.* 1975). In fact, these authors state that observations of SCC waters in Bering Strait are extremely rare. (It should also be remembered that because of the historical political climate access to Russian waters on the west side of Bering Strait has been very limited. Therefore, relative to the east side, relatively few measurements have been made in the western channel.) However, strong northerly winds prior to and during occupation of this transect could have forced SCC waters southward through the strait.

Fluorescence values are relatively uniform throughout this section and, as will be seen, relatively low in comparison to values obtained on other transects. Low pigment concentrations are typical of the river-fed ACW (Walsh *et al.* 1989) and presumably of the SCC as well.

Next consider the Cape Lisburne transect occupied on September 23 (Figure 3). The strong winds had abated by 9/22 and calm conditions prevailed allowing sufficient time for the coastal circulation to adjust dynamically to the new wind regime. Temperatures are relatively uniform across this section, whereas salinities are lowest adjacent to the coast and there is a suggestion of a weak salinity front at the western stations. Shoreward of this weak front the water column consists Alaska Coastal Water (ACW) while seaward of it the water mass consists of a mixture of ACW and Bering Shelf Water (BSW). The salinity distribution implies a weak northward baroclinic flow across the whole section.

Fluorescence values are several time greater than those obtained in Bering Strait and they approximately double in value proceeding seaward across the salinity front. The increase in fluorescence between the ACW water mass and the mixture of ACW and BSW is consistent with the higher particulate organic carbon carried by BSW (Walsh *et al.* 1989). That comparatively low fluorescence values were observed in the Bering Strait section is presumably due to the virtual absence of the BSW mass during occupation of that section.

Due to heavy ice conditions, we were able to occupy only a short transect (~25 km) extending southeast from the ice edge to near the coast near Point Franklin. This section cuts across the head of Barrow Canyon. As shown in Figure 4, conditions on this transect are considerably different from those to the south and reflect the influence of meltwater from sea-ice. Ice concentrations were greatest along the first 5 km of the transect and consisted of rotting floes as well as newly formed grease ice. Although there is considerable hydrographic complexity in this section, several features are readily discernible. First, the narrow core of warm (> 3^oC) subsurface waters near the center of the section represents ACW flowing northeastward along the east flank of Barrow Canyon and within the core of the Alaska Coastal Current. It is bounded to the west by the cold, saline Resident Chukchi Water (RCW). The upper 30 meters of the water column consist of ice meltwater and mixtures of this with ACW and RCW. Prominently featured in these transects are strong thermal fronts bracketing the ACW and the strong vertical stratification associated with the meltwater. The strongest stratification is observed at the westernmost station and maximum fluorescence values lie atop the pycnocline here. Oxygen saturation values at these stations are about 110% (Y. Sasaki and H. Ichii, personal communication) suggesting active photosynthesis by these phytoplankton. The implication of high biological production at this location is not unexpected given that enhanced primary productivity is often associated with stably stratified ice-edges (Niebauer *et al.* 1991). Although few primary production measurements have been made in the northeast Chukchi Sea, Feder et al., (1993) suggest that production at the ice-edge of this region might be a significant source of carbon for the benthos of the northeast Chukchi Sea. Moreover, while ACW is impoverished with respect to nutrients (Walsh *et al.* 1989), sufficient concentrations are available in RCW to support primary production at this level (Feder *et al.* 1993).

The transect shown in Figure 5 extends across the northern Chukchi Sea from Point Franklin in the east to Herald Sea Valley in the west. This transect runs parallel to the ice-edge and many of the stations were within 25 km of the ice-edge. The eastern half of the transect is well-stratified; the upper 25 m consists of a mixture of ice meltwater and ACW while beneath this layer ACW is observed. Nowhere on this section is RCW observed, indicating that winter waters had been flushed to the north by the time this transect was occupied. Heavy concentrations of melting ice were encountered overlying Herald Shoal where stratified conditions are also observed within the upper 10 m. Overlying the depression to the east of Herald Shoal and between these two stratified regions is a narrow zone of relatively warm (> 2.0°C), salty (> 32.p psu), and unstratified water consisting of a mixture of ACW and BSW. Fluorescence values are high within this band and I believe that it represents the northward extension of the high chlorophyll water observed along the western portion of the 9/23 occupation of the Cape Lisburne transect (see Figure 3). This zone is bracketed on either side by surface intersecting fronts. The orientation of the isohalines suggests strong northward baroclinic shear on the east side of this depression and weaker, southward baroclinic shear on the west side. The existence of strong northward flow on the east side of this depression is verified by the current meter data discussed in Chapter 3. The high fluorescence values observed in this depression suggest that this northward flow could be a significant source of particulate organic carbon for the benthos of the outer shelf. Whether or not the southward flow on the west is a permanent circulation feature associated with cyclonic flow around Herald Shoal, as suggested by Coachman *et al.* (1975), or a transitory circulation feature associated with the ice-edge cannot be addressed with this data set.

To the west of Herald Shoal and over the eastern slope of Herald Canyon is a second band of unstratified, relatively warm and saline water characteristic of BSW. It is bounded on the west by a strong ice-edge front overlying the center of Herald Canyon. Baroclinic flow along the ice-edge front is to the south, while along the east side of the canyon it is to the north. Fluorescence values are a maximum within the northward flowing BSW and decay rapidly on crossing through the ice-edge front.

Figure 6 shows the distribution of properties along the transect running from south to north along the axis of Herald Canyon. The section is characterized by a subsurface temperature maximum (indicated by the 2.5 °C isotherm) with an associated maxima in fluorescence. Surface waters consist of ice meltwater and mixtures of meltwater with BSW. Cold, saline RCW is observed at the north end of the transect and beneath 40 m depth. The data imply northward flow through Herald Canyon of BSW which carries a substantial particulate organic carbon load.

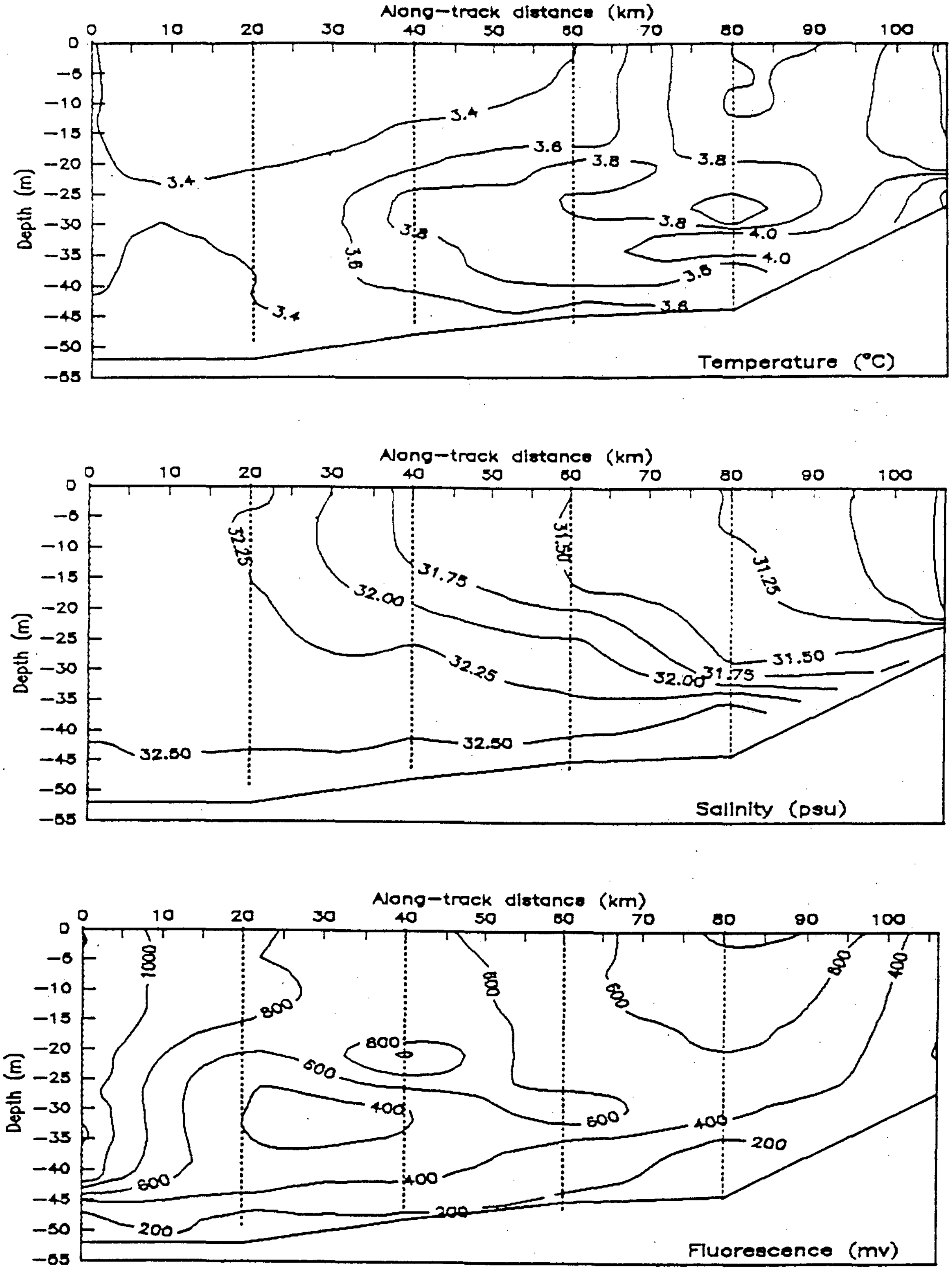

Figure 3. Contours of temperature (top), salinity (middle), and florescence (bottom) from west to east offshore off Cape Lisburne, 23 September 1992.

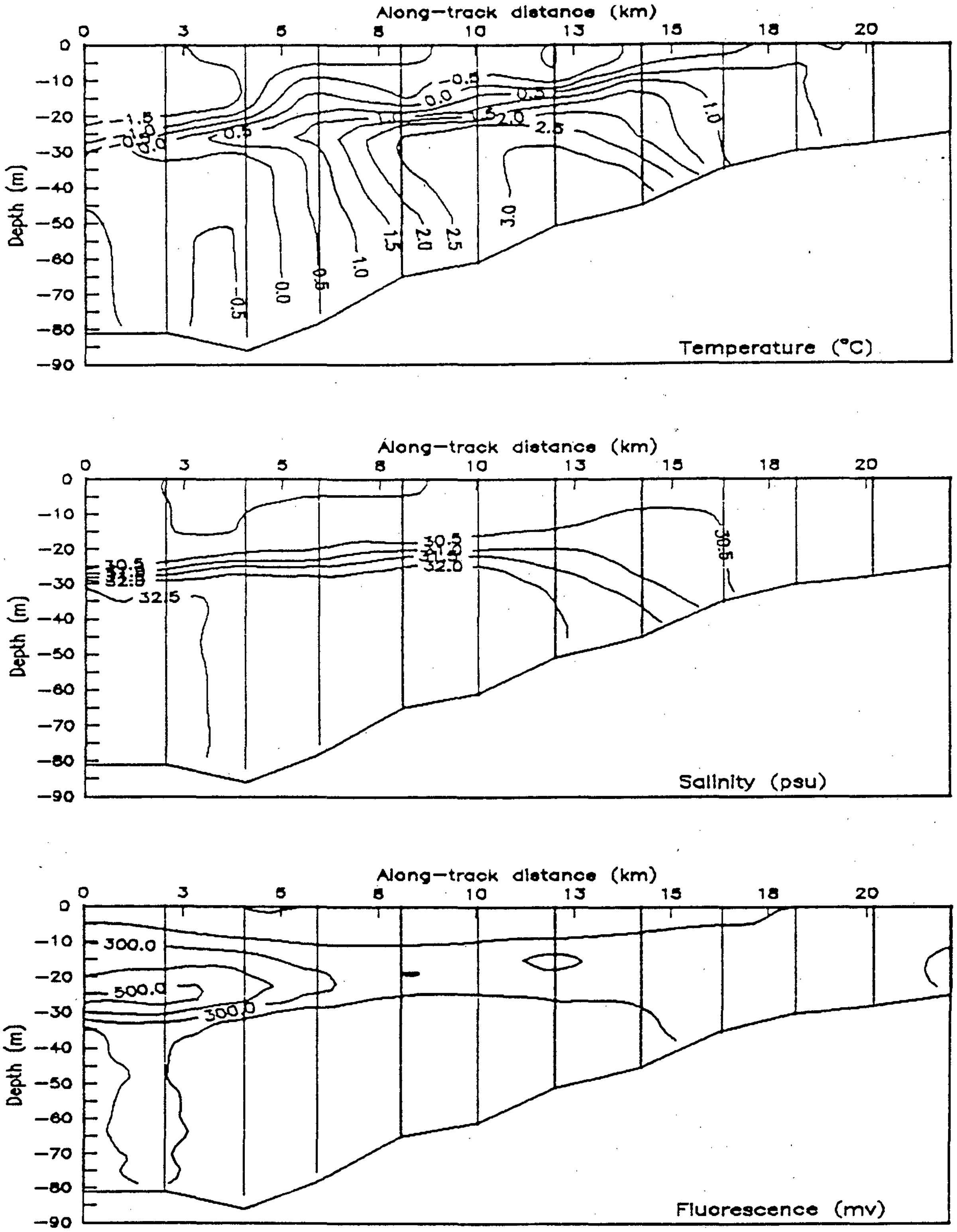

Figure 4. Contours of temperature (top), salinity (middle), and fluorescence (bottom) from northwest to southwest offshore of Point Franklin, 24-25 September 1992.

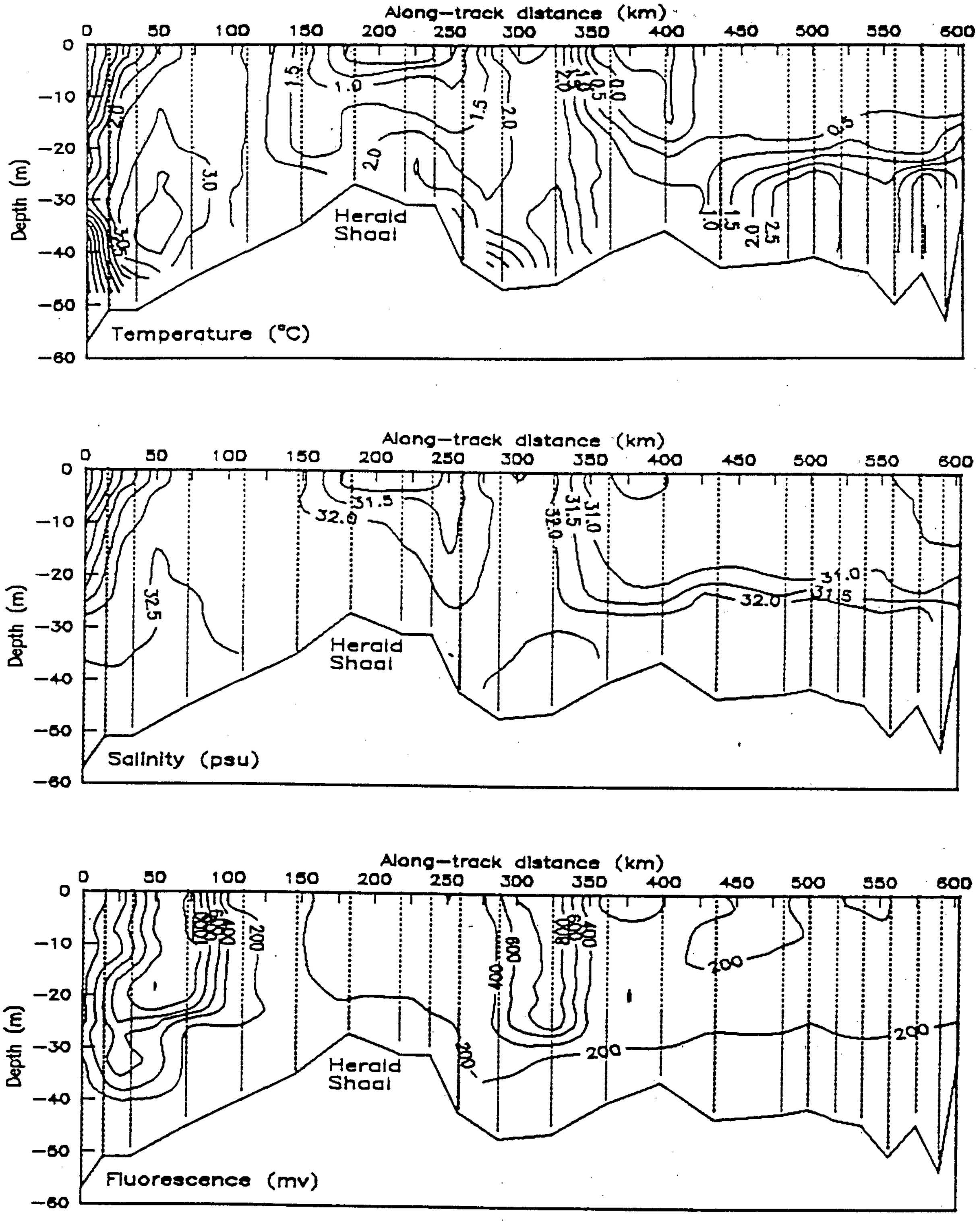

Figure 5. Contours of temperature (top), salinity (middle), and fluorescence (bottom) from Herald Valley to Point Franklin, 26 September to 1 October 1992.

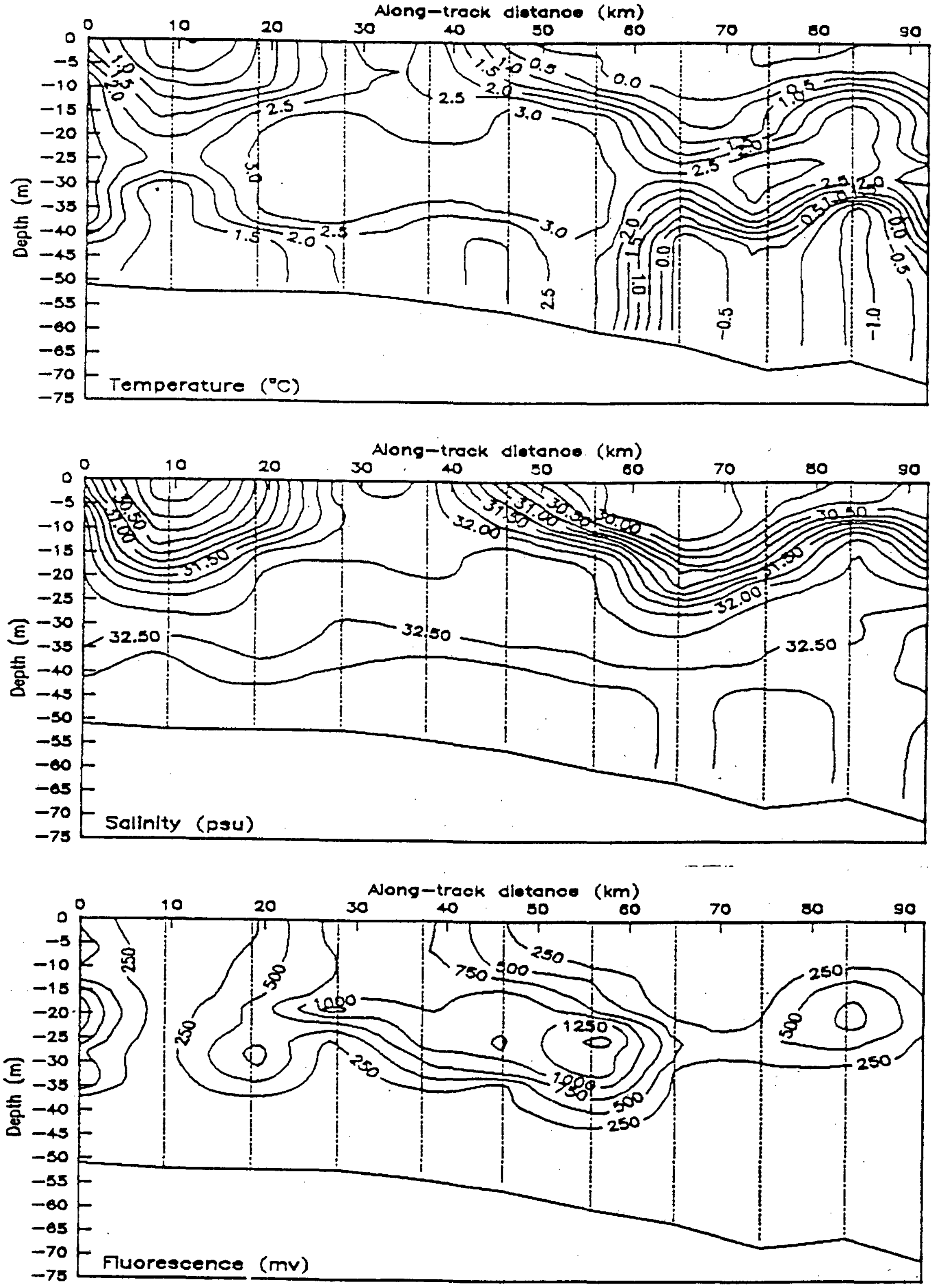

Figure 6. Contours of temperature (top), salinity (middle), and fluorescence (bottom) from south to north in Herald Valley, 30 September to 1 October 1992.

We next consider the three transects running perpendicular to the Chukotsk Peninsula at Cape Shmidt, Cape Vankarem, and Cape Uelen. Prominently featured on the Cape Shmidt section (Figure 7) is a wedge of cold, low-salinity water which extends offshore for approximately 120 km. Offshore of this point, and beneath the surface lies warmer, more saline BSW, and along the bottom is a mixture of RCW and BSW. With but one exception, the salinity contours adjacent to the coast slope upwards implying southeastward baroclinic flow. This coastally confined flow is the Siberian Coastal Current (SCC) discussed previously with respect to the Bering Strait transect. The SCC originates in the East Siberian Sea and is fed by ice-melt and coastal freshwater discharge (Coachman *et al.* 1975). Some Russian oceanographers suggest that the source might extend as far west as the Lena River which drains into the Laptev Sea (V. Pavlov, Arctic and Antarctic Research Institute, St. Petersburg, Russia) . Embedded within the SCC, approximately 50 km offshore, is an eddy or filament as suggested by the upward bowing of the isohalines. This feature is associated with a near-bottom lens of warm, saline BSW water and could be one mechanism by which SCC waters mix with those from the Bering Sea (Coachman and Shigaev, 1992). Fluorescence values are extremely low within the SCC, but higher offshore in the BSW water mass.

As shown on the Cape Vankarem transect (Figure 8) SCC waters are both warmer and saltier which is probably a consequence of mixing and entrainment of BSW into the SCC. However, the two water masses are clearly delineated by a front which intersects the surface about 100 km offshore. Note again that there is a rapid increase in fluorescence on crossing the salinity front which separates the SCC from the Bering Shelf water.

There are several curious features observed along the Cape Uelen-Point Hope transect (Figure 9). First, the cold, low salinity flow of the SCC has collapsed to a narrow band confined to within 25 km of the coast. Apparently the bulk of the SCC has recirculated into the interior of the Chukchi Sea between Cape Uelen and Cape Van Karem. Although this data set cannot address this issue, the change in coastal orientation and bottom slope approximately midway between Cape Vankarem and Cape Uelen (see Figure 1) suggests that retroflection of the SCC might occur here.

Second the central portion of the transect is dominated by a large anticyclonic (clockwise circulation) gyre centered approximately 100 km northeast of the Chukotsk Peninsula. This gyre has a radius of about 60 km and its center consists primarily of low salinity (< 32 psu) and relatively warm water (temperatures > 2.5 ^{o}C). The origin of the waters within the upper layers of the interior of this gyre cannot be determined precisely based upon the temperature and salinity properties. Although these are similar to those characteristic of ACW, geographically, this water mass is typically confined to the eastern Chukchi Sea (Coachman *et al.* 1975). However, mixtures of SCC water with BSW could also produce a water mass with the observed temperature and salinity properties. More detailed water mass analyses using the oxygen isotope and nutrient data collected on this cruise should resolve this issue.

Third, note that the stations nearest Point Hope have higher salinities than those within the gyre. Based upon earlier measurements (i.e., Coachman *et al.* 1975; Aagaard, 1988), we would have expected more dilute water at these stations as they typically lie within the northward flowing ACC. This observation in fact suggests that these low salinity waters were diverted offshore and contributed to the interior waters of the gyre.

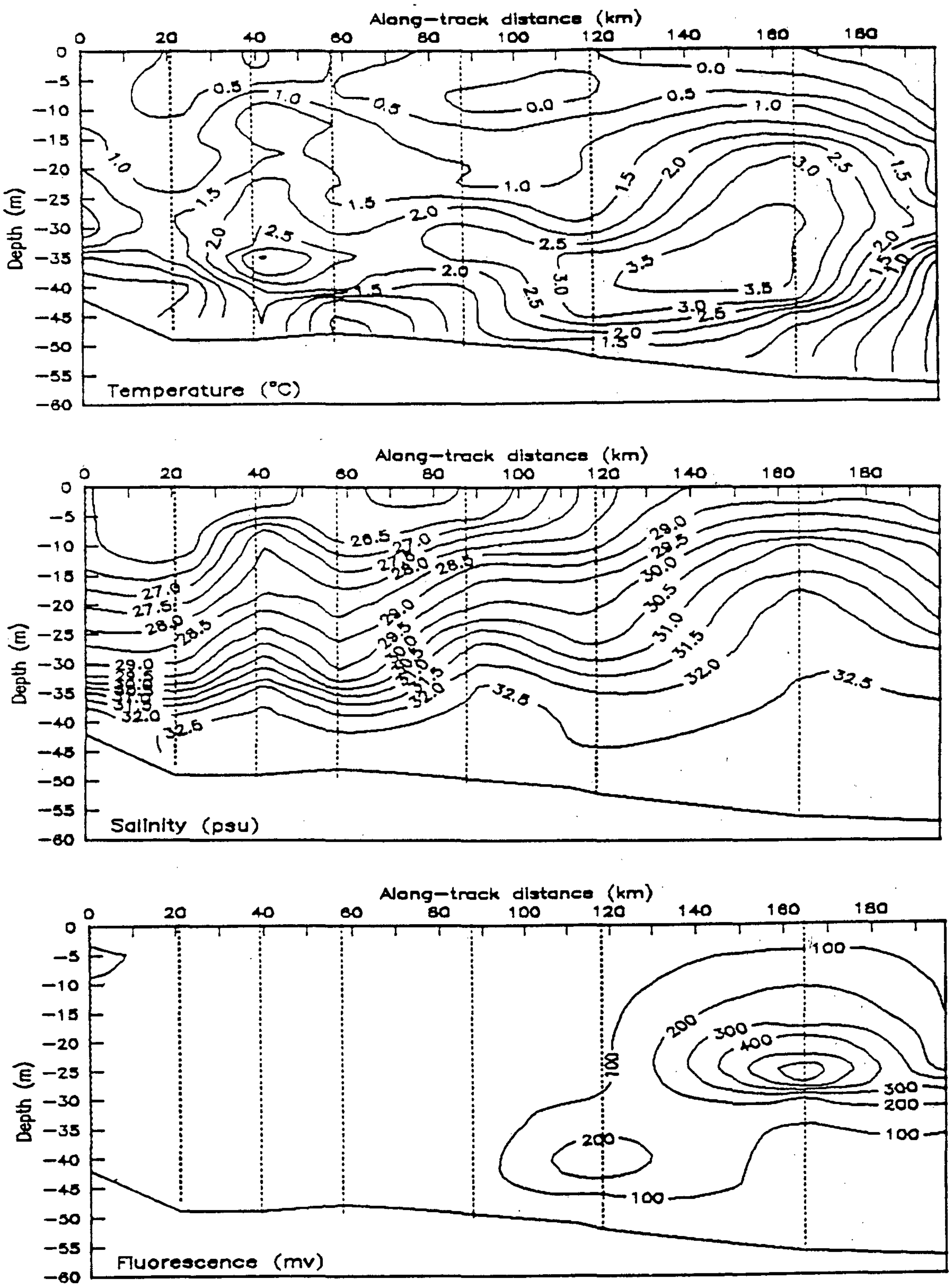

Figure 7. Contours of temperature (top), salinity (middle), and fluorescence (bottom) from southwest to northeast offshore of Cape Shmidt, 1 October 1992.

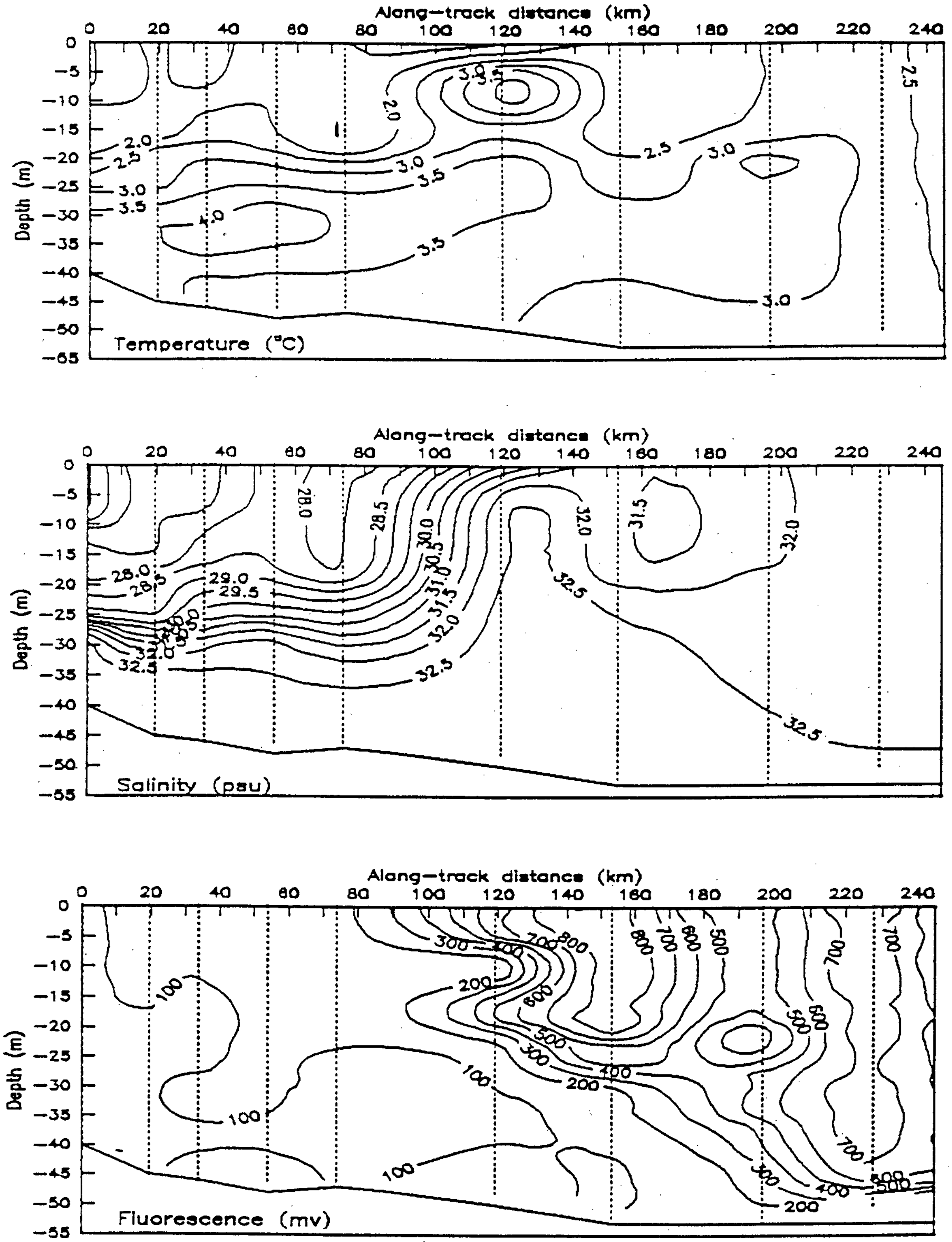

Figure 8. Contours of temperature (top), salinity (middle), and fluorescence (bottom) from Cape Van karem to Lisburne Peninsula, 2-3 October 1992.

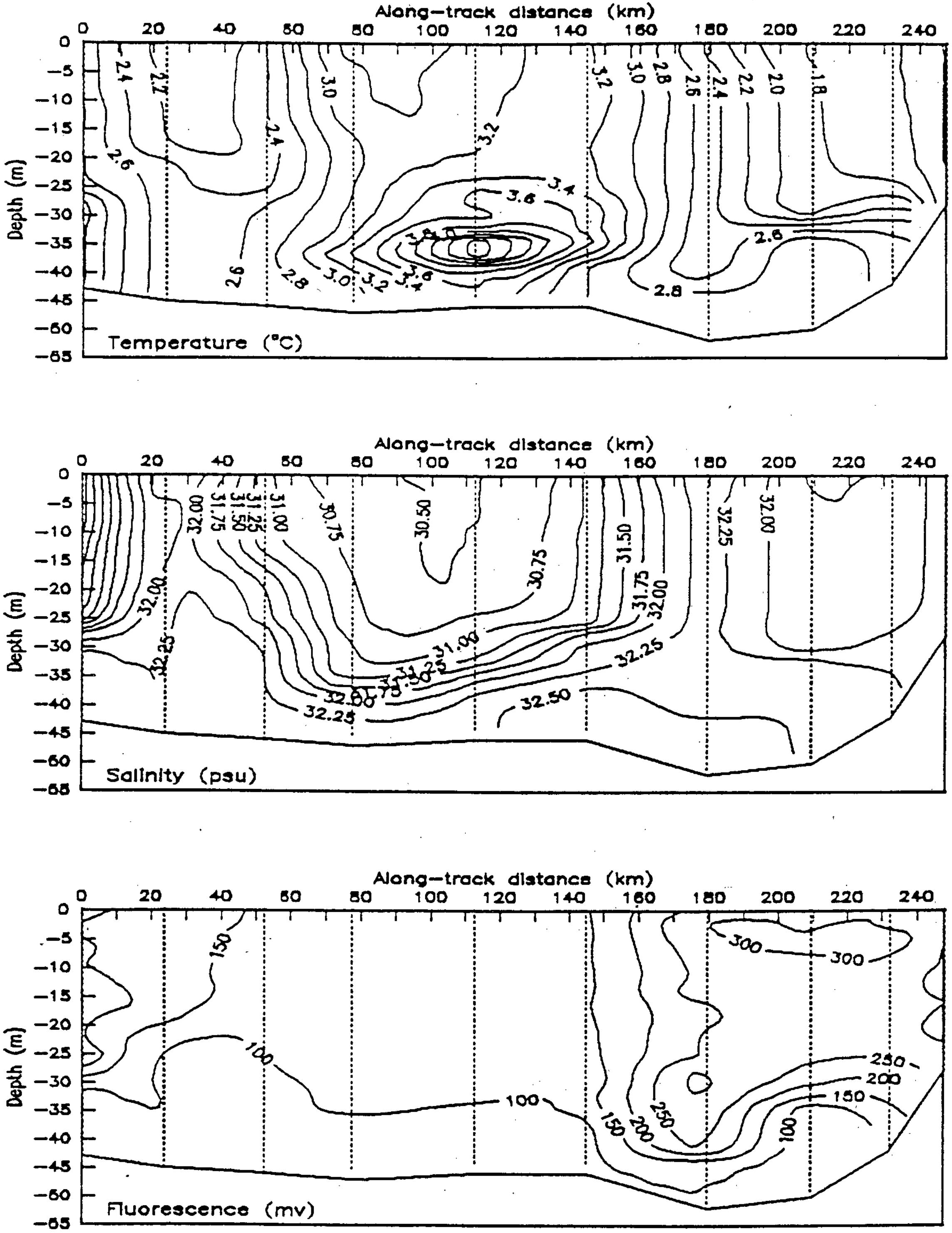

Figure 9. Contours of temperature (top), salinity (middle), and fluorescence (bottom) from Cape Uelen to Point Hope, 3 October 1992.

The packing of the isohalines along the boundaries of this gyre imply locally swift baroclinic velocities, whereas the relatively homogeneous water within the center of the gyre is moving more slowly. Oxygen saturation values at the bottom and within the center of this gyre are less than 70% (Y. Sasaki and H. Ichii, personal communication) and provide additional indication of persistently weak flow within the center of the gyre. Strong horizontal current shear (implied by the strong salinity gradient and opposing slopes of the isohalines) is encountered on crossing the southeastward flow of the SCC and the northwestward flow on the southern portion of the gyre. This divergent shear will cause water to upwell between these flows and this effect is suggested by the uplift of the 32.2 psu from 40 meters depth beneath the gyre center to about 20 m depth within the divergence zone.

Fluorescence values are substantially lower than the maxima observed in previous transects. In large part, these low fluorescence values are associated with the prevalence of ACW and SCC waters observed on this transect. Lowest fluorescence values are again observed within the SCC.

The last cross-section shown is the reoccupation of the Bering Strait transect (Figure 10). Although temperatures are about 2°C lower than those observed on the first occupation, little of this cooling can be a result of heat loss to the atmosphere as winds were calm and air temperatures were nearly equal to sea surface temperatures throughout most of the cruise. Rather, these differences must reflect a circulation change which resulted in the advection of cooler and saltier waters through the strait. In contrast to the first occupation, the data from this section shows northward baroclinic flow within the ACC on the east side of the strait. In the western channel southward baroclinic flow is observed within a wedge extending 25 km offshore at the surface to about 5 km offshore at the bottom. Water within this southward flow consists of a mixture of SCC water with BSW and ACW.

SUMMARY

Hydrographic results from fall 1992 have delineated the northward spreading of Pacific waters throughout the Chukchi Sea. The Bering Shelf fraction of these waters generally has higher fluorescence levels than the other shelf water components, consistent with it being enriched in particulate organic carbon. Persistent northward flow of this carbon-rich water to the east of Herald Shoal and along the east flank of Herald Canyon suggest that this northward flow could be a source of carbon to the benthic communities on the outer shelf of the northeast Chukchi Sea. As discussed in Chapter 3 resolving the circulation on the outer shelf is an important issue to be addressed in this regard. Enhanced primary production rates are also implied by the elevated fluorescence levels (and oxygen supersaturation) along the ice-edge overlying Barrow Canyon. If true, this productivity could also be an important carbon source to the benthic and fish communities of this region.

Observations from Bering Strait indicate that, at least occasionally, a portion of the Siberian Coastal Current flows southward along the west coast of Bering Strait. However, there is a significant reduction in the mass transport in this current between Cape Van karem and Bering Strait. Much of this flow must retroflect between these two regions, and mix and be recirculated throughout the Chukchi Sea. Little is known about this current but because of concerns regarding massive pollutant discharges into the rivers feeding the shelf seas of Eurasia (including the East Siberian Sea) we advise more emphasis be placed on this current and its influence on the Chukchi Sea in the future.

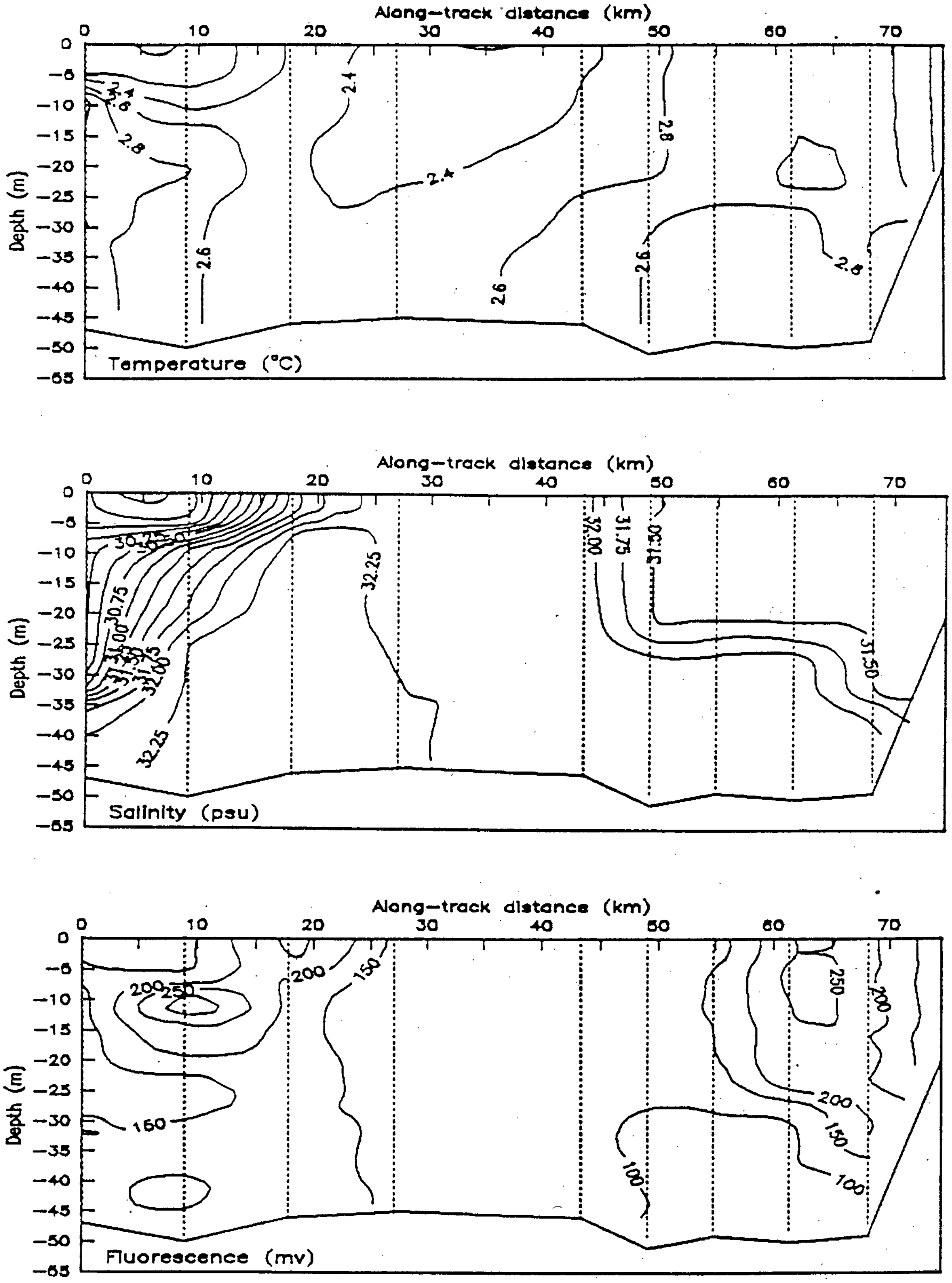

Figure 10. Contours of temperature (top), salinity (middle), and fluorescence (bottom) from west to east in Bering Strait, 4 October 1992.

CHAPTER 3

CIRCULATION AND FORMATION OF COLD, SALINE WATER ON THE NORTHEAST CHUKCHI SHELF

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Abstract.—Five current meter moorings were deployed in the northeast Chukchi Sea from October 1991 through August and/or September 1992. Four were deployed in the Alaska Coastal Current; two offshore of Cape Lisburne and two in Barrow Canyon. A fifth mooring was deployed in the central Chukchi Sea, east of Herald Shoal and approximately 250 km to the west of Barrow Canyon.

Current variations were: 1) spatially coherent throughout the northeast Chukchi Sea and 2) significantly coherent with the local wind field. Current variations offshore of Cape Lisburne were more coherent with winds over the northern Bering Sea than the winds over the northern Chukchi Sea suggesting that here the coastal current's dynamics are, in part, tied to sea-level adjustments associated with wind-driven transport variations in the Bering Strait.

At the Herald Shoal mooring site, the mean monthly flow was northward to contrast to earlier inferences based upon limited hydrography. Temperature and salinity properties are consistent with those for the nutrient- and carbon-rich Bering Sea Water mass flowing northward through the western channel of Bering Strait. Fall CTD casts and fluorescence values are also consistent with this interpretation and suggest that this flow might be a substantial source of carbon for the benthic communities on the outer Chukchi shelf.

On a monthly mean basis the shelf circulation was remarkably steady and swift throughout most of the year. However, from November 1991 through January 1992, when strong northeasterly winds blew over the Chukchi and northern Bering seas, near stagnant flow conditions ensued and the alongshore coherence of the coastal current was disrupted. By early December, shelf water temperatures had cooled to the freezing point and a large polynya system developed along Alaska's northwest coast. Ice production and the associated salt flux within these polynyas contributed to the formation of a shelf water mass with temperatures near the freezing point and salinities › 34 psu. Formation of this water mass was enhanced by the weak circulation which effectively increased the residence time of water parcels within the polynyas thereby allowing salinities to increase to an extent greater than would be expected if swift flow had persisted. Production of this dense water is therefore seen as a rectified response of the ice cover and the ocean to strong northeasterly winds which: 1) created the polynyas, 2) enhanced oceanic heat loss and ice production, and 3) led to weak shelf circulation.

With abatement of the strong northeasterly winds in late January, the normal shelf circulation mode was reestablished and most of the cold, saline water was flushed through Barrow Canyon over the course of the next two months. However, a substantial fraction of this dense water also drained to the northwest and through the broad channel between Hearld and Hanna Shoals.

INTRODUCTION

The upper layers of the Arctic Ocean's Canadian Basin carry the distinct signature Pacific Ocean waters (Coachman and Aagaard, 1974) that affect both its stratifications (Carmack, 1986) and chemistry (Codispoti, 1979; Wilson and Wallace, 1990). During transit across the shallow, but vast expanse of the Bering and Chukchi shelves, the Pacific inflow is substantially modified by coastal freshwater discharge and exchanges with the atmosphere, the sea-ice, and the bottom sediments and these interactions are also reflected in the thermohaline and biogeochemical properties of the Arctic Ocean (Aagaard *et al.* 1981, 1985; Jones and Anderson, 1986; Moore and Smith, 1986).

Pacific waters drain the Chukchi shelf through two prominent bathymetric features: Hope Sea Valley-Herald Canyon in the western half of the basin (Figure 1) and Barrow Canyon in the northeast corner of the shelf (Coachman, Aagaard, and Tripp, 1975; hereafter abbreviated as CAT). The former advects the high-salinity, nutrient-rich fraction of the Pacific inflow while the more dilute, nutrient-poor contribution flows northeastward within the Alaska Coastal Current (CAT, Walsh *et al.* 1989). The mean northward flow across this shelf is maintained by the secular sea-level difference between the Pacific and Arctic Oceans (CAT, Overland and Roach, 1987). However, the circulation varies in response to local winds at seasonal and synoptic time scales (Johnson, 1989; Aagaard, 1988; Overland and Roach, 1987, Spaulding *et al.* 1987) and presumably to the longer period wind-driven transport variations in Bering Strait identified by Coachman and Aagaard (1988). In addition, the shelf circulation is affected by forcing along the shelf/slope margin (Aagaard and Roach, 1990) and buoyancy effects. The latter includes dilution through coastal freshwater discharge and sea-ice ablation in summer and salinization by brines rejected from ice formed in coastal polynyas (Aagaard, 1988; Schumacher *et al.* 1983).

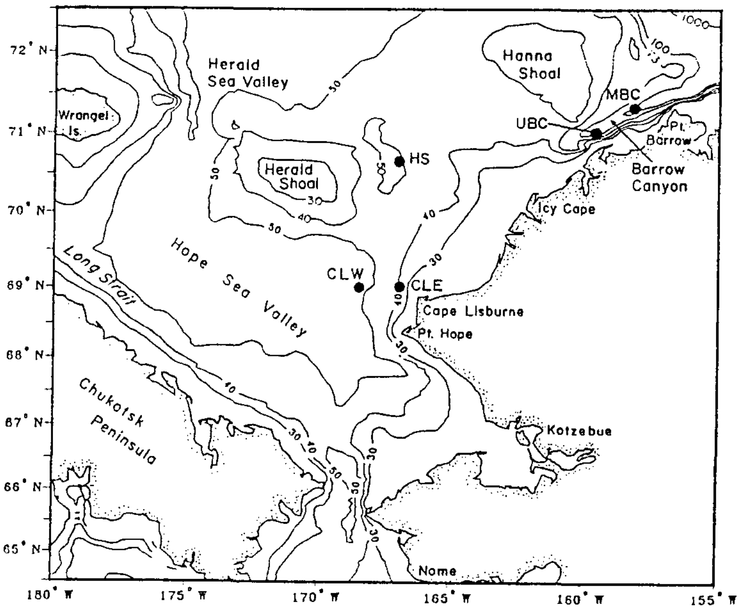

Figure 1. Bathymetric map of the Chukchi Sea, with geographic names and locations of current meter moorings. (CLW = Cape Lisburne West; CLE = Cape Lisburne East; HS = Herald Shoal; UBC = Upper Barrow Canyon; MBC = Middle Barrow Canyon.)

The cold, saline water formed by brine addition is particularly important to the long-term integrity of the Arctic Ocean's halocline (Aagaard *et al.*, 1981, Killworth and Smith, 1984; Bjork, 1989). In the western Arctic, the principal sources of brines are the coastal polynyas formed in winter on the northern Bering shelf and in the northeast Chukchi Sea (Cavalieri and Martin, *in revision*; hereafter abbreviated as CM). Dense water formed within the latter presumably drains through Barrow Canyon. Apparently, however, there are years when the cold, saline water formed within these polynyas is either not dense enough to ventilate the halocline or it follows a different path to the Arctic Ocean (Aagaard and Roach, 1990). CM show considerable interannual differences in both the size and the duration of polynya events on the northeast shelf and these are important factors affecting the volume and properties of the dense water formed. While the shelf circulation is important transporting dense water, it might also play a role in establishing conditions favorable to the formation of cold, saline water.

This study was largely motivated by needs to understand better the circulation and water mass properties on the northeastern shelf (between Herald Shoal and Barrow Canyon) where gas and oil exploration activities were underway. Particular emphasis was to be placed on the north central shelf (between Hanna and Herald Shoals) where the circulation is poorly known. In addition, this program provided an opportunity to add to the existing set of current measurements from Barrow Canyon in order to describe: 1) interannual variations in the circulation and water mass properties of the northeastern shelf, 2) the relationship between current variations in the coastal flow and the north central shelf, and 3) the vertical and along-canyon structure of near-bottom flows of cold, saline outflows as well as intrusions of Arctic Intermediate Water (AIW, [cf. Aagaard *et al.* 1985]) upwelled along the continental slope and within the Atlantic layer of the Arctic Ocean. With these goals in mind, the initial plan called for three moorings to be deployed on the north central shelf and two moorings in Barrow Canyon. However, extensive ice prevented the ship from reaching three of the planned positions. As a result, the moorings were deployed as follows: UBC (Upper Barrow Canyon) at the same location as the mooring described by Aagaard *et al.* (1985), MBC (Middle Barrow Canyon) near the center of the canyon approximately midway along its longitudinal axis, HS (Herald Shoal) in the depression to the east of Herald Shoal, CLW and CLE (Cape Lisburne West and East, respectively) offshore of Cape Lisburne. These last two mooring sites were in the same vicinity as those deployed by Aagaard (1988) and Coachman and Aagaard (1981). As it turned out, these proved useful in understanding the mid-winter production and transport of brine across the northeast shelf. Figure 1 shows the mooring locations.

The mooring data are augmented with satellite imagery obtained from the Special Sensor Microwave/Imager (SSM/I) and the Advanced Very High Resolution Radiometer (AVHRR). In conjunction with regional meteorological data, the imagery guides the interpretation of temperature and salinity measurements obtained by the current meters.

METHODS

Each mooring consisted of a variable number of Aanderaa model RCM7 and RCM4 current meters equipped with thermistors and conductivity cells. The topmost current meter at moorings UBC and MBC included a pressure sensor to monitor vertical mooring motion. Tables 1a and 1b provide specifics on the moorings and instrument record lengths. Each mooring included one current meter suspended three meters above the bottom and one current meter, less its vane, set in a well on the anchor. In Barrow Canyon, mooring UBC incorporated an additional instrument 12 meters above the bottom and MBC included instruments at 12, 18, and

25 meters above the bottom. As a one-year deployment period was anticipated, hourly samples were collected on meters suspended above the bottom and every two or three hours for meters installed in the wells. The rationale for a meter in the well was twofold: 1) to provide redundant measurements should the rotor, temperature, and/or conductivity cells on the meter suspended above the bottom fail and, 2) should ice conditions prevent recovery, the longer sampling interval would permit sufficient battery life to provide temperature and conductivity measurements for an additional year. Overall data return was good but the following exceptions are noted. The battery failed in June on meter MBC25 and its data storage unit contained a block of bad sectors which prevented recovering data recorded between March 28 and April 19. Speed comparisons with meter CLW and its counterpart in the well suggested that the threshold speed of the former was higher than the manufacturer's stated value (~1.5 cm/s). Moreover, the CLW record included several prolonged periods (2 - 10 days long) of threshold speeds while those from the well-instrument (and that at CLE) indicated weak, but above threshold speeds. Visual comparison between CLE and CLW suggested that the currents here are horizontally coherent in agreement with results obtained from previous deployments in this area (Aagaard, 1988; Coachman and Aagaard, 1981). Furthermore, the conductivity cells from both meters on mooring CLW were coated with barnacles upon recovery. Comparison with salinities from a CTD cast at the time of recovery showed that current meter salinities were nearly 1 psu lower. There was also a time-varying offset between both instruments making it impossible to decide which portions of the records might be usable. Because of these instrument problems data from the CLW mooring are not used. Biofouling problems also occurred on the conductivity cells from both meters at HS and salinities from these instruments were significantly lower than those obtained from a CTD cast at the time of recovery. However, from the beginning of the record until mid-April, there was no significant difference in the salinities between either instrument and because of this agreement the salinity data at HS is believed to be reliable through this period. Thereafter, the salinity records gradually diverged and the data were not used. Several ambiguities arose in the processing of the conductivity data from UBC12 which led us to exclude these data from further analysis.

Table 1a.—Locations of the Chukchi Sea moorings and the FNOC grid points for regional wind calculations.

Designator	Latitude, N		Longitude, W	
	Current Meter Moorings			
Cape Lisburne West (CLW)	69°	0.74’	168°	29.36’
Cape Lisburne East (CLE)	69°	1.02’	166°	57.52’
Herald Shoal (HS)	70°	39.67’	167°	1.64’
Upper Barrow Canyon (UBC)	71°	3.14’	159°	32.75’
Middle Barrow Canyon (MBC)	71°	19.90’	158°	9.95’
	Winds			
Northeast Chukchi Sea	70°	0.00’	165°	0.00’
Central Chukchi Sea	70°	0.00’	167°	30.00’

Table 1a. continued.

Designator	Latitude, N		Longitude, W	
Southern Chukchi Sea	67°	30.00'	167°	30.00'
Northern Bering Shelf	65°	0.00'	170°	0.00'

Table 1b.—Instrument depths and duration of the Chukchi Sea moorings (sampling interval = 1 hour).

Mooring	Depth (m)	Height[1](m)	Start Time (UT)		End Time (UT)	
CLW[2]	48	3	0300	Sept.30, 1991	2100	Sept22, 1992
CLE	42	3	2100	Sept.29, 1991	0100	Sept23, 1992
HS[3]	50	3	0700	Oct. 2, 1991	1500	Sept27, 1992
UBC3	76	3	0900	Oct. 1, 1991	0100	Sept. 4, 1992
UBC12[4]	64	12	0900	Oct. 1, 1991	0100	Sept. 4, 1992
MBC3	114	3	0500	Oct. 1, 1991	1500	Sept. 3, 1992
MBC12	105	12	0500	Oct. 1, 1991	1500	Sept. 3, 1992
MBC18	99	18	0500	Oct. 1, 1991	1500	Sept. 3, 1992
MBC25[5]A	89	25	0500	Oct. 1, 1991	1500	Mar.19, 1992
MBC25[6]B	89	25	1800	Apr. 5, 1992	1600	June18, 1992

[1] Above seafloor.

[2] Frequent rotor stalls, barnacle growth on conductivity cell, data from CLW not used.

[3] Conductivity drift beginning mid-April.

[4] Suspect temporary fouling on conductivity cell beginning mid-August, 1992.

[5] Bad sectors on data storage unit from 1600 March 19, 1992, to 1700 April, 1992.

[6] Battery failed on June 18, 1992.

Upon recovery, all instruments, except MBC12 and MBC3 (which were both redeployed), and those in the well, were post-calibrated. Comparison with the pre-deployment calibrations showed that drifts in conductivity and temperature were of the same order as the sensor's resolution (0.02°C for temperature and 0.013 mmho/cm for conductivity). Pressure records from MBC25 and UBC12 indicated maximum vertical excursions of between 2 and 3 meters. These pressure variations were not incorporated into the salinity calculation since their omission leads to errors about one order of magnitude smaller than the random error in salinity (estimated to be about 0.2 psu) due to measurement errors in temperature and conductivity. On three occasions, mooring MBC was subjected to upcanyon flows of warm, saline AIW which allowed *in-situ* checks using the temperature-salinity (TS) correlation of this water mass with the temperatures and salinities from the instruments. The comparison suggested that salinities at MBC25 were too high by about 0.08 psu and those at MBC18 were too low by about the same value and these offsets were applied to the respective salinity records from these instruments. After applying these calibrations and offsets, no additional adjustments were made although histograms and plots of the salinity differences among the instruments at MBC suggest salinity bias errors of at most

0.05 psu might still remain. Finally, TS plots were constructed during periods when cold, saline brine was observed at the moorings and these showed that the TS pairs generally clustered along the freezing point curve within the resolution limits of the instruments.

The current meter data were low-pass filtered using a fourth-order Butterworth filter (Roberts and Roberts, 1978) with a half-power point at a period of 35 hours. This filter passes 77% of the amplitude at periods greater than 40 hours and 99% at periods greater than 62.5 hours. Throughout this paper attention is restricted to variability at periods greater than 40 hours. Year-long time series of 6-hour surface winds were computed from surface atmospheric pressure fields supplied by the Fleet Numerical Oceanography Center (FNOC) on a 2.5° grid. These were generated by reducing and rotating the geostrophic wind by the factors given by Aagaard *et al.* (1988). The grid locations for the winds used in the subsequent analyses are shown in Table 1a.

To define the time history of polynyas along the northwest coast of Alaska nominally daily microwave data from the SSM/I were used to estimate open water areas following Cavalieri *et al.* (1991). The domain over which these estimates were made extends from near Pt. Hope to Pt. Barrow. Data from approximately 10% of the days of interest were missing and these were replaced by linear interpolation. All but one of the data gaps were of a single days' duration and the exception consisted of a 3-day gap within one sub-area of the domain.

Heat fluxes and daily ice and salt production rates were computed after Martin and Cavalieri (1989) and CM following standard procedures (e.g., Pease, 1987; Maykut, 1985; Alfultis and Martin, 1987). In this approach the evaporative heat loss term is neglected because of the uncertainties associated in its estimation (Pease, 1987). The long-wave radiative loss from the sea surface at a temperature of -1.8°C is constant and equal to $300/m^2$. To compute the remaining surface heat balance components, hourly air pressure and temperatures (air and dew point) from Barrow were subsampled at 6-hourly intervals and then combined with the wind speed estimates at 70°N, 165°W. According to Aagaard *et al.* (1988) the FNOC pressure field lags the actual observation time by about 12 hours and the wind time series were adjusted accordingly in all calculations. The Barrow weather station was the only meteorological station along the northwest coast of Alaska that routinely provided observations during the course of this study. Less frequent observations were available from the autonomic facility at Cape Lisburne. For the heat flux estimates, a proxy regional air temperature was constructed by adding 3.5°C to the Barrow temperatures. This value was obtained based upon temperature comparisons between Barrow and Cape Lisburne and Barrow and Wrangel Island (71°N, 179°W). Differences for the former pair averaged about 7°C while for the latter pair the average difference was about 2°C. In both cases Barrow was colder and the results agree with the climatological differences given by Brower *et al.* (1988). Sensible heat fluxes were computed at 6-hourly intervals and averaged into daily means. The incoming long-wave radiation flux was computed once per day using the cloud cover estimates from Barrow. Solar radiation was computed at latitude 70°N and then adjusted using the Barrow cloud cover estimates. For reasons described later, polynya seawater salinity was chosen to be 32.5 psu. According to Martin and Cavalieri (1989) and CM, the random error of a daily salt production estimate is about 33% using these methods to determine open water areas and the surface heat flux.

RESULTS

Currents.—For each instrument the record length mean flow (Table 2) was toward the Arctic Ocean (i.e., northward at Herald Shoal and Cape Lisburne and northeastward at Barrow Canyon) and, as such, they are consistent with northward forcing by the mean pressure gradient between the Pacific and Arctic Oceans (CAT, Overland and Roach, 1987; Spaulding *et al.* 1987). At each mooring site, the mean speeds vary in relation to the strength of the local bathymetric gradient and the height of the instrument above the sea bottom, e.g., maximum mean speeds are observed at UBC12 along the eastern wall of the upper canyon and minimum mean speeds are observed at the CLE where the bottom slope is weak. The influence of topography is also reflected in that, at each mooring site, most of the current variance is aligned along the local isobaths. This influence is greatest in Barrow Canyon where the flow is rectilinear and where more than 95% of the current variance is contained in the 50° - 65° °T (degrees true) sector.

Figure 2 shows time series of the currents from CLE, HS, UBC12 and MBC12 as well as for the wind at 70°N, 165°W. Each series consists of the velocity component projected along its respective principal axis of variance. All of the current time series show considerable variability including flow reversals lasting from 2 to 10 days duration. However, current variations were seasonally modulated such that, from October through January, both the number and intensity of the fluctuations (including the reversals) exceed those observed throughout the remainder of the record.

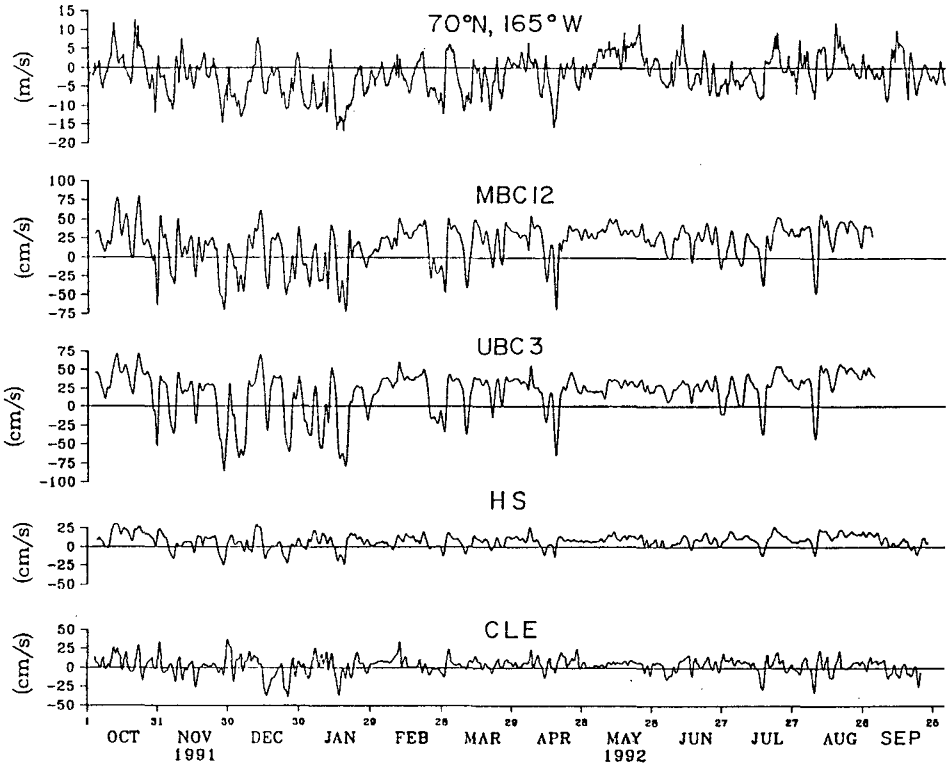

Figure 2. Low-passed filtered current velocity records, resolved along their principal axes, from northeast Chukchi Sea. Topmost time series is of the wind at 70°N, 165°W. Positive wind speeds are toward 43°T, negative wind speeds are toward 223°T.

Inspection of these current time series imparts the impression that flow variations are coherent across the northeast shelf and this was explored by computing the coherence squared (γ^2) and phase (ϕ) of the principal axis velocity components between instrument pairs. Spectral estimates were formed by convolution averaging in the frequency domain over a bandwidth of

0.0016 cph or 0.0015 cph (depending upon the record length) to yield 26 degrees of freedom. If coherence squared values were less than the 10% significance level then the hypothesis that the current fluctuations are incoherent over this bandwidth was accepted. Low-frequency fluctuations in Barrow Canyon are vertically coherent and in-phase; not surprising given that the maximum vertical distance between any two instruments is only 22 m. However, preliminary inspection of the velocity records obtained from a year-long ADCP (Acoustic Doppler Current Profiler) mooring deployed within one kilometer of the UBC site in 1992-93 indicates that the coherence extends throughout the water column (Y. Sasaki and N. Koyama, pers. comm.). Similarly, current variations were coherent and in-phase at all frequencies over the 40 km separation between UBC and MBC.

Table 2.—Current meter velocity statistics based upon 35-hour lowpass filtered data.

	Net Velocity		Principal Axis	
Instrument Designator	**Speed m/s**	**Direction °T**	**Direction °T**	**Variance (%)**
Cape Lisburne East (CLE)	0.03	340.6	344	87.0
Herald Shoal (HS)	0.08	350.4	355	77.2
Upper Barrow Canyon 3 (UBC3)	0.20	60.4	54	96.9
Upper Barrow Canyon 12 (UBC12)	0.23	71.6	57	98.2
Middle Barrow Canyon 3 (MBC 3)	0.14	62.1	61	97.0
Middle Barrow Canyon 12 (MBC 12)	0.17	61.7	64	97.4
Middle Barrow Canyon 18 (MBC 18)	0.21	59.7	65	97.5
Middle Barrow Canyon 25A (MBC 25A)	0.11	58.2	68	96.8
Middle Barrow Canyon 25B (MBC 25B)	0.25	70.0	68	96.6

Of more interest are the results obtained over larger horizontal separations and these are summarized in the plots of coherence squared and phase spectra for instrument pairs MBC12-HS, MBC12-CLE, and HS-CLE (Figures 3a-3c). These show that current variations on the northeast Chukchi shelf are remarkably coherent in both the alongshore (450 km between CLE and MBC) and offshore (250 km between MBC and HS) directions. Indeed, the results imply that approximately 50% of the low-frequency current variance at HS could be predicted from a mooring in Barrow Canyon (i.e., similar results obtain if the UBC currents are used in the analysis). While the phase differences among these pairs are small, at frequencies greater than 0.008 cph (periods less than 5 days) phase is negative for the MBC12-CLE and HS-CLE pairs indicating that current variations at the northerly sites lead those at Cape Lisburne by as much as half a day.

There are, however, two notable exceptions to this spatially coherent circulation field. First, in the frequency band centered on 1.2 x 10^{-3} cph (33-40 days), current fluctuations within the Alaska Coastal Current (MBC12-CLE; hereafter Alaska Coastal Current is abbreviated as ACC) are incoherent (note that, although significant, the coherence diminishes in this frequency band for the HS-CLE pair as well). As argued below this result is a consequence of the large-scale divergence of the wind field over the northern Bering and Chukchi Seas in December and January. The second feature to note is that while pairs MBC12-HS and MBC12-CLE are both coherent in the frequency band centered on 7.6 x 10^{-3} cph (5.5 days), the HS-CLE pair is incoherent in this frequency band. Current variations observed at this frequency in Barrow Canyon and along the Beaufort Sea continental slope are believed to be a reflection of eastward propagating continental shelf waves (Aagaard and Roach, 1990). Incoherence between HS and CLE at this frequency suggests that the cross-shelf extent of these waves is broad enough to affect motions at HS (and within Barrow Canyon) but not at CLE. If the hypothesis is true, then these waves influence circulation over a considerable expanse of the Chukchi Sea's outer shelf because the HS mooring site lies approximately 400 km south of the shelfbreak. Because MBC12 and CLE both lie within the ACC, the coherence observed between these moorings in this frequency band implies that they both detect the same nearshore current variations.

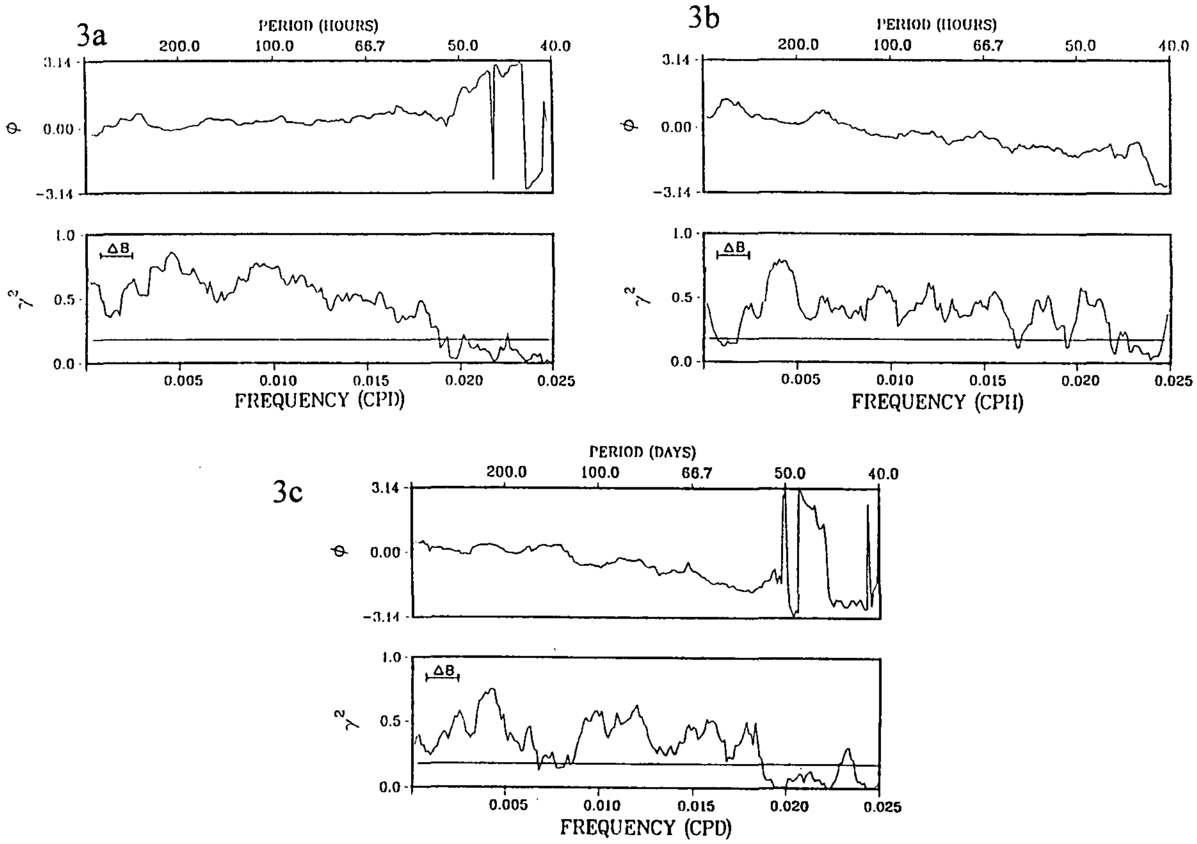

Figure 3 a,b,c. Coherence squared (γ^2) and phase (ϕ) between major axis velocity components for a) MBC12-HS, b) MBC12-CLE, and c) HS-CLE. The 10% significance level for coherence squared is shown by the horizontal line.

Previous studies have indicated that regional atmospheric processes affect current variability in Bering Strait (Coachman and Aagaard, 1988), in the coastal current (Johnson, 1989; Aagaard, 1988) and, to varying extent, in Barrow Canyon (Mountain *et al.* 1976; Aagaard and Roach, 1990). Inspection of the wind and Barrow Canyon current time series in Figure 2 suggests that the two are correlated. The relationship between wind-forcing and current fluctuations was examined in terms of the coherence squared and phase spectra between the winds and the component of the current aligned on its principal axis (Figures 4a-4e). For each case, winds estimated at the FNOC grid point closest to the mooring of interest were used in these calculations. For HS, the east and west wind components at 70°N, 167.5°W were jointly used to examine the current response in terms of the multiple and partial coherences (Bendat and Piersol, 1976). [The multiple coherence function defines that fraction of the current spectrum which is linearly related to both components of the wind.] The partial coherence isolates that portion of the current spectrum which is solely accountable for by one of the wind components.

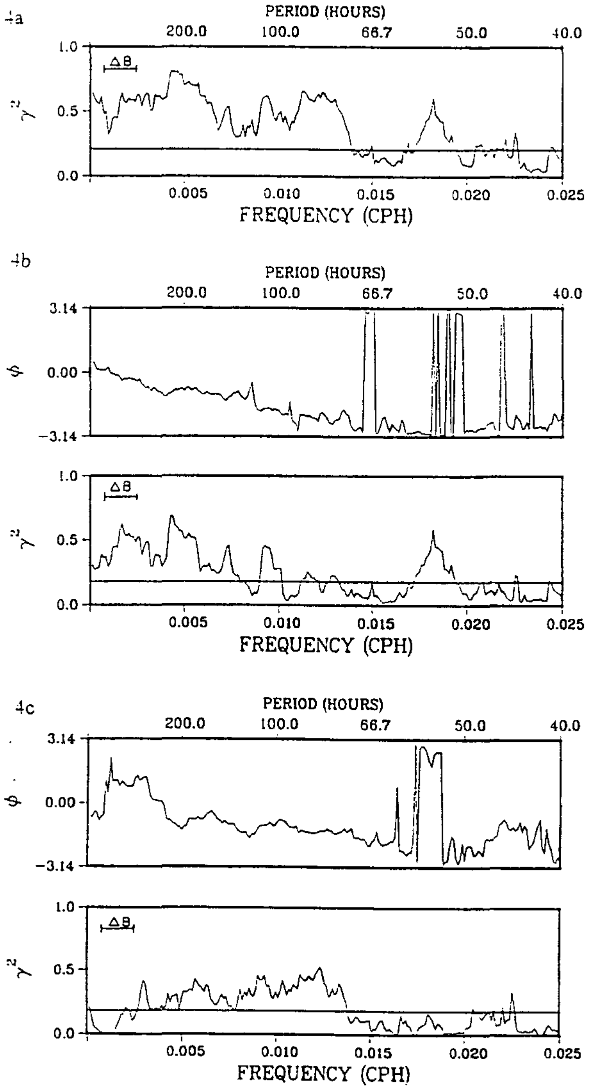

Figure 4 a,b,c. Coherence squared and phase between wind components and currents at HS. a) Multiple coherence squared; b) Partial coherence squared and phase (north-south wind and current); c) Partial coherence squared and phase (east-west wind and current). Wind components at 70°N, 167.7°W.

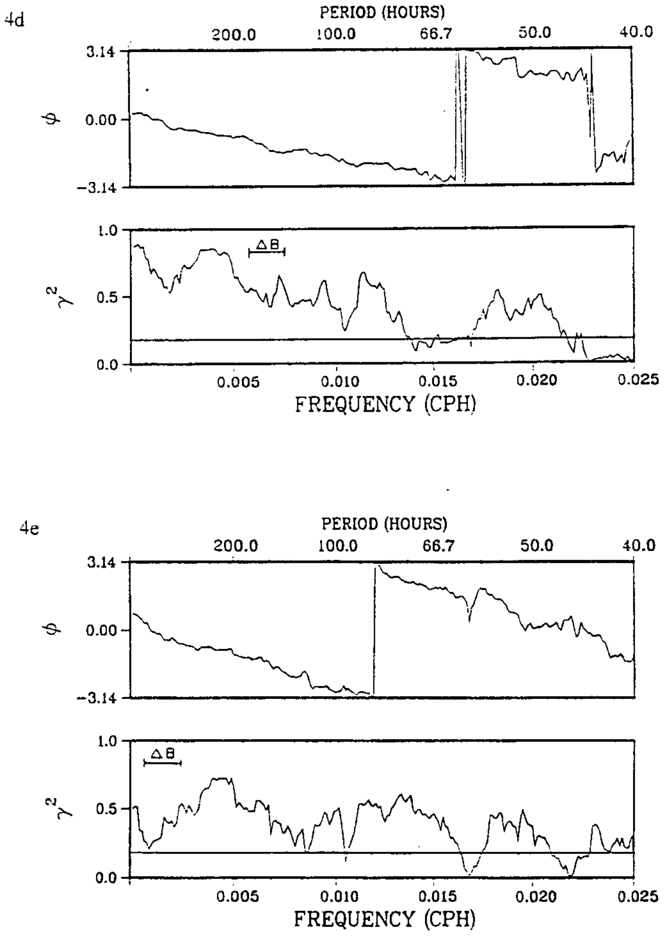

Figure 4 d,e. Coherence squared and phase between d) winds along 43°T at 70°N, 165°W, and MBC12 currents and e) north-south winds at 67.5°W, and CLE currents.

[
These coherence functions are the frequency domain analogues of the multiple and partial correlation coefficients.] For CLE and MBC12 only the alongshore components of the wind are used in the analysis (for CLE this is the north component of wind velocity at 67.5°N, 167.5°W while at MBC12 it is the wind velocity component projected along 43°T at 70°N, 165°W). (Results obtained using winds projected onto different coordinate system rotations and rotary cross-spectral results do not significantly change the results obtained from these variable pairs). Estimates of coherence squared and phase were calculated in the same manner as those displayed in Figures 3a-3c.

At HS, the multiple coherence squared (Figure 4a) between both wind components and the current is significant at frequencies less than 0.0125 cph (periods greater than 3 days) and indicates that about 50% of the current variance over this portion of the spectrum can be explained by the winds. Note, that while significant, the multiple coherence has relative minima at about one month and five days. As shown by the partial coherences the north-south wind component (Figure 4b) explains much of the current variability at frequencies less than .006 cph (periods greater than 7 days). These results imply that the HS current response to north-south wind forcing varies seasonally in relation to the frequency and intensity of synoptic storm systems. On the other hand, current variability over the mid-frequency band of 0.006 to 0.0125 cph (3 - 7 day periods) is largely due to the east-west wind component (Figure 4d, 4e). For both components, the currents are nearly in-phase or lag the winds by from 1 to 2 days.

In contrast, the wind-current relationship at MBC12 (Figure 4d) and CLE (Figure 4e) is simpler in that the along-shore component of the wind accounts for a significant fraction of the current's variance over most of the spectrum. In this regard, the results are consistent with the theoretical response of a coastal current to alongshore wind forcing (e.g., Csanady, 1982). The phase plots show that at both locations, currents lag the winds by about 1 day at periods longer than 3 days while at shorter periods they lead the winds by from 12 to 36 hours.

Coherence squared and phase spectra between CLE currents and the winds near Bering Strait (65°N, 170°W) and those along 70°N at 167.5°W and 165°W were also calculated. These results showed a significant degradation in coherence between CLE currents and the winds at the northern grid points but virtually no change in coherence (or phase) using winds from the southern grid point. The result indirectly corroborates the observations of Coachman and Aagaard (1981) and the model results of Spaulding *et al.* (1987) which showed that current variations near Cape Lisburne were correlated with the wind-driven flow in Bering Strait.

An important point of difference between the wind-current relationship at MBC12 and CLE is that, for the latter, winds account for less than 25% of the variance for frequencies centered at about 0.001 cph (33-44 days), whereas in Barrow Canyon winds explain more than 50% of the variance within this frequency band. It was noted above that current fluctuations at CLE were incoherent with those at MBC12 at similar time scales. To explore these issues further, Figure 5 shows the mean monthly current vectors and wind vectors at 65°N, 170°W and 70°N, 165°W. For each mooring, the monthly velocity vectors in October and from February through August differ only slightly from their record length means. However, from November through January, flow within the ACC (as shown by MBC12, UBC12, and CLE) is weak and variable. In December, Barrow Canyon flow was northward, while at Cape Lisburne it was southward. The situation reversed in January, with southwest flow in Barrow Canyon and northwest flow at Cape Lisburne. Thus, while flow within the Alaska Coastal Current was remarkably uniform over most of the year, this consistency broke down in late fall and early winter. The change in both the gain and the phase relationship between MBC12 and CLE during these months effectively erodes what would otherwise be a coherent relationship at low frequencies.

The January mean currents at Cape Lisburne and Barrow Canyon imply alongshore convergence in the coastal flow during this month. Mass balance is conceivably maintained by a compensatory flow to the northwest (in the gap between Herald and Hanna Shoals) and the observed northward flow at HS in January is consistent with this interpretation. As argued below, abnormally weak winter coastal flow and the January flow convergence affect: 1) the modal temperature and salinity properties of the dense water produced in the coastal polynyas, and 2) the trajectory that the cold, saline outflows take enroute to the Arctic Ocean.

The late fall-early winter disruption in the continuity of the ACC can be ascribed to differences in shelf-wide wind forcing. Coachman (1993) and Kozo and Torgerson (1986) claim that southward flow in Bering Strait is usually established if northerly wind speeds exceed ~8 m/s. In December, the mean southward flow observed at CLE coincided with a mean northerly wind speed of 8.1 m/s at 65°N, 170°W. In January, the mean northerly wind speed at this location was 7.7 m/s and therefore not sufficiently strong to reverse the flow in either Bering Strait or at CLE. Meanwhile, strong northeasterly winds (7.5 m/s) which blew in January over the northern Chukchi Sea were associated with the month-long flow reversal of the flow in Barrow Canyon.

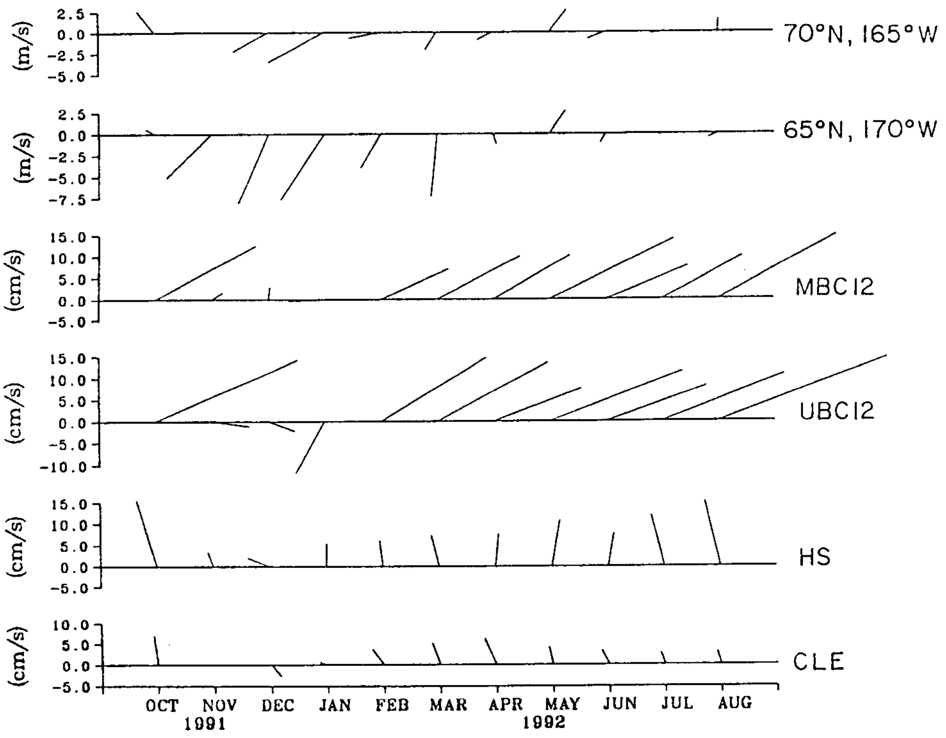

Figure 5. From bottom to top. Mean monthly current vectors at current meter locations. CLE, HS, UBC12, MBC12, and mean monthly wind vectors at 65°N, 170°W, and 70°N, 165 °W, respectively.

Temperature and salinity variability.—Figures 6 and 7 show time series of temperature and salinity for instruments MBC12, UBC3, HS and CLE. At both CLE and HS the seasonal temperature cycle consisted of: 1) a rapid cooling beginning in the last week of November which decreased temperatures to the freezing point, 2) a 7 - 8 month period during which time temperatures across the shelf remained near freezing, and 3) beginning in summer, a gradual warming that heralded the arrival of Bering Sea summer water. The late November cooling coincided with intense winds (Figure 2), vigorous surface cooling, and ice production which contribute to vertical mixing and erosion of the stratification remnant from the open water season. Thus, beginning in early December any additional oceanic heat loss must be balanced by latent heat released from ice formation. The seasonal temperature cycle at UBC3 and MBC12 is similar except that the period of near-freezing temperatures begins at the end of January instead of late November. This delay is related to the fact that the instruments here are at greater depth than those to the south, the time required to flush the shelf completely of summer water and to fall/early winter episodes of upcanyon advection of AIW. A second point of difference between the Barrow Canyon records and those to the south is that the arrival of warm water at UBC3 (and at UBC12) occurs nearly two months after its arrival at CLE. Dividing this time lag into the distance between CLE and UBC (400 km) suggests a mean speed of about 7 cm/s for the coastal current. Assuming that this value is representative of the mean summer speeds of the coastal current between Bering Strait and upper Barrow Canyon implies that the northeast Chukchi shelf was effectively flushed of winter water within a 3.5 month period.

Salinities also varied seasonally (Figure 7). At all locations, minimum salinities were observed in fall. Maximum salinities occurred in mid-January at CLE, early February at HS, and the latter half of March in Barrow Canyon. Following these winter maxima, salinities decrease gradually through spring and summer as less saline water is advected northward. At HS, the salinity maximum was preceded by a rapid increase in salinity which began in mid-January. In Barrow Canyon, salinity increased rapidly in early February coincident with the reestablishment of the normal shelf circulation regime (Figures 2 and 5) and this increase reflected flushing of the cold, saline water formed within the polynyas along the northwest coast of Alaska. There was also a shorter-lived brine outflow event in Barrow Canyon which occurred in mid-December. However, this outflow was more prominent at UBC3 than at MBC12 suggesting that much of it mixed with ambient shelf water as it flowed downcanyon. Three particular events of note were observed at MBC12 in late November, late January, and late April in tandem with strong southwestward (upcanyon) flow. These reversals affected an upcanyon transport of the high salinity (~34.3 psu), moderate temperature (~-0.5°C) water characteristic of AIW.

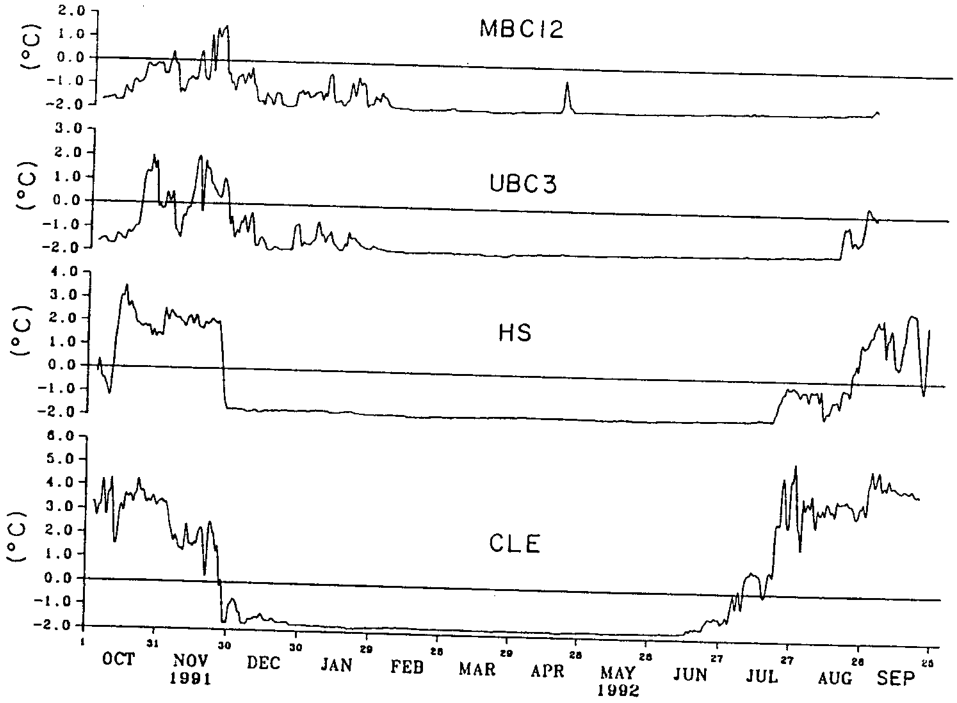

Figure 6. Low-pass filtered temperature records from current meter moorings in the northeast Chukchi Sea.

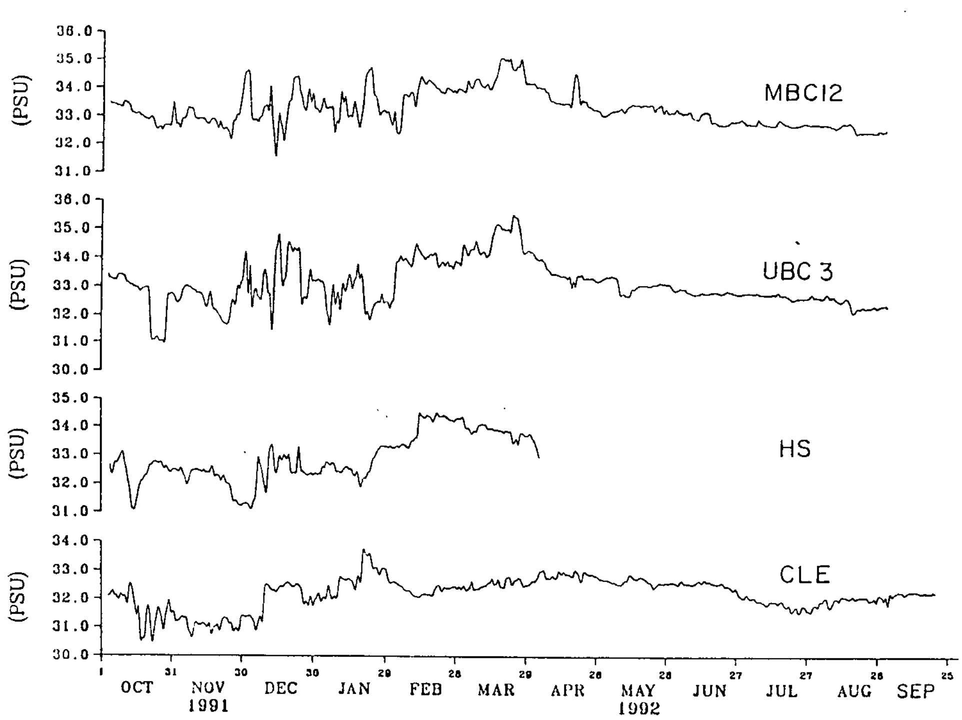

Figure 7. Low-pass filtered salinity records from current meter moorings in the northeast Chukchi Sea.

The temperature/salinity properties observed at the moorings segregate into several volumetric modes. Figures 8a-8c show these modes for moorings CLE, UBC3, and MBC12, respectively. The dominant mode at all sites has the moderate salinities (~32.5 psu) and the low temperatures (< -1.0°C) characteristic of Chukchi Sea winter water (CAT). At CLE, there is a secondary mode consisting of the warm, low salinity fraction of Bering Sea summer water flowing within the coastal current. (Following the nomenclature of CAT this fraction is termed Alaska Coastal Water [ACW]). This water mass is observed in fall 1991 (October and November) and late summer 1992 (July through August). By contrast, the summer water at HS consists of the Bering Shelf Water mode of Bering Sea summer water (CAT) that is both cooler and saltier than the ACW water mass observed at CLE (cf. Figure 6 and 7). In Barrow Canyon, the second most dominant water mass is a brine mode with salinities greater than 33.75 psu and temperatures at the freezing point. This mode is separated from the winter water mass by a third mode whose salinities fall between those of the winter water and the high salinity brine suggesting that it is a mixture of these two components.

The water property distributions observed at MBC12 and UBC3 differed markedly in two respects from those observed by Aagaard and Roach (1990) in 1986/87 and, in fact, were similar only in that winter water comprises the dominant mode in both years. In 1986/87 AIW was the second-most dominant water mass observed, whereas in 1991/92 unmixed AIW was observed infrequently (on the dates previously noted) at MBC and not at all at UBC. Moreover, brine products were conspicuously absent in 1986/87 whereas in 1991/92 they constituted the second most abundant water mass mode observed in Barrow Canyon.

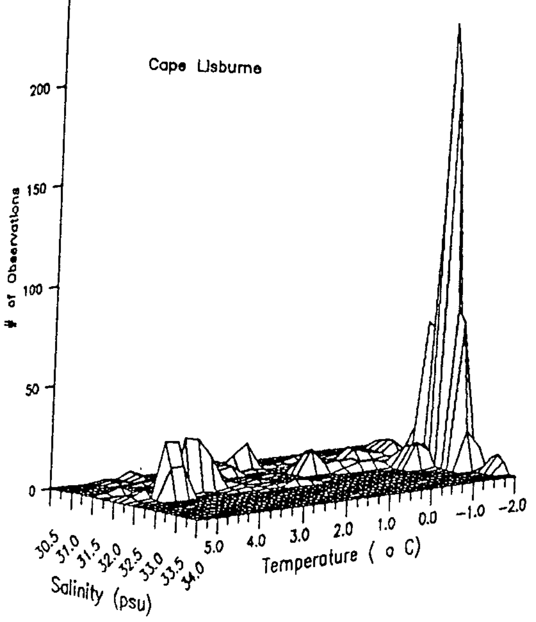

Figure 8a. Frequency plot of temperature-salinity pairs from current meter mooring (CLE).

8b

8c

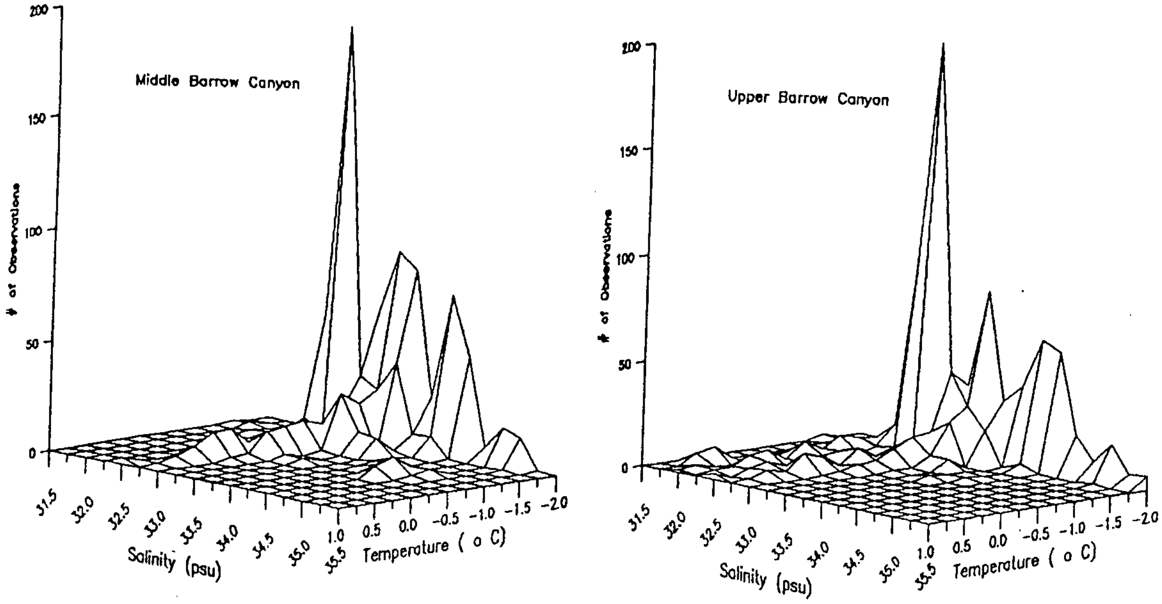

Figure 8 b, c. Frequency plot of temperature-salinity pairs from current meter locations b) MBC12 and c) UBC3.

Polynya Formation and Brine Production.—To investigate the connection between the brines observed at the moorings and the polynyas along the northwest coast of Alaska in the winter of 1991/92, heat fluxes and salt production rates were computed over areas of open water estimated from the SSM/I imagery obtained from early December through late March. The surface heat balance results are summarized in Figure 9 which shows time series of the individual components comprising this balance as well as the wind speed and mean daily adjusted Barrow air temperatures. Throughout the record, sensible heat flux variations were more closely related to wind speed than to air temperature. From December through February, the sensible heat flux dominates the surface heat budget and, as such, the net heat loss is also largely a function of the wind speed. (Note that in March, the dominant component of the surface heat balance is the longwave radiative loss.) Maximum heat losses occurred in December and January. The trend toward diminishing heat loss which began in February was a consequence of both a decrease in wind speed and an increase in solar radiation (the latter is identically zero from December through most of January at 70°N).

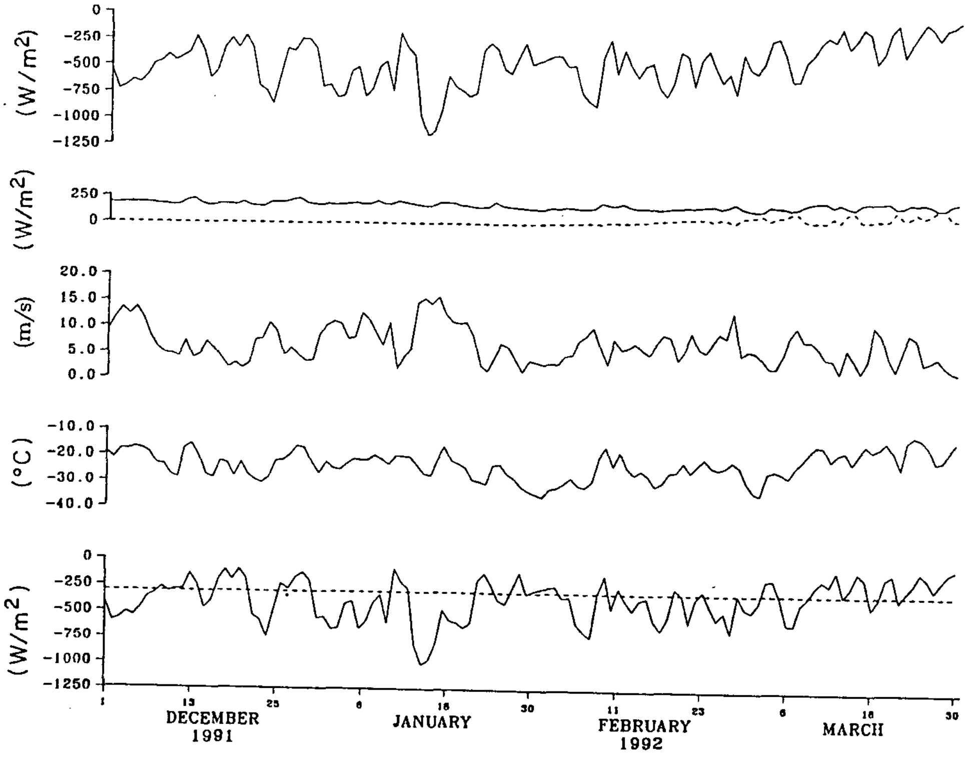

Figure 9. From bottom to top, time series of sensible (solid line) and long-wave outgoing radiation (dashed line), adjusted air temperature, wind speed, long-wave incoming radiation (solid line) and incoming short-wave radiation (dashed line), and net surface heat flux from December through March in the northeast Chukchi Sea.

Figure 10 shows daily time series of open water area, the east component of wind velocity (both at 70°N, 165°W), the net heat flux (assuming a water temperature of -1.8°C) and the daily and cumulative salt production. The starting date for the estimation of the latter begins on

December 4; the earliest date in this month for which SSM/I data were available. However, this choice is reasonable because, as shown previously, water column temperatures over the shallower (< 50 m) portions of the shelf had decreased to the freezing point by early December so that any additional oceanic heat loss was balanced by the production of ice. The salt flux and frazil ice salinity are dependent on polynya seawater salinity (Maykut, 1978; Martin and Kaufmann, 1981). The average salinity at CLE from December through March at CLE was about 32.5 psu and this value was chosen to be representative of the surface seawater salinity on the northeast shelf during this period.

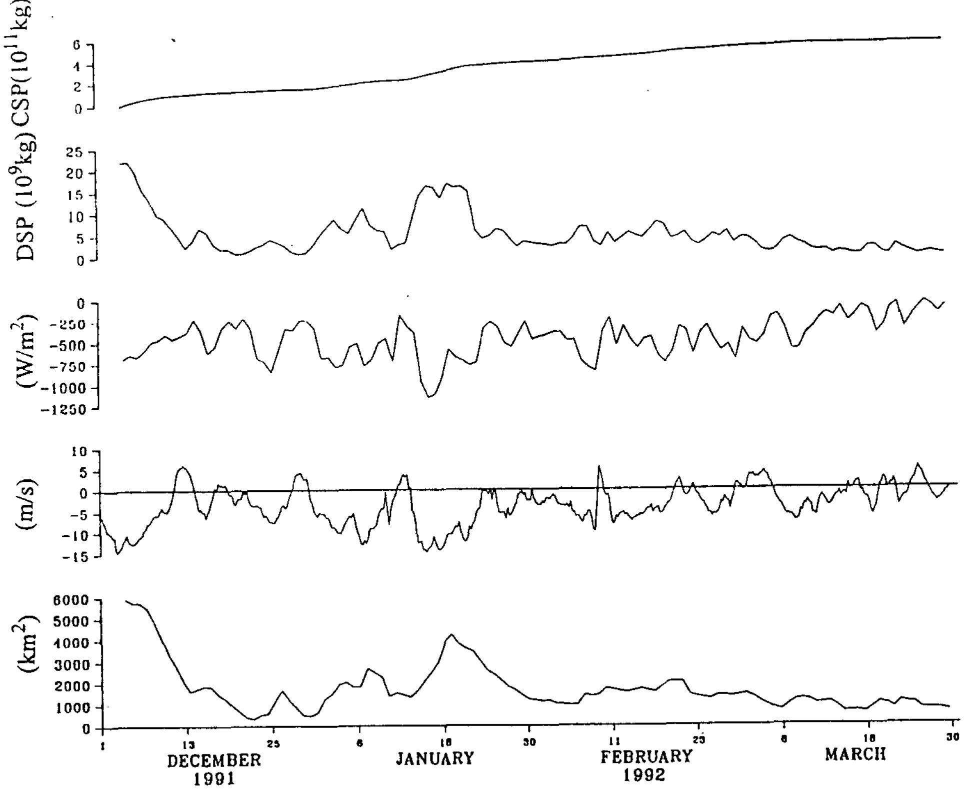

Figure 10. From bottom to top, time series of open water area, west (positive values) - west, (negative values) wind velocity at 70°N, 165°W, net surface heat flux, daily salt production and cumulation salt production from December through March in the northeast Chukchi Sea.

Open water area varied by more than an order of magnitude throughout this period and attained its seasonal maximum of ~5700 km^2 in early December and its seasonal minimum of ~350 km ^{2} in the third week of December. Following this minimum, open water area increased until mid-January but then diminished to about 1000 km^2 by the end of the month. From February through March open water area varied between 1000 and 2000 km^2. Both the SSM/I and AVHRR imagery showed that most of the open water area in February and March was associated with a narrow (5 - 10 km) flaw polynya athwart the fast ice between Barrow and Cape Lisburne. In contrast, the satellite imagery from the mid-January event revealed a broad expanse of open water and thin ice which extended as much as 80-100 km seaward of the shorefast ice. The duration and extent of these open water events paralleled the persistence and strength of the easterly winds. While this relation is readily apparent with respect to the early December and mid-January events, it holds for other times as well. Net heat flux also varies throughout these months and ranges between a maximum heat loss of 1150 W/m^2 in mid-January to a minimum heat loss of 40 Wm^2 at the end of March.

The combined effects of both the open water area and the heat flux are represented by the time series of daily salt production (DSP) and cumulative salt production (CSP_{HB}, the subscript refers to this term being estimated from the heat balance). The DSP was greatest during the early December and mid-January events and these large values are due to the simultaneous occurrence of both large open water area and heat loss. In effect, the salt production arose as a rectified response to the strong easterly winds which promoted polynya development and enhanced heat loss. The CSP_{HB} for this four month period was 5.7 x 10^{11} kg of which 80% was produced by mid-February. Moreover, 61% of the CSP_{HB} was produced during the periods of December 4-12 and January 1-31.

Can this salt production be accounted for in the current meter measurements? In short, no; the salt production presented above underestimates that required to account for the volume of brine observed by the moorings. In the following, data from the current meters are used to provide a second estimate of the cumulative salt production (termed CSP_{CM}) over this four month period. The procedure involves first estimating the volume of dense water flowing away from the polynya region. With this estimate in hand, CSP_{CM} can then be computed and compared to CSP_{HB}. The comparison will yield a rough approximation of the magnitude by which the latter is underestimated and will serve as a basis for addressing the assumptions employed in estimating the salt flux.

To calculate the dense water outflow requires estimates of the dense water salinity, outflow speed, and the cross-sectional area of the plume. For simplicity, calculations for Barrow Canyon are restricted to the period between February 12 and April 2 when most of the dense water was observed flowing downcanyon. Ignoring brine flows prior to this period implies that the result will underestimate the total volume of dense water produced. An estimate of the average plume depth was chosen after examining hourly time series of the salinity difference between instrument pairs. The mean salinity difference between MBC18 and MBC3 was about 0.1 psu over this period while the mean difference between MBC25 and MBC3 was about twice this value. These differences were mainly attributable to the late March outflow when maximum salinities (> 35 psu) were observed. At this time, occasional hourly salinity differences of ~1.0 psu were observed between MBC25 and MBC3 while those between MBC18 and MBC3 were generally half this value. The largest salinity differences tended to be clustered in bursts of several hours duration suggesting that they were associated with internal waves excited along the upper boundary of the plume. Hence, we chose a value of 20 m for the mean plume depth which we believe is a conservative but reasonable choice. The mean salinity within this layer was 34.2 psu and the mean outflow velocity was 0.2 m/s. Plume width was chosen to be 25 km and was based upon the lateral distance between the 100 m isobaths along the east and west wall of the canyon at MBC. This width is the same as that observed by Aagaard *et al.* (1985) from cross-canyon CTD transects conducted during a dense water outflow event in March 1982. With these values, we calculate that 4.5 x 10^{11} m^3 of water, with a mean salinity of 34.2 psu, flowed downcanyon during this 52 day period.

The source of high salinity water observed at HS from mid-February through early April must also be from the polynyas along the northwest coast of Alaska as the only other possible sources are the polynyas on the northern Bering Sea shelf (Schumacher *et al.* 1983; Muench *et al.* 1988). Although the SSM/I imagery shows well-developed polynyas here in early January and February of 1992, it is doubtful that these polynyas contributed the high salinity water observed at HS for a number of reasons. Chief among these are that: 1) there was no indication of northward advection of high salinity water at either CLE or CLW and 2) for this saline water to arrive at HS in mid-February implies a mean northward flow of 0.3 m/s and currents of this magnitude contradict the mean January flow estimated at CLE. Next, we assumed that the dense water observed at HS reflects a broader outflow into the north central Chukchi Sea through the gap between Herald and Hanna Shoal. The assumed plume width is 250 km (the distance between the 40 m isobath bounding Hanna and Herald Shoal) and its height above sea-bottom was chosen to be 5 m. This depth is consistent with the 3 meter height of the instrument above the bottom and with the salinity cross-section from March 1982 (Aagaard *et al.* 1985) which shows the 34 psu isohaline extending seaward from the coast within a thin bottom layer. Plume speed was chosen to be 0.02 m/s and was determined as follows. First, the arrival of the high salinity water at HS in February lags by two months the December polynya event and by one month the January polynya opening. As the mooring was approximately 100 km west of the open water/thin ice boundary as determined from January AVHRR imagery a northwesterly velocity of about 0.01-0.03 m/s is inferred. A second estimate was derived by assuming that the mean January onshelf flow at UBC12 of 0.13 m/s approximates the average cross-sectional current speed at the head of Barrow Canyon where the width is about 20 km and the water depth is about 75 m. These numbers yield a southwestward transport of ~2 x 10^5 m^3/s. This transport was assumed to be balanced by a northwesterly flow between Hanna and Herald Shoals, because the Cape Lisburne moorings show negligible transport in January across this section. The depth between these shoals is about 45 m and, in conjunction with the channel's width, implies a mean speed of 0.02 $m\text{-}s^{-1}$. Both estimates are consistent with one another and with the numerical model results of Spaulding *et al.* (1987; their Figure 12b) for this shelf's circulation when forced by easterly winds. With these values, we calculate that 1.2 x 10^{11} m^3 of water, with a mean salinity of 33.9 psu, flowed through this gap during the 56-day period from February 10 and April 5.

The CSP_{CM} required to balance these outflows follows from Alfultis and Martin (1987) and, after rearranging their equation 8, is estimated accordingly:

$$CSP_{CM} = V_{dw}*[(S_{dw} - S_{sw})]*\varrho_{dw}$$

where ϱ_{dw} is the salinity of the dense water outflow, $V_{dw}$is the volume of dense water, $S_{sw} = 32.5$ psu, is the initial polynya seawater salinity, and P_{dw} is the density of S_{dw} at the freezing point. (The CSP_{CM} computed in this way can be very sensitive to the choice of either S_{dw} or S_{sw}. However, changes in S_{dw} will be buffered by changes in V_{dw} due to compensatory changes in plume depth, the vertically averaged plume speed, and the duration of the dense water outflow.) Performing this calculation for the two outflows and summing the results yields a CSP_{CM} of 9.6 x 10^{11} kg. Of this total, 82% is required to balance the Barrow Canyon outflow. Hence, CSP_{CM} is (at least) about 70% greater than that estimated from the surface heat balance approach.

To overcome this deficit would require an additional average daily heat loss of 350 W/m^2 over the December to March period. Relative to the sensible heat flux term, the magnitudes of the other terms contributing to the surface heat balance are small and are either of the same magnitude or smaller than the additional heat loss required. Thus it seems unlikely that these could be the source of the discrepancy. The sensible heat flux could be underestimated if wind speeds or the transfer coefficient are too low or if air temperatures are too warm. Aagaard *et al.* (1990) compared 6-hourly wind speeds estimated from the FNOC surface pressure fields with those measured at coastal weather stations along the Chukchi and Beaufort coasts and found that mean wind speeds differ by less than 1 m/s[1] although the FNOC wind estimates are consistently higher. The air temperatures used in the heat balance equation were essentially obtained upwind of the polynya during such events and therefore, if biased, are more likely too cold rather than too warm (Pease, 1987; Sverdrup, 1933). The transfer coefficient used (2 x 10^{-3}), while a subject of considerable uncertainty, falls well within the parametrized values (Pease, 1987). In short, in order to increase the magnitude of the sensible heat loss term to satisfy the salt deficit would require unrealistic changes in wind speeds, air temperatures, and/or the heat transfer coefficient.

Nor can the discrepancy be satisfied by changing the seawater salinity which in our calculation of the DSP was assumed to be constant. A reasonable argument could be advanced that due to the near-stagnant shelf circulation of December and January polynya salinities increased over time. However, in our formulation the relationship between salt flux and seawater salinity is linear, hence even large changes in S_{sw} will not significantly improve our results. For example, increasing the salinity by 8% (from 32.5 to 35 psu) increases CSP_{HB} by the same percentage.

The difference might result from the fact that our calculation ignores the salt flux contributed by ice growth in areas of thin ice. Because of the insulating effect of the sea-ice cover oceanic heat loss decays rapidly with ice thickness. For example, according to Maykut (1978) the oceanic heat losses through ice thicknesses of 0.1, 0.2, or 1 m are 40%, 25%, and 8% respectively of the heat loss through open water. To estimate the additional salt production that might be contributed by ice production in areas of thin ice we assumed that the spatially averaged ice thickness inshore of the 40 m isobath and between 68°N and 70°N is 1 m. The area of this region is 45,000 km^2 and it lies within the thin ice boundary seen in the January AVHRR imagery. The average net daily heat loss (over open water) from December through March was 425 W/m^2 which corresponds to a oceanic heat loss of 30 W/m^2 over 1 m of ice. Thus ice growth in this region could contribute an additional 9 x 10^{11} kg of salt throughout this period and this production is more than sufficient to satisfy the estimated salt deficit.

DISCUSSION

While the extensive ice-cover in the fall of 1991 prevented us from achieving several of the original objectives, the modified program did provide new insights into the circulation over the central shelf and permits a comparison with previous observations of the coastal current and of dense water production on this shelf.

The current meter results from Herald Shoal indicated steady northward flow in all months of the year. In contrast, CAT inferred a southeasterly flow here and through the gap formed by these shallows and suggested that part of this flow joined the coastal current before draining through Barrow Canyon. However, summer and fall ice maps for the Chukchi Sea frequently show a northward indentation in the ice-edge to the north and east of Herald Shoal which is presumably a consequence of enhanced melting by warm water advection from the Bering Sea (Paquette and Bourke, 1981). The perennial nature of this ice-edge feature was, in fact, well-known in the 19th century when it was used as a rendezvous point by whalers venturing to and from their hunting grounds in the Chukchi Sea (Bockstoce, 1986). Hence, the earlier ice-edge observations tend to corroborate the mooring results and suggest that the mean northward flow observed here is a persistent feature of the shelf circulation. Because this flow consists mainly of Bering Shelf Water rather than Alaska Coastal Water, its organic carbon load is richer than that of the coastal current to the east (Walsh *et al.* 1989). Indeed, striking differences are seen between the vertical profiles of fluorescence (Figure 11) from CTD stations occupied at the HS mooring site and from another some 50 km further to the east in the fall of 1992 and similar differences were observed in fall 1993. Presumably some of this carbon-rich water spreads to the northeast and sustains the relatively high benthic biomass and the large numbers of marine mammals which forage on the benthos on the outer shelf of the northeast Chukchi Sea (Feder *et al.* in revision).

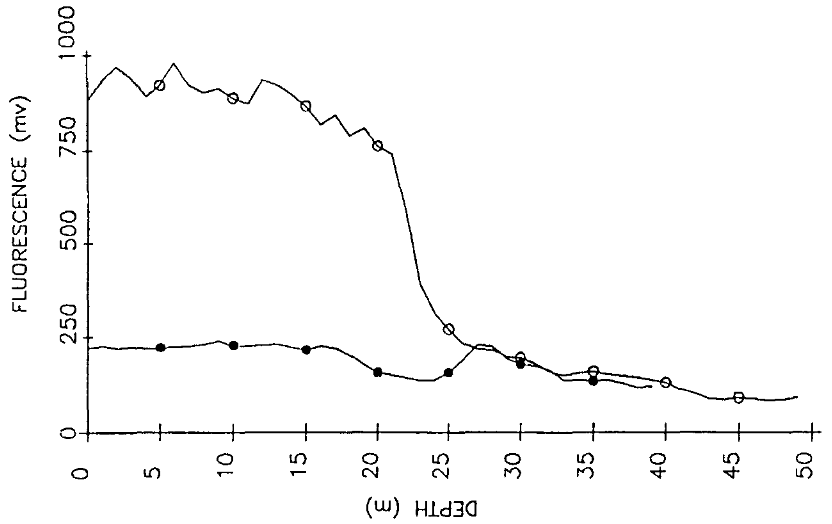

Figure 11. Vertical profiles of fluorescence at current meter mooring site HS (open circles) and at 70.72°N, 165.83°W (solid circles) on September 27, 1992.

We have argued, based upon circumstantial evidence, that northwesterly flow ensued between Herald and Hanna Shoals in the winter of 1992 in response to alongshore convergence of the coastal current. However, significant questions remain regarding the temporal and spatial structure of the flow field over the north central shelf. Muench *et al.* (1991) and Colony and Thorndike (1984) show that here the prevailing drift of ice is westward and downwind. The issue is somewhat clouded by Johnson's (1989) current measurements which, while of only a few days' duration, show eastward flow along the northwest side of Hanna Shoal during a period of strong northeasterly winds which reversed the coastal current. These observations suggest that subsurface flow on the outer shelf might be uncoupled from the wind. Nor are numerical models clear on this issue for Spaulding *et al.* (1987) show that under southerly wind forcing the vertically averaged flow here is eastward, while under easterly wind forcing the flow is westward. On dynamical grounds, we expect that north of Herald Shoal and Herald Sea Valley the flow would turn east and continue parallel the isobaths along the outer shelf. Additional forcing might be provided by the undercurrent flowing eastward along the shelf-slope margin as Aagaard (1984) maintains is the case for the subsurface flow along the outer Beaufort shelf. From the perspective of predicting pollutant dispersal pathways, either from marine industrial activities on the outer shelf or those advected from Eurasian sources, resolving the circulation regime in this region is regarded as critical.

The upwelling observations in Barrow Canyon presented here along with those from Aagaard and Roach (1990) help to better define the spatial scale over which upcanyon excursions of AIW affect the shelf. In both years the upwelling events occurred primarily in fall and early winter. Moreover, their frequency (10-15 events between October and January), duration (5-10 days), and intensity (mean speeds of about 0.5 m/s) were similar in both years. The persistence and intensity of these reversals is such that water from along the continental slope could easily traverse the 250 km longitudinal extent of the canyon. Yet observations of AIW on the shallower reaches of the shelf are extremely rare (Bourke and Paquette, 1976). Aagaard and Roach (1990) observed that the outflows, which immediately followed upcanyon intrusions of AIW, were a blend of shelf water and AIW and therefore, they concluded that significant mixing occurred upcanyon from their moorings. Our moorings detected unmixed AIW very infrequently at the mid-canyon site and not at all at the head of the canyon. Although the two data sets come from different years, collectively they suggest that much of this mixing must occur in the lower half of the canyon thereby diluting much of the AIW before it reaches the upper canyon and the shallower portions of the shelf.

This data set, those described by Aagaard and Roach (1990) and Aagaard *et al.* (1990) for 1986/87, and that presented by Aagaard (1988) for 1981/82 allow several comparative statements to be drawn regarding interannual differences in flow on the northeast Chukchi shelf. The velocity records from Barrow Canyon for these years are generally similar, differing primarily from late fall through early winter. For example, the records from 1981/82 differ from the other two years in that few current reversals occurred after November in Barrow Canyon. If these reversals are driven by wind-forced shelf waves propagating along the continental slope, then the 1981/82 results imply that these were less energetic in that year compared to either 1986/87 or 1991/92. Moreover, Aagaard's (1988) records from offshore of Cape Lisburne show relatively steady year-round flow. Thus it would seem that the alongshore convergence of the coastal current that was seen in the winter of 1991/92 was not a feature of the shelf circulation in the winter of 1981/82. In 1986/87, the Barrow Canyon records suggest that, beginning in mid-December, currents reversed across the shelf for about three weeks but by early January they were once again strongly northeastward. Thus, the data from these earlier years suggests nothing comparable to the period of prolonged weak flow as observed from November 1991 through January 1992. However, given the small number of data sets available it would be premature to determine which, if any, of these winters is typical.

Because of the weak mid-winter circulation, the residence time of a water parcel on the shelf and in the polynyas was prolonged. Consequently, brines accumulated within the polynya and increased a water parcel's salinity to a greater extent than would have been possible if the parcel was advected rapidly through the region. We maintain that because weak flow prevailed over the northern Bering shelf as well, this effect enhanced shelf salinities in this region as well.

We note that there are several significant consequences associated with diversion of coastal water to the northwest. First, such a flow provides a mechanism by which pollutants from the coastal zone can be dispersed onto the north central shelf. Second, as mixing with ambient shelf water alters the water mass properties of the shelf-produced brines flowing into the Arctic Ocean, different mixing regimes are expected depending upon the flow path. The flow trajectory will also affect the biogeochemical properties of the dense water as these will be influenced by exchange with the seabed and the time in which the plume is in contact with the bottom. Third, the outflowing dense water will affect the momentum balance along the continental slope and the nature of this forcing will depend, in part, upon whether the outflow is spread over a broad area or confined to a narrow channel such as Barrow Canyon (Shaw and Csanady, 1983).

There are also differences among these years in polynya extent, the duration of open water events, and the cumulative salt production. As the regions analyzed by CM differ somewhat from those considered here a direct comparison cannot be drawn at this time. However, CM do show that the CSP_{HB} in 1981/82 was twice that of 1986/87 and these differences are largely due to diminished open water area in 1986/87. Tentatively, it appears that the CSP_{HB} and open water area of 1991/92 falls between the values observed in these earlier years. Preliminary examination of the wind records suggest that differences in polynya size as well as the shelf circulation relate to interannual differences in the large-scale wind-forcing over the Chukchi Sea and the northern Bering Sea. Additional analyses along these lines are currently underway.

SUMMARY

Five current meter moorings were deployed in the northeast Chukchi Sea from October 1991 through September 1992. Four were deployed in the Alaska Coastal Current; two offshore of Cape Lisburne and two in Barrow Canyon. A fifth mooring was deployed in the central Chukchi Sea approximately 250 km west of Barrow Canyon.

The results show that current variations were: 1) spatially coherent throughout the northeast Chukchi Sea and 2) significantly coherent with the local wind field. However, currents offshore of Cape Lisburne were more coherent with winds over the northern Bering shelf than they were with winds over the northern Chukchi Sea suggesting that here the coastal current's dynamics are, in part, tied to sea-level adjustments associated with wind-driven transport variations in Bering Strait.

The data depict a shelf circulation which is remarkably steady and swift in most months of the year. However, from November 1991 through January 1992, flow on the northeast shelf was nearly stagnant and the along-shore coherence of the coastal current broke down. Disruption of the coastal flow occurred simultaneously with the formation of polynyas along Alaska's northwest coast which enhanced shelf salinity due to brine rejection from growing ice. Hence, the formation of cold saline water is viewed as a rectified response of the ice and ocean to strong northeasterly winds which: 1) favored polynya development, 2) enhanced sensible heat loss, and 3) led to weak shelf circulation. The salinization effect was enhanced by the weak circulation which effectively increased the residence time of water parcels within the polynyas thereby allowing salinity to increase to a greater extent than would be expected if strong flow had persisted. In January, basin-scale differences in winds forced alongshore convergence within the coastal current because strong winds reversed the flow in Barrow Canyon but not in Bering Strait or offshore Cape Lisburne.

Most of the cold and saline dense water formed in these polynyas entered the Arctic Ocean through Barrow Canyon after the normal shelf circulation was reestablished in February. However, because of convergence within the coastal current in January, a substantial portion of the dense water drained to the northwest; through the channel between Herald and Hanna Shoal.

Estimates of total salt produced from ice formed in the polynyas are at least a factor of two smaller than salt flux estimates based upon the current meter observations. However, it seems plausible that additional salt produced in areas of thin ice, which are not easily ascertained by the satellite imagery, would be more than sufficient to remove the observed discrepancy.

CHAPTER 4

WATER MASSES AND TRANSPORT OF YOUNG-OF-THE-YEAR FISH INTO THE NORTHEASTERN CHUKCHI SEA[1]

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Abstract.—It is hypothesized that some fish species in the northeastern Chukchi Sea are maintained through transport from more southern areas. We examine this hypothesis and report on the abundance and distribution of young-of-the-year Arctic cod and Bering flounder in relation to water masses. Ichthyoplankton were sampled with a variety of mid-water gears during 1989-1991. Arctic cod dominated the catches and occurred throughout the northeastern Chukchi Sea with higher concentrations at northern stations during all three years. They rarely occurred at southern stations when Bering Shelf Water (BSW) was present. Larval Arctic cod (› 6.3 mmSL) were caught mid-July in 1991 indicating reproduction extends into late July. Bering flounder occurred primarily in areas dominated by the Alaska Coastal Water (ACW) as far north as 71° N. They did not occur when Resident Chukchi Sea Water was present. We conclude that populations of Bering flounder in the northeastern Chukchi Sea are maintained by the transport of larvae in the ACW. While these fish and others may be routinely advected into the northeastern Chukchi Sea by Alaska Coastal Water, Resident Chukchi Water may be a critical factor in delimiting their northern distribution.

INTRODUCTION

Many species of fish from the north Pacific Ocean and Bering Sea have their northern range bordering the Chukchi Sea, e.g., starry flounder (*Platichthys stellatus*), Pacific halibut (*Hippoglossus stenolepis*), and Pacific cod (*Gadus macrocephalus*). Others, however, commonly occur in the region and are considered Arctic, e.g., Arctic cod (*Boreogadus saida*) (Alverson and Wilimovsky 1966; Allen and Smith 1988). Three species of Gadidae occur in the northeastern Chukchi Sea. Arctic cod is the dominant species (Pruter and Alverson 1962; Alverson and Wilimovsky 1966; Gillispie *et al.* Chapter 7) and has a circumpolar distribution. They are found near the ice edge, migrate, and spawn under the ice (Ponomarenko 1968) and are a key link in the transport of energy from lower to higher trophic levels (Craig *et al.* 1982). Additionally, Arctic cod is an important prey for eleven species of marine mammals, twenty species of marine birds, and four species of fish (Lowry and Frost 1981). Six species of adult flatfish commonly

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occur in the Chukchi Sea of which Bering flounder is dominant (Pruter and Alverson 1962; Smith *et al.* Chapter 6). Bering flounder range from Tatar Strait in the west to the Chukchi Sea through the Bering Sea to the Aleutian Is. (Andriyashev 1937; Pruter and Alverson 1962). Pruter and Alverson (1962) hypothesized that species like the Bering flounder might be maintained by import from the northern Bering Sea to the Chukchi Sea. To investigate this possibility we sampled planktonic young-of-the-year fishes in the late summer or fall of 1989-1991. From these samplings we describe the relationship of Bering flounder (*Hippoglossoides robustus*) to the physical oceanographic conditions in the northeastern Chukchi Sea and compare this distribution to that of Arctic cod.

The passive movement of planktonic oceanic fish larvae and post-larvae is affected by currents (Sinclair 1988). Distributions of Atlantic cod, *Gadus morhau* (Elizarov 1965), herring, *Clupea harengus* (Jakobsson 1969), and capelin, *Mallotus villosus* (Stergiou 1991) have been associated with changes in the distribution of water masses in the North Atlantic. Arctic populations of saffron cod, *Eleginus gracilis*, are known to vary in distribution and abundance with differing current regimes (Vasil'kov *et al.*1981). The relationship of ice cover, as well as other physical factors affected by atmospheric forcing, affects the distribution of walleye pollock, *Theragra chalcogramma* (Vasil'kov and Glebova 1984).

The currents in the northeastern Chukchi Sea are dominated by flow from the Bering Sea, which is caused by the Arctic Ocean being approximately 0.5 m lower than the Pacific Ocean (Stigebrandt 1984). Secondarily, the direction and strength of the wind, especially in summer, influences the rate of northerly flow and periodically imposes southerly flow over the shelf (Coachman and Shigaev 1992). The result is that three water masses predominate in the northeastern Chukchi Sea, the Alaska Coastal Water (ACW), Resident Chukchi Water (RCW), and Bering Shelf Water (BSW). Their distribution is influenced by the wind, and modified by the freezing and melting of seasonal sea ice (Weingartner, Chapter 2). The flow of currents northward introduces nutrients, phytoplankton and zooplankton into the Chukchi (Walsh *et al.* 1989).

MATERIALS AND METHODS

A bongo net, Isaac-Kidd midwater trawl (IKMT), and a beam trawl were used to sample young-of-the-year (YOY) fish during late summer and autumn of 1989-1991. The bongo net was 60 cm in diameter with 1.0 mm mesh netting, and a 0.5 mm meshed codend, and sampled 0.28 m^2 of water. The IKMT had a 1.8 m head bar and a net having 5.0 mm mesh, a 1.0 mm mesh codend, and sampled approximately 2.65 m^2 of water. Both nets were fitted with a calibrated flow meter suspended in the mouth of the nets. In 1989 the IKMT was deployed from the *Alpha Helix*. In 1990 and 1991 the IKMT and bongo net were deployed from a 33.5 m trawler. In 1991 a 2.24 m^2 square beam trawl was also used, the net's mesh of which graded in size from 6.5 mm to 4.0 mm with a 1.0 mm lining in the cod end. It was deployed from the *Oshoro Maru* (University of Hokkaido). Also in 1991, as a pilot program the bongo net and IKMT were deployed from a 9 m skiff operating from an anchored barge. All nets were pulled at a speed of approximately 2 kts and deployed in double oblique tows from surface to near bottom.

All collections were preserved in 5% sea water-formalin solution and returned to the laboratory. Fish were separated from the plankton samples, identified to the lowest taxonomic level possible following Matarese *et al.* (1989), and preserved in 80% ethanol. Standard lengths (SL) were measured on all undamaged fish to the nearest 0.1 mm; no shrinkage corrections were applied. The densities for each station were calculated as the mean of two replicate tows and reported as number/1000 m^3. Total number of fish captured is reported for the beam trawl collections due to the absence of a flow meter.

General station locations were chosen to increase the probability of sampling different water masses. Latitude and longitude were determined with a Global Positioning System. At the end of each sampling, vertical profiles of salinity, temperature, and depth were obtained with a Seabird SBE 19 conductivity-temperature-depth instrument. These data were used to classify each station as to one of four water masses present on the northeastern Chukchi Sea's shelf following the scheme of Coachman and Shigaev (1992) and Weingartner (Chapter 2). Two water masses, Alaska Coastal Water (ACW) and Bering Shelf Water (BSW), originate in the Bering Sea. The ACW flows northward from the Bering Sea along the coast of Alaska and is influenced by freshwater input, primarily the Yukon River (Weingartner, Chapter 2). It is characterized by relatively warm temperatures of 2 - 6° C and salinity less than 31.5 psu. BSW is colder (0 - 3°C) and more saline (> 32.5 psu) than ACW and also flows northward to the west of ACW. Resident Chukchi Water (RCW) is a combination of Arctic Ocean Water and water from the melting and freezing of sea-ice. RCW is characterized by low temperatures (<1°C) and high salinity (32 - 33 psu).

Wind stress curl at 67.5° N 167.5° W for 1981 - 1991 was obtained from Figure 11 in Weingartner (Chapter 2). Salmon (1992) calculates the north-south wind stress curl for the Chukchi Sea from atmospheric pressure data for 1981 - 1990.

RESULTS

Members of nine families were captured of which Cottidae, Gadidae, Pleuronectidae, Stichaeidae, Liparidae, and Agonidae were present in all years (Table 1).

Table 1.—Percent abundance of each species sampled by oblique tows with the Isaccs-Kidd mid-water trawl (IKMT), beam trawl, and a bongo net during summers of 1989, 1990, and 1991. Species indicated by a "t" were less than 2% of the total catch.

YEAR **GEAR**	**1989** **IKMT**	**1990** **Bongo**	**1990** **IKMT**	**1991** **Beam**	**1991** **Bongo**
Cottidae	2	3			
Myoxecephalus	t	t	t	6	t
M. "verucosa	t	0	t	0	0
Gymnocanthus spp.	0	0	t	2	t
G. tricuspis	3	0	t	0	0
Porocottus sp.	0	0	t	0	0
Gadidae					
Boreogadus saida	79	16	36	83	85
Eleginus gracilis	0	10	19	2	t
Theragra chalcogramma	0	t	t	3	0
Pleuronectidae					
Hippoglossoides robustus	7	23	18	t	0
Pleuronectes spp.	t	t	t	0	0

Table 1. continued

YEAR GEAR	1989 IKMT	1990 Bongo	1990 IKMT	1991 Beam	1991 Bongo
Cottidae	2	3			
P. asper	t	t	t	0	0
P. proboscideus	t	t	t	0	0
Platyichthys stellatus	0	0	t	0	0
Lepidopsetta spp.	0	t	t	0	0
Agonidae					
Aspidophoroides olriki	t	0	t	t	0
A. bartoni	t	0	0	0	0
Agonus acipenserinus	t	0	0	t	0
Stichaeidae					
Stichaeus punctatus	t	t	7	t	10
Lumpenus "sp.	2	t	6	3	t
Liparididae					
Liparis sp.	t	t	5	t	t
Ammodytidae					
Ammodytes hexapterus	3	14	3	0	t
Bathylegidae	0	t	t	0	0
Pholididae	0	0	0	0	t
Zoracidae					
Lycodes sp.	t	t	t	0	0
Total number - fish	2068	99	581	379	76
Total number - stations	21	48	48	17	16

Zoarcidae, Bathylagidae and Pholididae occurred occasionally and were least abundant. Arctic cod dominated the pelagic larval and juvenile fish fauna in all 3 years. Species and abundance varied greatly between years with a notable reduction of pleuronectids in 1991.

During 3 - 9 September 1989, sampling was limited to 21 stations along two lines of longitude (169° and 168° W) in the northeastern Chukchi Sea (Figure 1). ACW was present at the surface throughout the study area (Figure 1). BSW was evident at the most southern station below 10 m. RCW underlay the ACW north of 70° N below 20-25 m. Seven families of fishes were caught in the IKMT of which YOY Arctic cod (79%) and Bering flounder (7%) were most common (Table 1). Arctic cod were present at all stations irrespective of water type. They were most common north of 70° N in ACW/RCW where densities at three stations ranged from 130 to 403 fish/1,000 m^3 (Figure 1). Two stations at the boundary of the ACW and ACW/RCW water masses had densities of 137 and 709 fish/1,000 m^3. South of this area the densities were much lower and ranged from 2.4 to 31 fish/1,000 m^3. YOY Arctic cod ranged from 27 - 52 mmSL. Bering flounder larvae were present at stations south of 71° N primarily in ACW or ACW and BSW. Densities reached 32 fish/1,000 m^3 at the two stations along 70° N. These fish ranged in size from 15 - 34 mmSL.

During 16 August to 16 September 1990 we sampled 48 stations throughout the northeastern Chukchi Sea (Figure 2). ACW was evident in surface waters throughout the area. Two additional water masses were present underneath the ACW; BSW occurred in the southeastern stations and RCW occurred in the northern stations (Figure 2). Thermoclines and pycnoclines were only evident where ACW overlay a colder, more saline water mass. Eight families of fishes were captured with Arctic cod, saffron cod, and Bering flounder dominating (Table 1). YOY Arctic cod made up 36% of the catch with the IKMT and were caught at all stations. Abundance exceeded 25 fish/1,000 m^3 at 3 stations north of Icy Cape (Figure 2). Size averaged 33 mmSL and ranged from 12.2 - 5.1 mmSL. The distribution of larval Arctic cod captured with the bongo net reflected that of the YOY caught with the IKMT. Their abundance, however, was much lower varying from 0.1 to 0.7 fish/1,000 m^3. Bering flounder were also captured in the IKMT but south of 71°N. At stations where they occurred, densities ranged from 1.1 to 4.6 fish/1,000 m^3. Bering flounder occurred in ACW and where ACW overlaid BSW Bering flounder larvae captured in the bongo net reflected the same distribution as figure 1 those captured in the IKMT and also occurred south of 71° north in ACW. Densities, however, were much lower which ranged from 0.1 to 0.4 fish/1000 m^3. The bongo net captured smaller fish which averaged 15 mmSL and ranged in size from 7.6 - 25.7 mmSL. The IKMT averaged 29 mmSL and ranged from 8.3 to 51.5 mmSL.

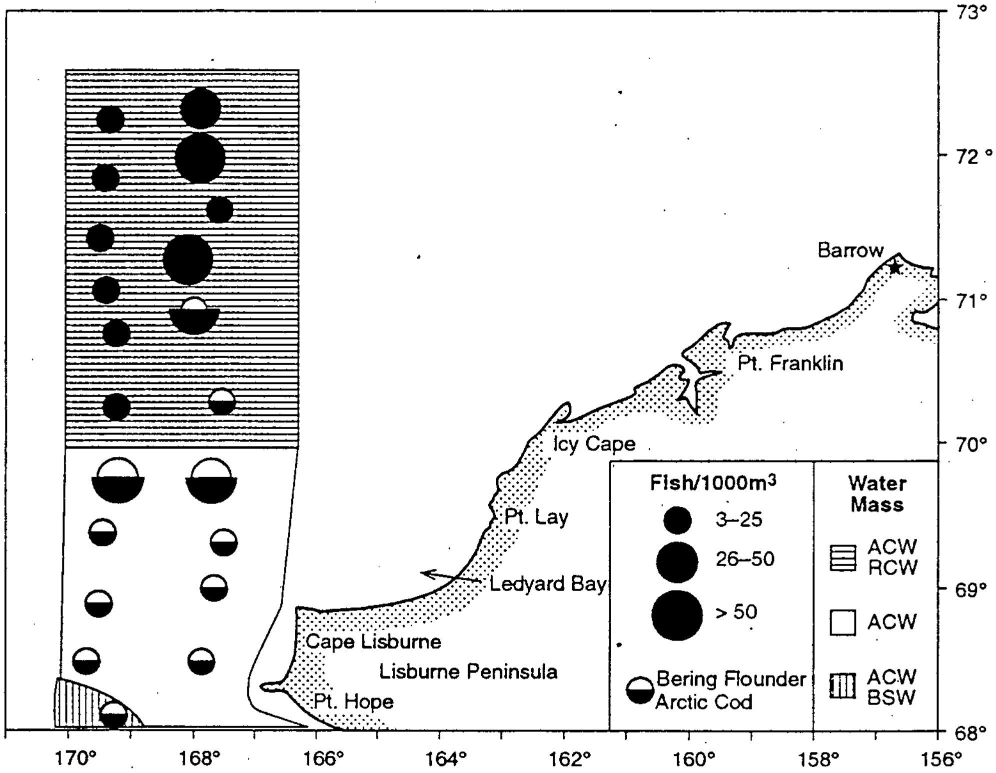

Figure 1. Abundance and distribution of Arctic cod and Bering flounder captured with the Isaccs-Kidd mid-water trawl in 1989. Densities are in fish/1,000 m^3. Water masses indicated by shading.

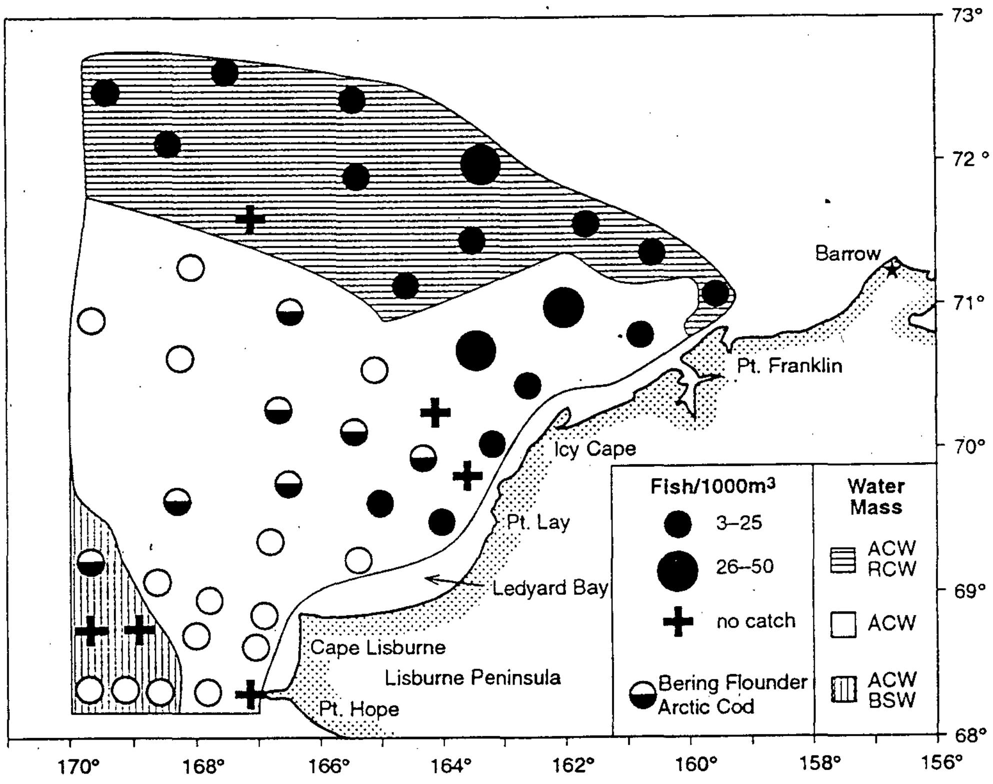

Figure 2. Abundance and distribution of Arctic cod and Bering flounder captured with the Isaccs-Kidd mid-water trawl in 1990. Densities are in fish/1,000 m^3. Water masses indicated by shading.

During 25-31 July 1991 we sampled 17 stations with the beam trawl. ACW was present south of 70°N and ACW/RCW occurred north of 69°30'N (Figure 3). Seven families of fish were caught in the beam trawl with Arctic cod (83%), *Myoxocephalus* spp. and *Stichaeus punctatus* the dominant species (Table 1). Arctic cod were caught throughout the study area, the highest numbers occurring in RCW where up to 65 fish per half hour tow. Average size was 14 mmSL and ranged between 7 - 36 mmSL. One Bering flounder was caught in ACW. Sampling with the bongo net during 2 - 25 September fish were caught at 5 of 16 stations. Again Arctic cod dominated (85%), and occurred in ACW/RCW and RCW. Sizes averaged 14 mmSL ranged between 7 - 37 mmSL. No Bering flounder were caught. Sampling near the ice edge from the skiff during 16 July, Arctic cod captured in the bongo net averaged 11.8 mmSL and ranged between 6.3 - 19.5 mmSL. In 16 August the average size was 13.1 and ranged between 8.2 and 23 mmSL.

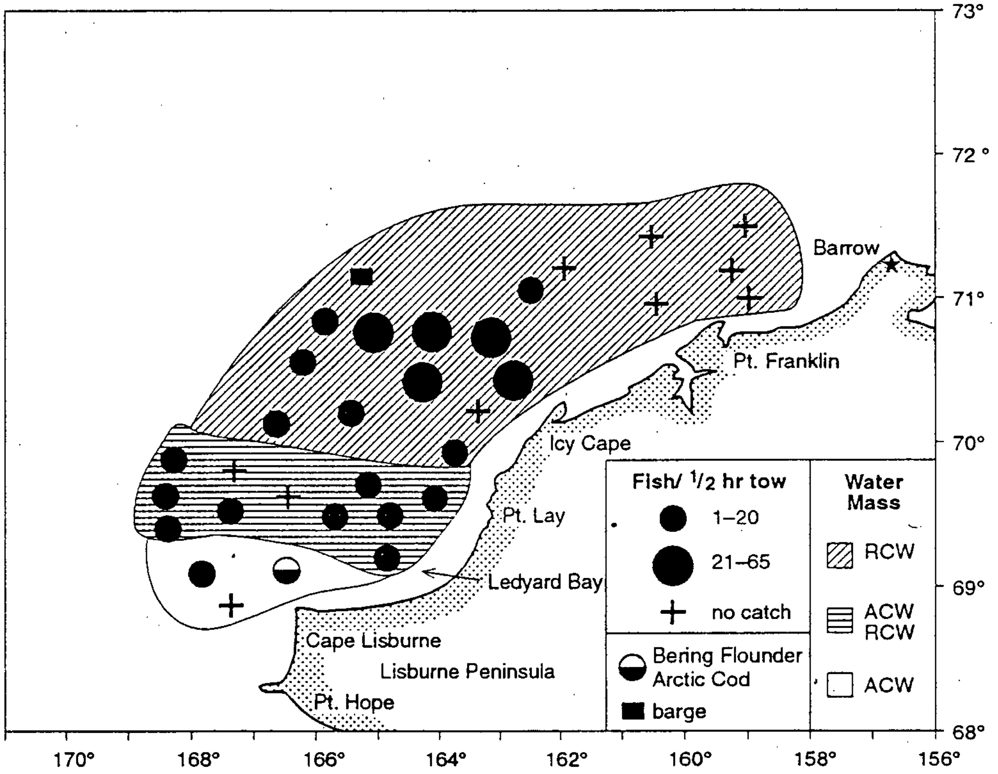

Figure 3. Abundance and distribution of Arctic cod and Bering flounder captured with the Issacs-Kidd mid-water trawl in 1991. Densities are in fish/1,000 m^3. The square is the barge location. Water masses indicated by shading.

DISCUSSION

The water of the northeast Chukchi Sea is primarily derived from two water types, BSW and ACW, flowing from the Bering Sea. RCW is a combination of Arctic Ocean water devected onto the shelf and mixing with waters formed from the freezing and melting during the previous winter (Weingartner, Chapter 2). Pruter and Alverson (1962) suggested that some of the marine fishes and invertebrates inhabiting the area maintain their populations only through continual recruitment of eggs and larvae transported northward. If so, it would be expected that the larvae of those fish with their main distribution primarily in the Bering Sea might be more associated with the ACW and the BSW in the northeast Chukchi Sea. In contract, those fish with their center of distribution in the Arctic Ocean might be more associated with the RCW.

In 1989 and 1990, the surface water mass extending throughout the study area was ACW (Figures 1 and 2). RCW occurred on the bottom from 70°N northward. In 1991, however, a different distribution was observed. ACW extended as far north as 70°N while RCW was prevalent throughout the water column northward. The distribution of YOY Bering flounder reflects the distribution of those water masses. Bering flounder were present during 1989 and

1990 in ACW and ACW/BSW but absent from ACW/RCW. In 1991 only one YOY Bering flounder was captured and it was in ACW (Figure 3). *Pleuronectes* spp. dominated by yellowfin sole (*P. asper*), and sandlance (*Ammnodytes hexapterus*), followed the same general pattern. These fish are primarily distributed in the Bering Sea and extend into the Chukchi Sea (Allen and Smith 1988). In 1989 and 1990 *Pleuronectes* spp. occurred in ACW, and sandlance was sampled from ACW and ACW/RCW but were absent in 1991 (Table 1). This suggests that YOY Bering flounder, and quire possibly yellowfin sole and sandlance, were advected into the northeastern Chukchi Sea with ACW.

Change in the distribution and abundance of organisms is coincident with the boundary between ACW and RCW which forms a semi-permanent front along the bottom between 70° and 71°N (Weingartner, Chapter 2). The distributions of adult (Smith *et al.* Chapter 6) and YOY (Figures 1 - 3) Bering flounder are close aligned with the position of RCW and the influx of ACW along the front and appears to be a boundary. In 1990 adults were most abundant in ACW south of 70°N, while few were present in RCW (Smith *et al.* Chapter 6). In 1991 abundance was very low relative to 1990 and restricted to the area south of 70°N. Additionally, Feder *et al.* (1990) identified two distinct benthic communities that change characteristics near 71°N.

YOY Arctic cod were distributed throughout the northeastern Chukchi Sea, with higher concentrations at or near stations where RCW was present. In waters off Greenland (between 69° and 72°N) a high abundance of Arctic cod was noted in the mid 1920's and absence since the mid 1930's (Rass 1968). This decline was attributed to the warmer climate which occurred at that time. These observations suggest that the distribution of arctic cod might change as a result of climatic shifts.

Climatic conditions in the northeastern Chukchi Sea were similar in 1989 and 1990. Winds during July-November were northward, resulting in an eastward displacement of ACW and an increased flushing of RCW from the shelf (Weingartner, Chapter 2). In contrast, during 1991 the winds were predominantly southward limiting the northern extent of ACW and pushing RCW southward.

In summary, we report two significant findings. First, the smallest Arctic cod caught (6.3 mmSL) in mid-July 1991 were the size of newly hatched larvae (5.5 mmSL; Rass 1968). Previous studies state that Arctic cod hatch no later than February in these waters (Matarese 1989). Our data suggests that the time of hatching may extend to mid-July.

Second, our data supports Pruter and Alverson's (1992) hypothesis. To further test this we reexamined an earlier study. In September and October of 1970 a team of scientists conducted a survey of the southeastern Chukchi sea (Websec-70 1972). Using the data reported by Quast (1972) and the temperature and salinity profiles of Ingham and Rutland (1972) reported in this study, we reconstructed the water masses present and YOY distribution. The ACW was present nearshore and to 71°N (Figure 4) while RCW was not present south of 69°30'N. Arctic cod were present at all stations but Bering flounder occurred only at stations south of 69°30'N and were associated with ACW. Water mass characteristics, and distribution of pelagic juvenile fish species indicate that the conditions of 1970 were similar to those in 1989 and 1990.

We conclude that populations of Bering flounder in the northeastern Chukchi Sea are maintained by the transport of larvae in the ACW and the northern limit of Bering flounder is undoubtedly connected to the presence of RCW. Hence, while these fish and others may be routinely advected into the northeastern Chukchi Sea by Alaska Coastal Water, Resident Chukchi Water may be a critical factor in delimiting their northern distribution.

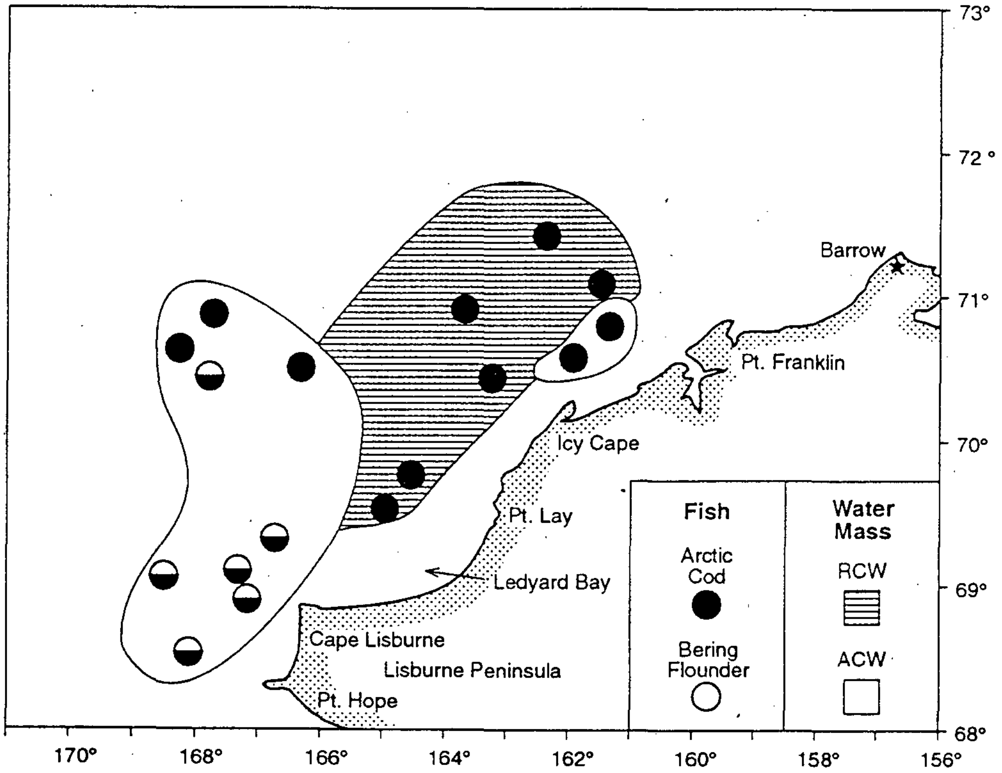

Figure 4. Distribution of Arctic cod and Bering flounder captured with the Isaccs-Kidd mid-water trawl in 1970. Water masses indicated by shading. Based on data from Quast (1972), and Ingham and Rutland (1972).

We conclude that populations of bering flounder in the northeastern Chukchi Sea are maintained by the transport of larvae in the ACW and the northern limit of Bering flounder is undoubtedly connected to the presence of RCW. Hence, while these fish and others may be routinely advected into the northeastern Chukchi Sea by Alaska Coastal Water, Resident Chukchi Water may be a critical factor in delimiting their northern distribution.

ACKNOWLEDGMENTS

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CHAPTER 5

BIOLOGY OF THE ARCTIC STAGHORN SCULPIN, *GYMNOCANTHUS TRICUSPIS*, FROM THE NORTHEASTERN CHUKCHI SEA[1]

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Abstract.—Distribution, abundance, age structure, growth and reproduction were examined for the Arctic staghorn sculpin captured by otter trawl in the northeastern Chukchi Sea, Alaska. High biomass and numbers generally occurred inshore and south of Icy Cape (70°15'N). Mean biomass for 1990 and 1991 were 8.4 and 4.7 kg/km^2, respectively. Highest biomass and abundance values obtained for a station were 67 kg/km^2 and 8050 individuals/km^2, respectively. Both biomass and abundance were variable between years, trawl stations and replicate hauls of a single station. Mean biomass and abundance were significantly higher in 1990 than in 1991.

The oldest female observed was 9 years old; the oldest male was 8. The age structure changed dramatically from 1990 to 1991. In 1990, 42% of the population was $\geq$ 4 years old but in 1991 only 9% was $\geq$ 4 years old. The 1987 year class was virtually missing. After 3 years of age, females grew faster and reached larger size than males.

Both sexes increased gonad indices over the sampling period, achieving mean values of about 6% for males and about 15% for females by late September. The species is dimorphic with respect to pelvic fin length. Considering gonad indices, length of pelvic fins and presence of ova, it appears that males begin to reach maturity at 60-70 mm standard length while first maturity in females occurs at to about 90 mm.

The Arctic staghorn sculpin exhibited interannual variability in distribution, abundance and age structure. This variability suggests that the species is existing in an unpredictable and dynamic habitat that may result in recruitment failures, perhaps mass mortalities and/or dispersal of individuals.

INTRODUCTION

The Arctic staghorn sculpin is a circumpolar member of the family Cottidae inhabiting continental shelves of the Arctic and subarctic oceans (Andryiashev 1954). In the subarctic, it is found in the north Atlantic south to the Gulf of St. Lawrence (Leim and Scott 1966), the Chukchi Sea and the Bering Sea to the Gulf of Anadyr and Nataliya Bay (610°N) (Andryiashev 1954). It is common in the Chukchi and Beaufort Seas (Frost and Lowry 1983) and was one of

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the most abundant fish species caught by benthic trawl in the three years of this study. The purpose of this study was to expand our knowledge of the fish species, ecological interactions of these fishes and oceanographic constraints upon them.

MATERIALS AND METHODS

Fish were captured with a NMFS 83-112 survey otter trawl towed at approximately 2 kts. The trawl had a 25.2 m headrope and a 34.1 m footrope set back 7.1 cm from a tickler chain. The cod end was 90 mm stretched mesh into which a liner of 33 mm stretched mesh was inserted. Each trawl station consisted of two 30 min hauls. Width of the net opening was determined electronically with a Scanmar system incorporating sensor-transmitters attached to the outer wings of the net opening. Area sampled (m^2) was determined by multiplying the width of the net opening by the distance trawled. Distance trawled was determined from the ship's position (latitude and longitude as determined with a Global Positioning System) at the start and end of each haul. Trawl station locations listed in Table 1 are the end locations of the first haul at that station. Biomass (kg/km^2 trawled) and abundance (number of $fish/km^2$ trawled) were calculated by averaging the two 30 min hauls at each station. Mean biomass and abundance values for the two years were compared with a Mann-Whitney U test (Zar 1984).

Table 1.—Station locations sampled in 1990 and 1991 in the northeast Chukchi Sea. Included are depth (m), bottom temperature (°C), bottom salinity (psu), abundance (number/ km^2), and biomass (kg/km^2) of Arctic staghorn sculpin.

Station	Date	Latitud		Longitude		Depth	Bottom	Bottom	Abundanc	Biomass
#	d/m/y	°	'N	°	'W	m	°C	Salinity (psu)	#/km^2	kg/km^2
1	16081990	71	55	168	48	50.4	-1.24	33.31	35.1	1.6
2	17081990	71	33	167	45	46.8			0	0
3	17081990	71	29	167	02	46.8			36.7	1.1
4	17081990	71	09	165	54	41.4			282	4.5
5	18081990	70	48	164	11	45	-0.19	32.21	77.8	2.8
6	21081990	68	23	166	51	18	12.65	29.69	216	3.8
7	21081990	68	28	167	16	45	7.09	30.84	2560	40.1
8	21081990	68	29	168	03	54	2.54	32.59	2240	25.7
9	22081990	68	33	168	45	54	2.11	32.41	1690	37.3
10	22081990	68	39	168	47	52.2	2.09	32.44	756	14.1
11	22081990	68	46	168	42	52.2	2.72	32.06	526	6.7
12	22081990	68	51	167	56	48.6	2.55	32.26	1060	10.8
13	23081990	68	52	167	27	45	5.04	31.71	688	4.6
14	23081990	68	52	166	28	41.4	10.85	29.64	1320	13.4
15	23081990	68	68	166	20	36	10.49	29.78	19.8	0.4
16	24081990	69	69	167	39	46.8	2.75	32.2	155	2.5
17	24081990	69	11	168	22	48.6	3.19	32	371	4.4
18	24081990	69	12	168	50	50.4	2.21	32.33	402	5.4
19	30081990	69	07	164	54	21.6	10.7	29.45	8040	66.6

Table 1. continued

Station	Date	Latitud		Longitude		Depth	Bottom	Bottom	Abundanc	Biomass
#	d/m/y	°	'N	°	'W	m	°C	Salinity (psu)	#/km^2	kg/km^2
20	30081990	69	17	165	41	30.6	8.92	30.34	708	8.9
21	30081990	69	26	166	31	37.8	7.09	32.27	392	5.9
22	31081990	69	38	167	18	45	5.83	31.77	531	4.2
23	06091990	70	22	162	43	30.6	3.5	31.11	379	5.4
24	06091990	70	32	163	21	39.6	2.59	31.74	400	2.2
25	07091990	70	49	160	28	52.2	-0.58	32.58	0	0
26	07091990	70	56	160	53	52.2			0	0
27	07091990	71	09	161	55	46.8	-1.02	32.82	0	0
28	08091990	71	34	163	39	43.2	-1.07	32.99	0	0
29	08091990	71	59	165	22	41.4	1.12	32.26	0	0
30	08091990	72	03	166	48	45	0.81	32.39	12.9	0.6
31	09091990	71	34	164	56	39.6	0.61	32.25	20.5	0.5
32	09091990	71	05	163	20	43.2	0.16	32.27	0	0
33	09091990	70	52	161	39	39.6	2.19	31.68	113.5	7
34	09091990	70	32	161	23	27	3.95	30.95	1250	3.9
35	10091990	69	58	163	15	19.8	5.69	30.35	2070	26.3
36	10091990	69	59	163	32	23.4	5.84	30.33	729	5.4
37	10091990	70	26	164	42	43.2	4.25	31.66	0	0
38	11091990	70	45	165	48	41.4	4.37	31.6	143	3
39	11091990	71	04	167	25	39.6	2.08	32.19	0	0
40	11091990	70	49	168	40	39.6			21.9	1
41	13091990	70	31	167	38	46.6			110	0.9
42	13091990	70	13	166	06	45	5.68	31.84	152	1.1
43	14091990	70	04	164	55	39.6	6.47	31.26	155	1.5
44	14091990	69	48	164	04	28.8	6.91	29.62	1010	7.4
45	14091990	69	39	163	18	14.4			733	13.3
46	14091990	69	33	164	00	48.6	7.52	29.7	3990	42
47	15091990	69	37	164	40	27	7.08	30	879	15.8
48	16091990	69	42	166	11	41.4	6.49	31.44	91	1
90-16	14091991	69	00	167	25	47	1.48	31.82	0	0
90-21	16091991	69	23	166	28	39	4.24	30.99	0	0
90-22OH	16091991	69	38	167	41	47	-0.38	32.66	110	2.5
91-28	17091991	69	46	167	03	47	-1.28	33.18	106	2.4
91-22OH	17091991	69	40	168	31	51	0.39	32.44	283	2.4
91-29	18091991	69	53	167	59	48	0.16	32.44	133	2.1
91-27	18091991	70	01	168	48	40	0.17	32.66	0	0
90-27	19091991	71	12	161	54	46	-1.65	33.3	0	0
90-31	19091991	71	36	160	12	51	-1.72	33.48		
91-32	20091991	71	37	159	02	51	-1.73	33.51	32.6	0.7
91-33	20091991	71	14	158	40	115	-1.59	33.37	0	0
91-34	20091991	71	06	158	38	52	-1.38	33.32	464	7.1
90-23	21091991	70	21	162	53	30	-1.34	33.33	1800	27.5

Table 1. continued

Station	Date	Latitud		Longitude		Depth	Bottom	Bottom	Abundanc	Biomass
#	d/m/y	°	'N	°	'W	m	°C	Salinity (psu)	#/km^2	kg/km^2
91-35	21091991	71	59	159	23	27	-1.47	32.27	0	0
90-36	22091991	70	01	163	27	38	-1.14	32.21	969	13.2
90-43	22091991	69	57	164	53	33	-1.21	33.08	243	1
90-06	23091991	68	26	166	38	18	7.09	29.48	2720	15.9

A total of 255 (1990) and 315 (1991) individual fish were returned to the laboratory for examination. We measured total and standard lengths (mm), total fish weight (g), stomach content weight (g), gonad weight (g) and pelvic fin length (mm). The value for fish weight used in subsequent calculations and ratios was determined by subtracting stomach content weight from total fish weight. Gonosomatic index equaled gonad weight/fish weight x100. We removed and preserved otoliths, ovaries and stomach contents. Analysis of stomach contents is reported by Coyle *et al.* (Chapter 8). Mean lengths and other indices were compared with a t-test; slopes of regressions were compared with another t-statistic (Zar 1984).

Two different techniques were used to evaluate age, surface aging and break and burn. In the surface technique, the annulus on the otolith viewed with transmitted light was defined as the translucent zone. In fishes four years old or younger, this zone could be traced entirely around the otolith. In older fish the zone was incomplete but most easily visible on the rostrum (anterior end). The annulus observed in burnt otolith sections was defined as the dark zone. The surface pattern of annuli on otoliths of 374 fish was read using a dissecting microscope. The ages determined from both techniques were compared for 178 fish and only two did not agree; both differed by one year. Otoliths were measured along their longest axis with an ocular micrometer calibrated with stage micrometer.

Fecundity estimates were determined volumetrically for six of the most mature females. Eggs were separated from ovarian tissue by gently rolling the ovary between thumb and index finger and then carefully rinsing away the extraneous ovarian tissue. The volume of ova was measured in a graduated cylinder; a subsample of 0.5 ml was removed and counted. From this subsample 100 ova were randomly selected and measured along their longest axis.

RESULTS

Distribution and Abundance.—Arctic staghorn sculpin were present at 39 of 48 stations sampled in 1990, however none were collected north of 700°15'N (Icy Cape). Where present, Arctic staghorn sculpin occurred in numbers ranging from 13 to 8050 individuals/km^2 (Figure 1a), and biomass varied from 0.45 to 66.6 kg/km^2 (Figure 1b). Generally, high biomass and numbers occurred inshore and south of Icy Cape. Considerable variability in abundance was observed among stations and also between hauls at the same station. For instance, at several stations one of the two hauls yielded no Arctic staghorn sculpin while the other did. Mean abundance for all 48 stations was 716 ± 1345 individuals/km^2; mean biomass for all 48 stations was 8.4 ± 13.5 kg/km^2.

In 1991 Arctic staghorn sculpin were present at 10 of 17 stations, ranging from 32 to 2,720 individuals/km^2 (Figure 1c) and from 0.7 to 27.5 kg/km^2 (Figure 1d). Again, highest abundances and biomasses were from inshore stations south of Icy Cape. Mean abundance for the 16 stations for which we have data was 429 ± 776 individuals/km^2; mean biomass was 4.7 ± 7.8 kg/km^2. Comparison of abundance and biomass values for the two sample years indicated significantly higher values for 1990 ($p < 0.001$).

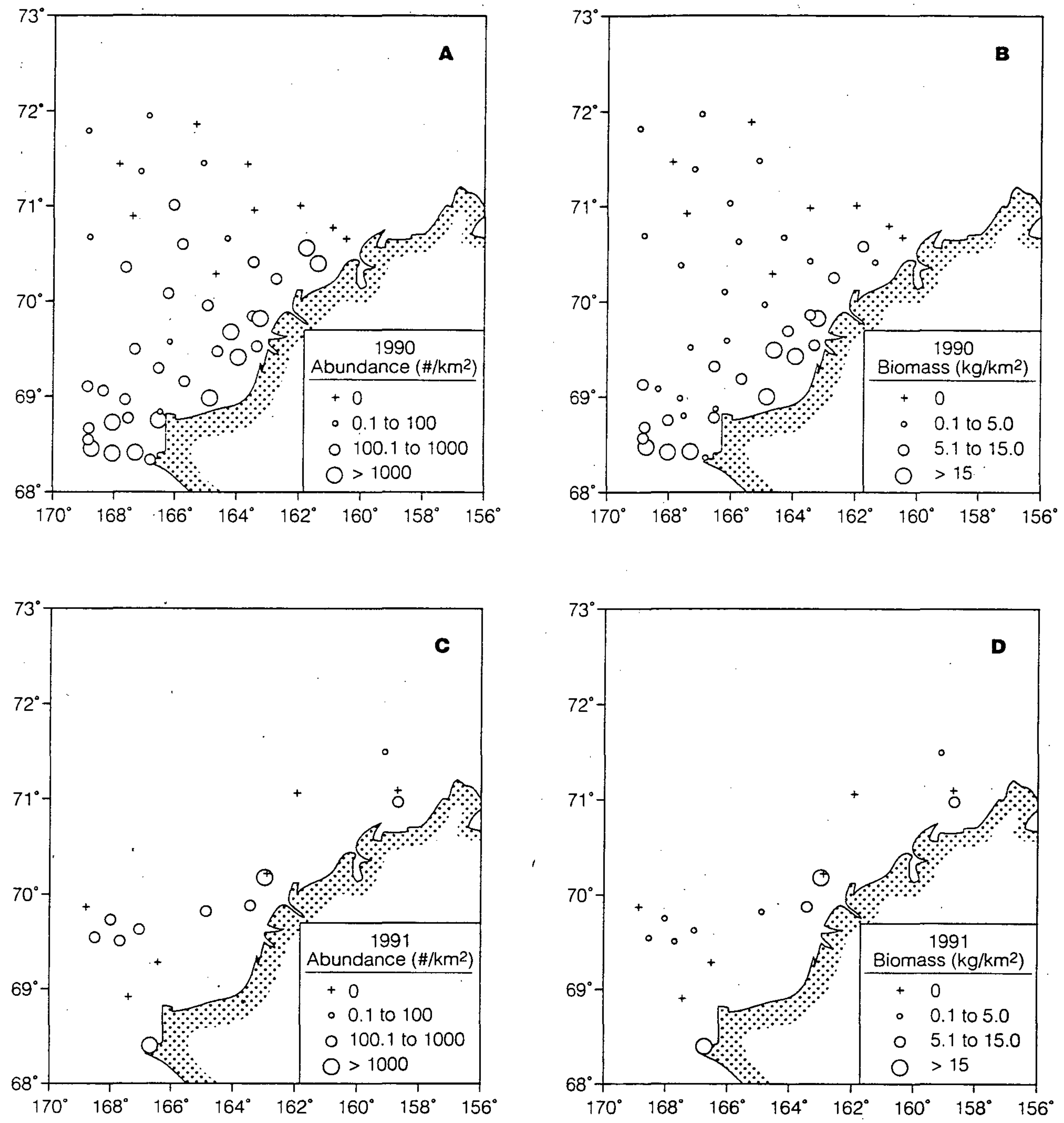


Figure 1. Abundance (numbers of individuals/km^2) and biomass (kg/km^2) of Arctic staghorn sculpin in the northeastern Chukchi Sea. (A) abundance in 1990; (B) biomass in 1990: (C) abundance in 1991; (D) biomass 1991.

Length and Weight Relationships.—Total length was a linear function of standard length for 1990 fish ($r^2 = 0.98$; Table 2). Similarly, otolith length was a linear function of standard length ($r^2 = 0.92$; Table 2).

Table 2.—Functional relationships developed from measurements of Arctic staghorn sculpin in this study.

Y	**X**	**Equation**	**r^2**	**n**
Total Length (mm)	Standard Length (mm)	$y = 1.14x + 2.64$	0.98	274
Otolith Length (mm)	Standard Length (mm)	$y = 0.043x + 0.444$	0.92	102
Weight (g)	Standard Length (mm)	$y = 5.73 \cdot 10^{-6} x^{3.29}$	0.98	274
Mean Length of Females (mm)	Age (y)	$y = 140 (1 - e^{-0.383[x - 0.165]})$		235
Number of Eggs per Gram	Body Weight (g)	$y = -2.02x + 215$	0.85	6
Gonad Weight of August Females (g)	Body Weight (g)	$y = 0.109x - 1.09$	0.87	27
Gonad Weight of August Males (g)	Body Weight (g)	$y = 0.023x - 0.017$	0.37	15
Gonad Weight of September Females (g)	Body Weight (g)	$y = 0.145x - 0.281$	0.91	50
Gonad Weight of September Males (g)	Body Weight (g)	$y = 0.0553x - 0.091$	0.84	40
Pelvic Fin Length of Females (mm)	Standard Length (mm)	$y = 0.224x - 4.92$	0.82	40
Pelvic Fin Length of Males (mm)	Standard Length (mm)	$y = 0.265x - 5.15$	0.68	39

Rearranging the linear equation allows prediction of fish length (x) based on otolith length (y). A standard length-weight regression calculated for all fish sampled in 1990 conformed to a power curve ($r^2 = 0.98$; Table 2).

Age Structure.—Maximum longevity among the 374 individuals examined from 1990 and 1991 was 9 years for females and 8 years for males. For 1990 the oldest females and males were 8 years old. In 1991 the oldest female was 9 years; the oldest males were only 3 years old.

Overall, the age structure of the population in the northeastern Chukchi Sea differed markedly in 1990 and 1991 (Figure 2; Table 3). In 1990 41.6% of the population consisted of fish ≥ 4 years old; 4.4% were ≥ 6 years old. In contrast, in 1991 only 8.9% of the population was ≥ 4 years old; only 1.4% was 6 years old. Of 148 individuals aged from 1991 only three were 4 year old fish. Among the 216 individuals aged from 1990 only five were 3 years old. Of 148 individuals aged from 1991 only three were 4 years old fish.

Table 3.—Mean length (mm) at age of Arctic staghorn sculpin in southern and northern regions of the study area in 1990 and 1991.

		Age										Mean		
	Area	0	1	2	3	4	5	6	7	8	9	Size	Age	N
						1990								
	Southern	—	—	76±10.8	80	107±10.8	119±8.7	122±9.3	140	118	—	108.1	4.18	
Female		0	0	4	4	1	32	6	5	1	1	0		50
	Northern	33	47±5.2	61±5.7	82±2.9	104±10.1	112±5.2	0	131±13.4	136±0.7	—	81.0	2.94	
		1	32	10	2	39	7	0	2	2	0			95
	Southern	—	54±8.5	67±3.8	80±7.1	92±7.9	92±0.0	101.0	—	—	—	77.2	2.86	
Male		0	7	14	3	15	2	1	0	0	0			42
	Northern	—	45±1.5	65±10.8	0	85±1.1	94±5.7	—	—	100	—	65.8	2.36	
		0	9	23	0	6	2	0	0	1	0			41
						1991								
	Southern	—	—	64±4.8	82±8.9	—	—	—	—	—	—	68.0	2.22	
Female		0	0	39	11	0	0	0	0	0	0			50
	Northern	—	—	57±5	72±11.1	100±7.0	115±7.2	—	—	—	133±0.7	84.8	3.66	
		0	0	9	11	3	8	0	0	0	2			33
	Southern	—	—	62±4.5	77±4.2	—	—	—	—	—	—	63.3	2.06	
Male		0	0	47	3	0	0	0	0	0	0			50
	Northern	—	—	60±4.9	69±3.7	—	—	—	—	—	—	63.8	2.46	
		0	0	7	6	0	0	0	0	0	0			13 374

Mean lengths at age were calculated for fishes from the northern and southern parts of the study area for 1990. The only significant difference observed was in age 2 females; southern fish were larger ($t = 5.27$; $p < 0.001$). Comparing mean length at age of age classes in the southern part of the study area from 1990 and 1991 (Table 3) showed significantly larger fish ($p < 0.001$) in 1990 in both age 2 females ($t = 4.91$) and age 2 males ($t = 4.22$). No such difference was found in length at age for any age class in the northern part of the study area. Comparing growth rates of the two sexes (both areas and both years combined) we found that males and females grow at the same rate in the first three years. By the end of the fourth year, however, females were significantly larger (Table 4). Von Bertalanffy growth curves were calculated and fitted to the combined mean length at age data (Figure 3; Table 2).

Reproductive Biology.—Fecundity, based on egg counts of only six females, ranged from 3030 to 5414 eggs in fish ranging from 112 to 134 mm standard length (25.6 to 57.4 g body weight). Fecundity as a function of body weight resulted in a linear equation exhibiting a poor fit of the data ($F = 4.5$; $r^2 = 0.53$). These fecundity values equate to 154 to 91 eggs/g of carcass weight (total weight-stomach contents weight-gonad weight), respectively. When number of eggs/g is plotted against body weight a linear regression with negative slope results (Table 2).

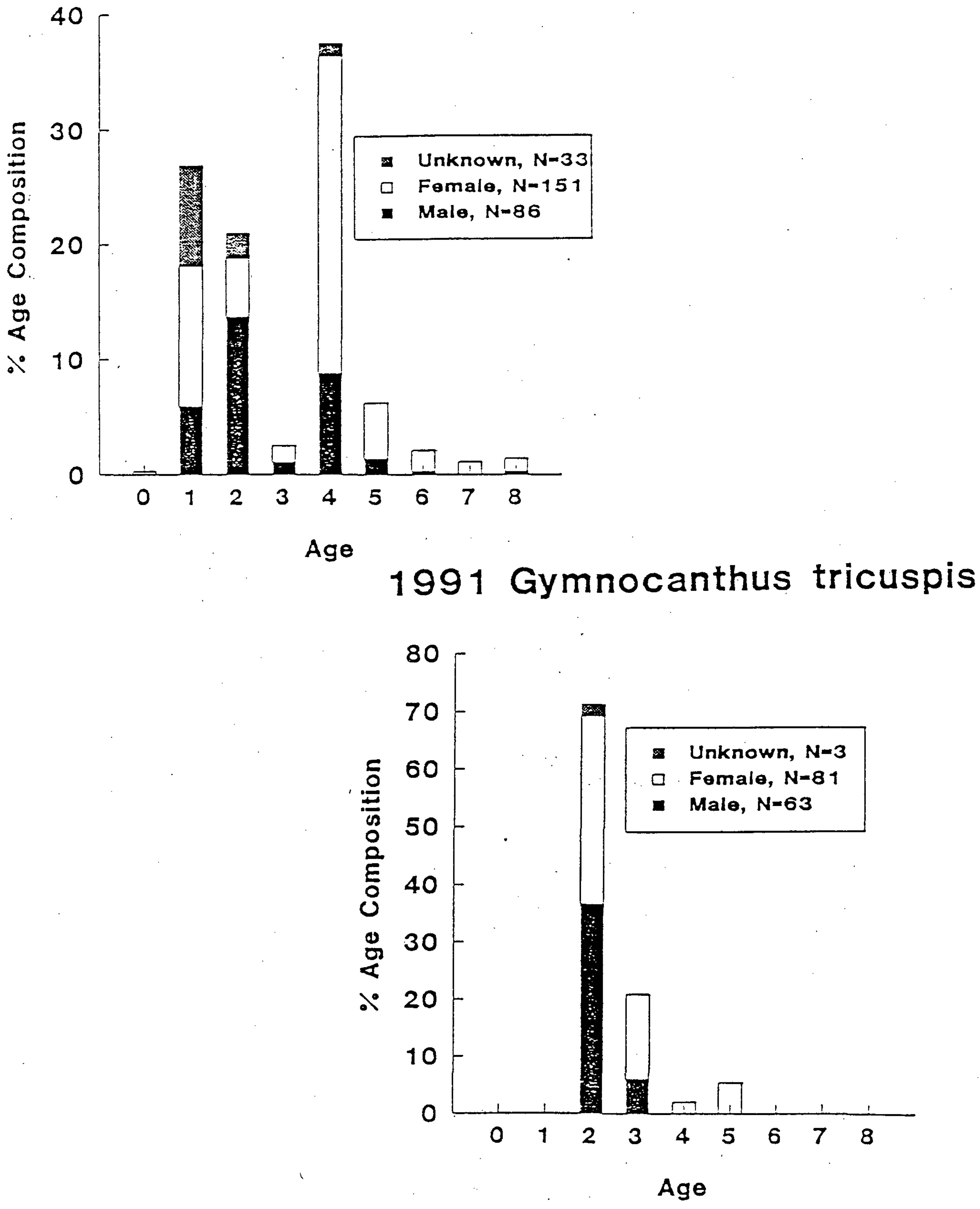
Table 4.—Mean standard length (mm) at age for Arctic staghorn sculpin from the northeast Chukchi sea, 1990 and 1991 data combined. Values are mean length in mm ± one standard error. Numbers in parentheses are sample sizes for the different age classes.

Age	0	1	2	3	4	5	6	7	8	9
M		49±1.8 (16)	64±0.8 (91)	74±1.8 (12)	88±1.6 (24)	93±1.7 (4)	101 (1)		100 (1)	
F	33	48±0.9 (1)	63±0.8 (33)	78±2.0 (62)	105±1.2 (26)	115±1.6 (78)	122±4.2 (21)	134±6.3 (5)	130±6.2 (3)	134±0.5 (2)

When gonosomatic index was examined in relation to standard length for all 1990 Arctic staghorn sculpin there was wide variation in gonad development for a particular size interval of fish. Gonad indices for males ranged from 0 to about 7%. The range for females was 0 to19%. Body weight-gonad weight relationships were developed for both sexes at 1990 Stations 10 and 35 to try to assess whether collection date was a possible influence on gonosomatic variation. At Station 10, sampled on 22 August, there were significant relationships for both males and females (Table 2). Gonad-body weight relationships at Station 35, sampled 10 September, are presented in Table 2. The slopes of female relationships from the two sample dates were significantly different ($t = 5.32$; $p < 0.001$); and so were the slopes of male relationships ($t = 6.97$; $p < 0.001$). Males and females of this species are divergent not only in growth rate and longevity but also in pelvic fin development (Figure 4). Males have proportionally longer pelvic fins and in mature fish, these fins are banded in coloration. Plotting pelvic fin length versus standard length for each sex yielded linear regressions (Table 2). These regressions differ significantly in slope ($t = 5.94$; $p < 0.001$). The regression lines begin to diverge at about 60 mm SL and are quite distinct at lengths above 70 mm SL. This suggests that sexual maturity in males occurs at lengths from about 60 to 70 mm SL. The data relating gonad index to SL indicates that some males as small as 60-70 mm have gonads as large as 6-7% of the body weight, among the maximum values obtained in this study.

DISCUSSION

Distribution and Abundance.—Distribution of Arctic staghorn sculpin over the study area was not uniform. Replicate trawl hauls at the same location did not necessarily agree on the abundance or even the presence of this species. We were unable to discern bottom type directly at trawl stations and, therefore, could not correlate abundance or presence with bottom type. However, Andriyashev (1954) reported this species burrowed in sandy or sandy-muddy bottoms, was often present on pebbly bottoms and was rarely encountered on mud or clay bottoms. Plotting the 1990 station locations at which Arctic staghorn sculpin was absent on the map of sediment classes for the northeast Chukchi Sea (Feder *et al.* 1989; Figure 3) revealed that three of the stations were over mud bottom, five over gravelly mud and one over gravelly sand. This suggests that much of the variation in abundance of this species may be explicable based on the



1991 Gymnocanthus tricuspis

Figure 2. Population age structure of Arctic staghorn sculpin in the northeast Chukchi Sea: upper panel, all 1990 data combined; lower panel, all 1991 data combined.

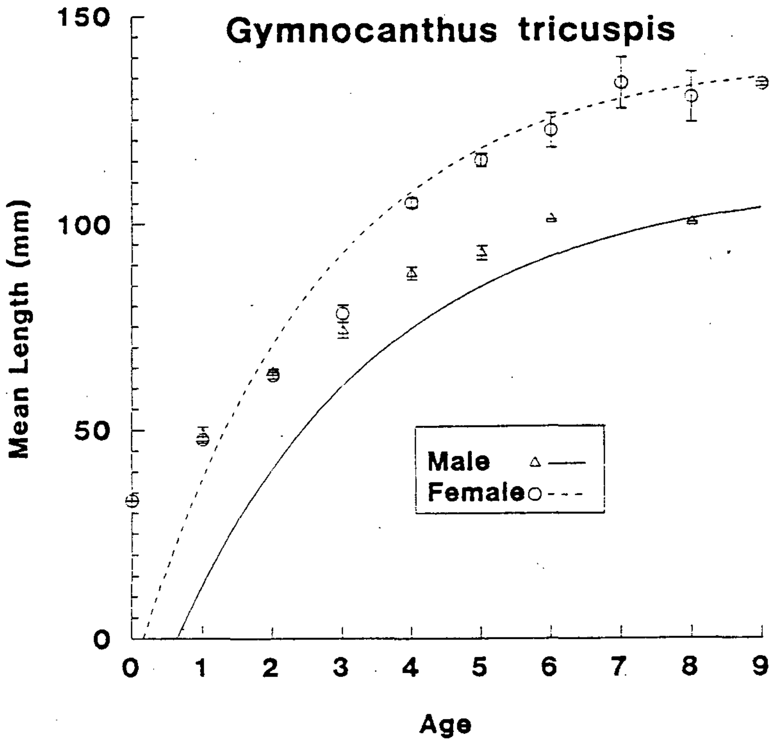


Figure 3. Mean length at age and von Bertalanffy equations for male and female Arctic staghorn sculpin from the northeast Chukchi Sea (1990 and 1991 length at age combined). The equation for females is: $y = 140\ (1 - e^{-0.38[x - 0.165]})$; the equation for males is: $y = 110\ (1 - e^{-0.338[x - 0.161]})$.

broad scale and local distribution of sediment types in the Chukchi Sea. Over its entire geographic range, Arctic staghorn sculpin tolerates considerable temperature (-1.7 to +12.5°C) and salinity (16-35 psu) ranges but is primarily a species inhabiting temperatures of below or close to 0°C and salinities of 32-35 psu (Andriyashev 1954).

Our mean biomass values can be compared to those of Wolotira *et al.* (1977) since they also used the 83-112 trawl with the same codend liner, towed at approximately the same speeds. They reported biomasses of 3.5 kg/km^2 in the southeast Chukchi, 2.9 kg/km^2 in Kotzebue Sound and 8.2 kg/km^2 in the northern Bering Sea north of St. Lawrence Island. Our biomasses of 8.4 and 4.7 kg/km^2 for the northeastern Chukchi Sea for 1990 and 1991, respectively, are similar in magnitude.

Age and Length Relationships.—Arctic staghorn sculpin, with a maximum age of 9 years, appears to be shorter-lived than its congeners. Tokranov (1988) found maximum ages of *G. pistilliger* and *G. galeatus* from the coast of Kamchatka to be 11 and 13 years for males and females, respectively. Three year old fish were very scarce in 1990 and 4 year old fish were scarce in 1991 suggesting that the 1987 class had very poor recruitment success. Because the stations from which fish were aged ranged from the extreme southern boundary of the study area to far to the northeast, this possible recruitment failure was widespread and could have resulted from a large-scale perturbation in the environment. Further, the marked difference in age distributions of Arctic staghorn sculpin in the two sample years suggests that variation in the physical environment may result in recruitment failures or mass mortality in this species.

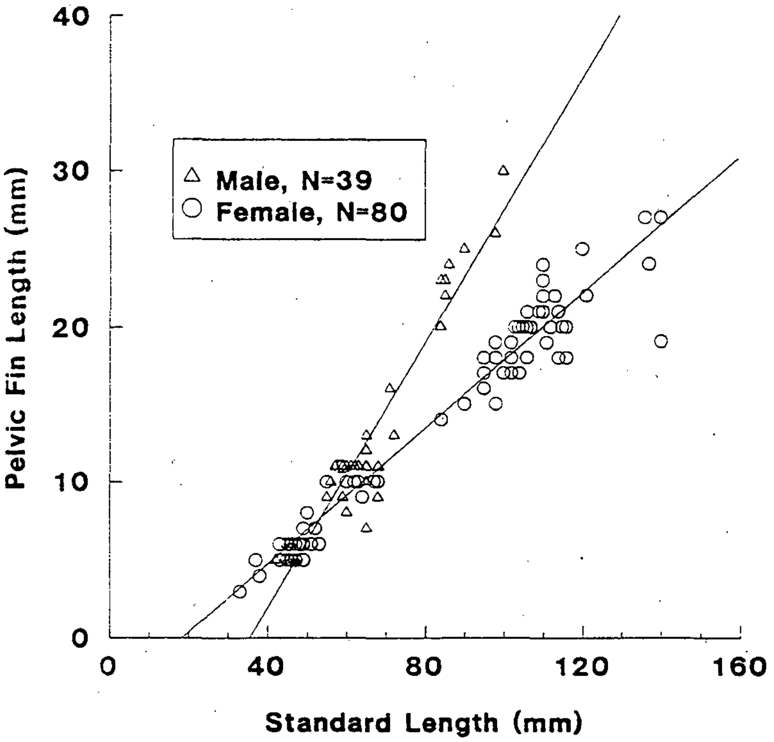


Figure 4. Pelvic fin length as a function of standard length in Arctic staghorn sculpin from the northeast Chukchi Sea.

Males and females grow at similar rates for the first three years. Beyond 3 years, females grow faster and, ultimately, much larger. Mean length at age in males plateaus at about 110 mm SL; females at about 140 mm SL. Data for Arctic staghorn sculpin from the Laptev Sea (Andriyashev 1954) supports the disparity in growth rates of the different sexes we report beyond 3 years. Adjusting Andriyashev's (1954) total lengths to standard lengths produces mean length at age data almost identical to those reported in Table 4, above.

The largest specimens of Arctic staghorn sculpin, 300 mm TL, came from the western coast of Greenland (Andriyashev 1954). The population off Greenland must find conditions for growth much more favorable than populations in the Chukchi and Laptev Seas.

Reproductive Biology.—The scatter of gonosomatic indices exhibited in our specimens probably resulted from pooling fish caught over a one month period during which gonadal development was occurring rapidly. This possibility is supported by the significant differences in slopes of both female and male gonad weight to body weight regressions. These slopes represent gonad indices. Another factor that may contribute to the wide variance in pooled indices is that not all individuals spawn yearly.

In comparison to those from station 10, the ovaries of females at Station 35 appeared to be more mature and contained well developed ova. Based on the slopes of these regressions, one could infer that gonad weight increased from about 2% to 5% of body weight in males and from about 11% to 15% of body weight in females during the month of August. We conclude that the sampling date (10/9/90) at Station 35 was nearer the spawning period for this population.

Based on gonad indices and sexual dimorphism in the pelvic fin of Arctic staghorn sculpin (Figure 4) it appears that males become sexually mature at lengths of 60-70 mm SL, corresponding to ages 2 and 3. Andryiashev (1954) indicated that sexual maturity is attained, apparently, toward the fourth year of life. Dimorphism in pelvic fin length in Arctic staghorn sculpin was also reported by Backus (1957). However, based on data in Backus (1957; Figure 2) no clear divergence of male and female pelvic fin lengths appears until standard lengths of about 120 mm.

Our female gonosomatic indices suggest that the onset of maturity (as indicated by GSI values of 10% or higher) occurs at lengths of about 90 mm SL, corresponding to ages 3 and 4 (Table 2). These values agree with Andryiashev (1954) and are similar to those reported by Tokranov (1981) for *G. detrisus* in Kamchatka waters. Tokranov (1981) reported first maturity at ages 3 and 4 and lengths of 18-22 cm. All males were mature in their fifth year (22-24 cm); all females in their sixth year (24-26 cm).

G. detrisus spawns in December and January in Kamchatka waters when ovary weights amount to 17-24% of body weight. The September ovary indices exhibited by Arctic staghorn sculpin (15% of body weight) are approaching the spawning values for *G. detrisus*. Further, Andryiashev (1954) reported female Arctic staghorn sculpin from the Kara and White Seas with ripe eggs in the second half of September. Absolute fecundities in this study (3,030-5,414) are similar to those reported for Arctic staghorn sculpin by Andryiashev (1954) (2,060 to 3,512 for females of 117 to 158 mm) but lower than the 6,100-72,000/female reported for *G. detrisus* (Tokranov 1981). The lower fecundity values are undoubtedly due to the size difference between Arctic staghorn sculpin and *G. detrisus*. Relative fecundity in Arctic staghorn sculpin ranged from 91-154 eggs/g (this study); *G. detrisus* produces 40-225 eggs/g (Tokranov 1981).

Food Webs.—The Arctic staghorn sculpin was found as prey in Arctic cod and Bering flounder in this research project (Coyle *et al.* Chapter 8). It also is prey to Atlantic cod in eastern Arctic Canada (Dunbar and Hildebrand 1952) and to an eelpout, *Lycodes turneri*, at Point Barrow (Walters 1955). Based on the occurrence of pelagic larvae of this species in spring and early summer (Pertseva, cited in Andriyashev 1954), *G. tricuspis* is susceptible to planktotrophic predators during this season. Young of the year recruit to the benthic habitat in late summer (Andriyashev 1954) and, at that time, become available as prey to benthophages.

Sculpins, perhaps including Arctic staghorn sculpin, are an occasional prey of ringed seals in the Chukchi Sea (Lowry *et al.* 1980). Bearded seals also prey on sculpins incidentally but primarily feed on benthic crustaceans and clams (Lowry and Frost 1981) including some of the same genera as are found in the diet of Arctic staghorn sculpin. Gray whales and, to a lesser extent, bowhead whales feed on benthic amphipods in the Chukchi Sea (Frost and Lowry 1981) and, therefore, share a food resource with the Arctic staghorn sculpin.

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CHAPTER 6

BIOLOGY OF THE BERING FLOUNDER, *HIPPOGLOSSOIDES ROBUSTUS*, FROM THE NORTHEASTERN CHUKCHI SEA[1]

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Abstract—Biomass, abundance, distribution, growth and age structure were determined for Bering flounder, *Hippoglossoides robustus*, collected by benthic trawl in 1990 and 1991. Both biomass and abundance were dramatically different in the two years of this study. Mean biomass declined significantly from 17.2 kg/km^2 in 1990 to 0.79 kg/km^2 in 1991. Our data plus historical information on species abundance and age distribution in the Chukchi Sea suggest that this species is subjected to an unstable physical environment that may cause either mass mortalities, recruitment failures or both. This possibility is consistent with the difference in growth rates from the 1950's and the 1980's and is consistent with recent data on interannual variability in wind and current directions and larval abundance.

Examination of length-weight and age-length relationships indicated that females, beyond the third year, grew faster and larger than males. L_∞ values for males and females were 211 mm and 241 mm (TL), respectively. Maximum age in this study was 11 years.

INTRODUCTION

This paper is part of a fisheries and oceanographic study of the northeastern Chukchi Sea. The purpose of this study was to expand our knowledge of the fish species, ecological interactions of these fishes and oceanographic constraints upon them. The Bering flounder, *Hippoglossoides robustus*, was the most common flatfish captured in benthic trawls in the study area during 1990 and 1991. In this paper we report on the distribution, abundance, length-weight and age relationships and make other inferences about the life history of this species.

The Bering flounder differs from its close relative the flathead sole, *Hippoglossoides elassodon*, in several anatomical characteristics. In addition to having a more markedly curved lateral line and a wider interorbital space, the Bering flounder has lower dorsal and anal fin ray counts (D 67-79; A 51-60) than the flathead sole (D 76-86; A 60-69) (Shmidt 1950, Andriyashev 1954). The geographic ranges of these two species overlap considerably. The flathead sole occurs from northern California, through the Gulf of Alaska, across the Bering Sea and southward to Japan (Hart 1973). The Bering flounder is much more restricted in its distribution, occurring from Tatar Strait to the Chukchi Sea and extending through the Bering Sea to the Aleutian

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[1] Submitted for publication in Fish Ecology in Arctic North America.

Islands (Quast and Hall 1972). In the area of overlap it is unclear whether interbreeding occurs or to what extent niche specialization has led to reduced competition between these two very similar forms.

The Bering flounder falls prey to Arctic cod (Coyle *et al.* Chapter 8) and to several marine mammals including white whales (Frost and Lowry 1981) and bearded seals (Lowry and Frost 1981). Pruter and Alverson (1962) found the Bering flounder to be the most abundant flatfish in the southeast Chukchi Sea, most frequently occurring at depths ≥ 44 m. Moiseev (1953) found that the Bering flounder occurs in greater abundance at subzero temperatures than at temperatures above 0°C. Although present in the Chukchi Sea in August of 1959, the Bering flounder occurred at extremely low population densities (Pruter and Alverson 1962).

MATERIALS AND METHODS

Fish were captured from 16 August through 16 September, 1990 and from 14 September through 23 September, 1991. A NMFS 83-112 survey otter trawl was towed at approximately 2 kts. The net had a 24.2 m headrope, 34.1 m footrope set back 7.1 cm from a tickler chain. The cod end was 90 mm stretched mesh into which a liner of 33 mm stretched mesh was inserted. Each trawl station consisted of two 30 min hauls. Area sampled (m^2) was calculated by multiplying the width of the net opening by the distance trawled. In 1990 the opening of the net was verified by use of a Scanmar mensuration unit attached to the wings of the net. Distance trawled was determined from the ship's position (latitude and longitude) at the start and end of each haul. Trawl station locations listed in Table 1 are the end locations of the first haul at that station. Biomass (kg/km^2 trawled) and abundance (number of fish/km^2) were calculated by averaging the two 30 min hauls at each station (Table 1). Mean biomass and abundance values for the two years were compared with a Mann-Whitney U test (Zar 1984).

Table 1.—Trawl station locations, depths, bottom temperatures, abundances and biomasses of Bering flounder for the 1990 and 1991 sample periods.

Station	Date	Latitude		Longitude		Depth	Bottom	Bottom	Abundance	Biomass
#	d/m/y	°	'N	°	'W	m	°C	Salinity (psu)	#/km^2	kg/km^2
1	16081990	71	55	168	48	50.4	-1.24	33.31	35.1	1.1
2	17081990	71	33	167	45	46.8			67.5	2.6
3	17081990	71	29	167	02	46.8			208.	3.9
4	17081990	71	09	165	54	41.4			36.8	0.6
5	18081990	70	48	164	11	45	-0.19	32.21	15.6	0.7
6	21081990	68	23	166	51	18	12.65	29.69	0.	0.
7	21081990	68	68	167	16	45	7.09	30.84	793.	27.7
8	21081990	68	29	168	03	54	2.54	32.59	2010.	66.7
9	22081990	68	33	168	45	54	2.11	32.41	6430.	223.8
10	22081990	68	39	168	47	52.2	2.09	32.44	3280.	126.9
11	22081990	68	46	168	42	52.2	2.72	32.06	1690.	66.7
12	22081990	68	51	167	56	48.6	2.55	32.26	953.	36.8
13	23081990	68	52	167	27	45	5.04	31.71	1100.	43.5
14	23081990	68	52	166	28	41.4	10.85	29.64	147.	6.7

Table 1. continued

Station #	Date d/m/y	Latitude °	'N	Longitude °	'W	Depth m	Bottom °C	Bottom Salinity (psu)	Abundance #/km^2	Biomass kg/km^2
15	23081990	68	58	166	20	36	10.49	29.78	19.8	1.3
16	24081990	69	06	167	39	46.8	2.75	32.21	1100.	42.9
17	24081990	69	11	168	22	48.6	3.19		2330.	70.7
18	24081990	69	12	168	50	50.4	2.21	32.33	1820.	66.1
19	30081990	69	07	164	54	21.6	10.7	29.45	37.7	1.8
20	30081990	69	17	165	41	30.6	8.92	30.34	48.9	2.2
21	30081990	69	26	166	31	37.8	7.09	31.27	235.	9.5
22	31081990	69	38	167	18	45	5.83	31.77	254.	6.3
23	06091990	70	22	162	43	30.6	3.5	31.11	0.	0.
24	06091990	70	32	163	21	39.6	2.59	31.74	0.	0.
25	07091990	70	49	160	28	52.2	-0.58	32.58	0.	0.
26	07091990	70	56	160	53	52.2			0.	0.
27	07091990	71	09	161	55	46.8	-1.02	32.82	0.	0.
28	08091990	71	34	163	39	43.2	-1.07	32.99	0.	0.
29	08091990	71	59	165	22	41.4	1.12	32.26	0.	0.
30	08091990	72	03	166	48	45	0.81	32.39	13.	0.6
31	09091990	71	34	164	56	39.6	0.61	32.25	0.	0.
32	09091990	71	05	163	20	43.2	0.16	32.27	0.	0.
33	09091990	70	42	161	39	39.6	2.19	31.68	0.	0.
34	09091990	70	32	161	23	27	3.95	30.95	0.	0.
35	10091990	69	58	163	15	19.8	5.69	30.35	0.	0.
36	10091990	69	59	163	32	23.4	5.84	30.33	0.	0.
37	10091990	70	26	164	42	43.2	4.25	31.66	0.	0.
38	11091990	70	45	165	48	41.4	4.37	31.64	44.3	0.5
39	11091990	71	04	167	25	39.6	2.08	32.19	11.9	0.5
40	11091990	70	49	168	40	39.6			11.	1.
41	13091990	70	31	167	38	46.6			60.	0.9
42	13091990	70	13	166	06	45	5.68	31.84	58.7	1.1
43	14091990	70	04	164	55	39.6	6.47	31.26	66.5	2.
44	14091990	69	48	164	04	28.8	6.91	29.62	21.8	1.
45	14091990	69	39	163	18	14.4		32.60	32.6	0.7
46	14091990	69	33	164	00	48.6	7.52	29.71	11.	0.5
47	15091990	69	37	164	40	27	7.08		0.	0.
48	16091990	69	42	166	11	41.4	6.49	31.44	182.	7.7
90-16	14091991	69	00	167	25	47	1.48	31.82	0.	0.
90-21	16091991	69	23	166	28	39	4.24	30.99	0.	0.
90-22OH	16091991	69	38	167	41	47	-0.38		12.3	0.6
91-28	17091991	69	46	167	03	47	-1.28	33.18	11.9	0.5
91-22OH	17091991	69	40	168	31	51	0.39	50.39	70.8	1.6
91-29	18091991	69	53	167	59	48	0.16	32.44	0.	0.
91-27	18091991	70	01	168	48	40	0.17	32.66	99.9	4.6
90-27	19091991	71	12	161	54	46	-1.65	33.30	0.	0.
90-31	19091991	71	36	160	12	51	-1.72	33.48		
91-32	20091991	71	37	159	02	51	-1.73	33.51	32.6	0.7

Table 1. continued

Station	Date	Latitude		Longitude		Depth	Bottom	Bottom	Abundance	Biomass
#	d/m/y	°	'N	°	'W	m	°C	Salinity (psu)	#/km^2	kg/km^2
91-33	20091991	71	14	158	40	115.	-1.59	33.37	0.	0.
91-34	20091991	71	06	158	38	52	-1.38	33.32	0.	0.
90-23	21091991	70	21	162	53	30	-1.34	33.33	0.	0.
91-35	21091991	71	59	159	23	27	-1.47	33.27	0.	0.
90-36	22091991	70	01	163	27	38	-1.14	33.21	33.4	0.1
90-43	22091991	69	57	164	53	33	-1.21	33.08	88.6	0.3
90-06	23091991	68	26	166	38	18	7.09	29.48	23.5	4.3

A total of 232 individual fish were returned to the laboratory and examined. Initial laboratory data collection included measurement of fish total and standard lengths (mm), fish weight (g), stomach content weight (g), gonad weight (g) and the preservation of otoliths, stomach contents and ovaries. The value for fish weight used in subsequent calculations and ratios was determined by subtracting stomach content weight from total weight. Gonosomatic index equaled gonad weight/fish weight x100.

The annulus on the otolith viewed with transmitted light was defined as the thin, translucent zone. In fishes four years old or younger, this zone could be traced entirely around the otolith. In older fish the zone was incomplete but most easily visible on the rostrum (anterior end). The annulus observed in burnt sections of otoliths was defined as the dark zone. The surface pattern of annuli on otoliths of 125 fish was read using a dissecting microscope. Otoliths were measured with an ocular micrometer calibrated with a stage micrometer.

RESULTS

Distribution and Abundance in Study Area—Bering flounder occurred at 32 of 48 stations sampled in 1990 and eight of 16 stations sampled in 1991 (Figure 1). Nineteen of the 24 stations at which the Bering flounder was missing were north of 70°N. The northernmost point in distribution in this study was above 72°N (1990 Station 30) and the easternmost point was 159°W (1991 Station 90-32). Where present, Bering flounder abundance ranged from 11 to 6436 individuals/km^2 (Table 1). Biomass ranged from 0.1 to 223 kg/km^2 (Table 1). The 1990 data (Figures 1a and 1b) show that, generally, highest biomass and numbers of Bering flounder occurred in the southernmost part of the study area (south of 69°30'N and west of 167°W).

Considerable variability in abundance was observed among stations and also between hauls at the same station. For instance, at several stations one of the two hauls yielded no Bering flounder while the other did. Replicate hauls at the same station differed up to fifteen fold in biomass (1990 Station 21) and up to threefold (1990 Station 14) in abundance. Our mean abundance estimates for all stations sampled in 1990 and 1991 (995 and 429 individuals/km^2, respectively) differed significantly ($U = 785$; $p < 0.001$). Similarly, 1990 and 1991 mean biomass estimates (17.2 and 0.79 kg/km^2, respectively) also differed significantly ($U = 825$; $p < 0.001$). Eight stations were sampled in both field seasons. Mean abundance and biomass at these stations in 1990 (207 individuals/km^2; 7.6 kg/km^2, respectively) were significantly higher ($U = 85$; $p < 0.001$) than the estimates for 1991 (19.7/km^2; 0.66 kg/km^2, respectively). This reduced abundance and biomass in 1991 was associated with significantly lower temperatures in 1991. Comparing the eight stations common to both years we found mean bottom temperatures of 5.4 and 0.9°C, respectively ($U = 54$; $p < 0.05$).

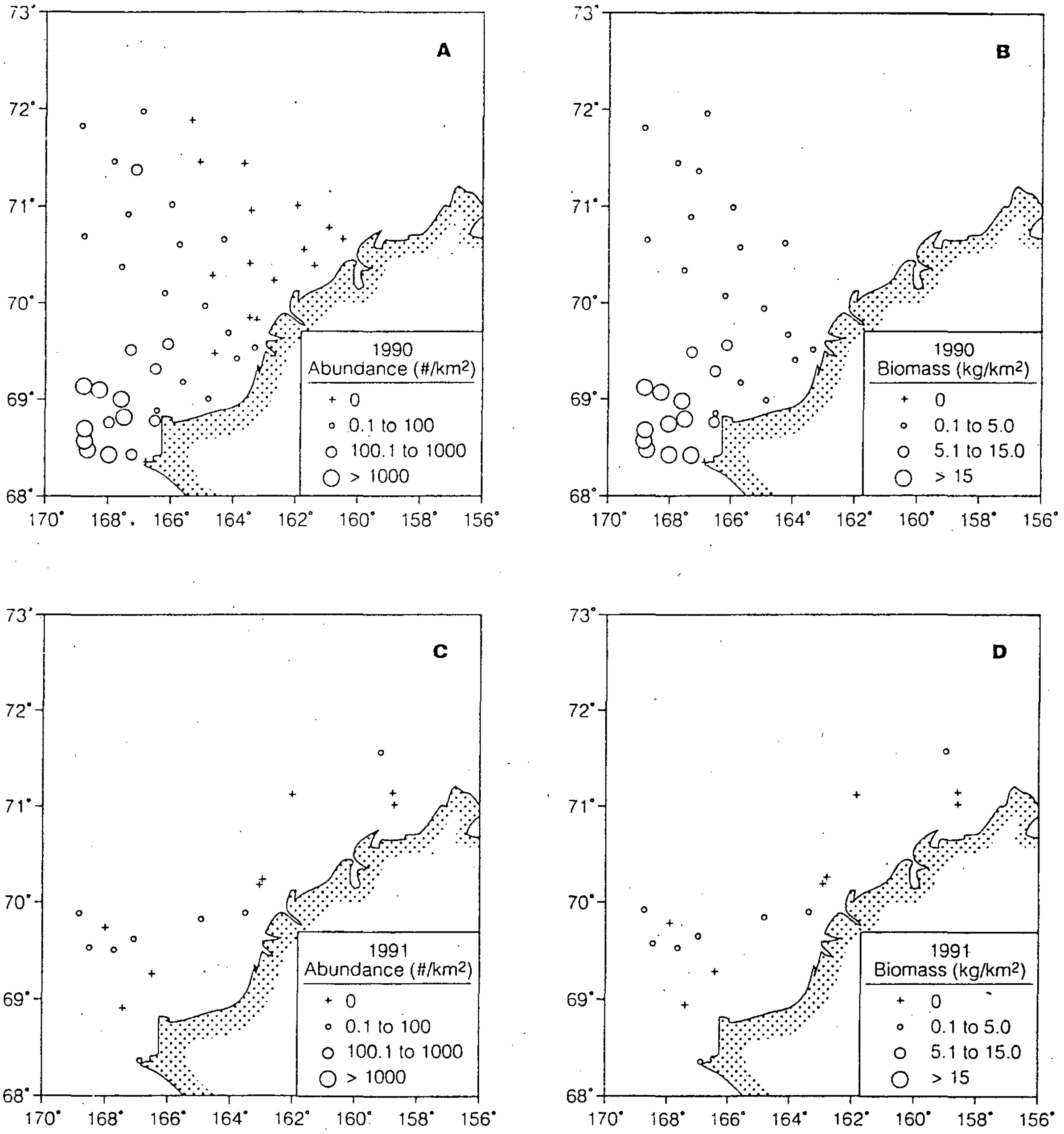

Figure 1. Abundance (numbers of individuals/km^2) and biomass (kg/km^2) of Bering flounder in the northeastern Chukchi Sea. (A) abundance in 1990; (B) biomass in 1990; (C) abundance in 1991; (D) biomass in 1991.

Otolith, Length and Weight Relationships—Both total length and otolith lengths were linear functions of standard length in Bering flounder (Table 2). Rearranging the equation representing otolith length versus fish standard length allows the prediction of fish length (x) based on otolith length (y): $x = (y - 0.383)/0.026$. Weight was found to be a power function of fish standard length (Table 2).

Age and Growth—Maximum longevity among the 125 individuals examined in this study was 11 years for females and 8 years for males (Figure 2). About 75% of the population consisted of fish $\geq$ 5 years old.

Table 2.—Functional relationships developed from measurements of Bering flounder in this study. Coefficients of determination (r^2) and sample sizes for each relationship are included.

Y	X	Equation	r^2	n
Total Length (mm)	Standard Length (mm)	$y = 1.15x + 4.24$	0.99	126
Otolith Length (mm)	Standard Length (mm)	$y = 0.026x + 0.383$	0.92	135
Weight (g)	Standard Length (mm)	$y = 4.89 \cdot 10^{-6}\ x^{3.25}$	0.99	135
Mean Length of Females (mm)	Age (y)	$y = 206\ (1 - e^{-0.215[x - 0.009]})$		67
Mean Length of Males (mm)	Age (y)	$y = 180\ (1 - e^{-0.230[x - 0.185]})$		58
Gonosomatic index of Females (% body wt.)	Standard Length (mm)	$y = 2.37 \cdot 10^{-7\ x\ 3.20}$	0.84	69

Mean lengths at age were calculated for fishes from the study area. These mean lengths suggest that in the first three years males and females grow at the same rate. By the end of the fourth year, however, females appear to be significantly larger (Table 3).

Table 3.—Mean length (mm) at age of male and female Bering flounder from 1990.

Age	1	2	3	4	5	6	7	8
males	48 (1)	77±2.9 (4)	95±2.9 (10)	106±2.0 (6)	122±3.1 (30)	122±4.4 (4)	-	157±6.5 (3)
females	-	80±3.0 (3)	98±2.6 (6)	116 (1)	135±2.0 (29)	143±3.1 (11)	154 (1)	175±3.4 (16)

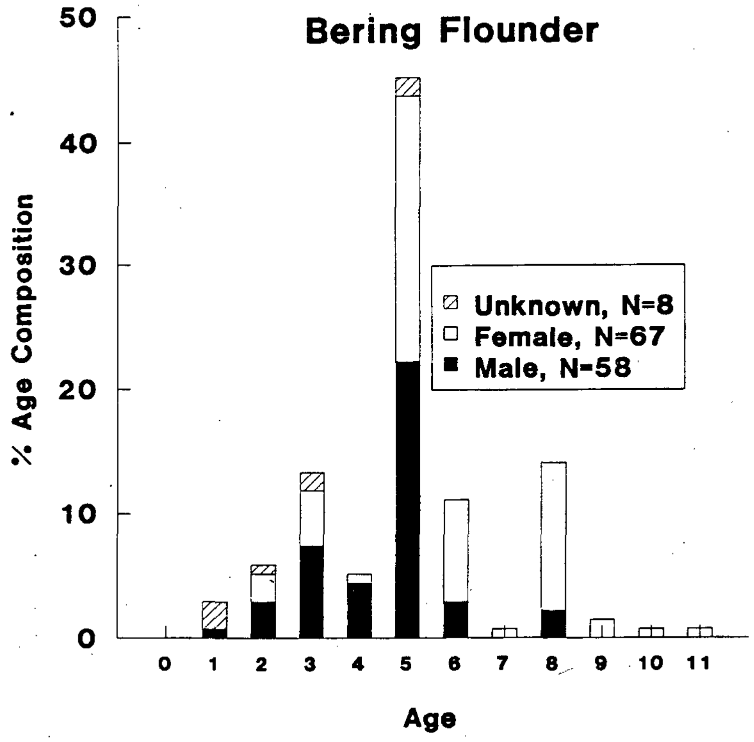

Figure 2. Population age structure of Bering flounder in the northeast Chukchi Sea: all 1990 data combined; n = 133.

Von Bertalanffy growth parameters were calculated from the mean length at age data (Figure 3). The L_0 for females was 241 mm TL (206 mm SL); $t_0 = 0.009$. L_0 for males was 211 mm TL (180 mm SL); $t_0 = - 0.185$.

Reproductive Biology—Gonosomatic index was plotted as a function of standard length for males and females collected in 1990. For males, the result was a scatter of points with wide variation in gonad development for a particular size interval of fish. Gonad indices for males ranged from 0 to about 2%. Female gonosomatic indices could be fit with a power curve (Table 2). Female gonads ranged from near zero to about 7% of body weight.

DISCUSSION

Distribution and Abundance—Distribution of Bering flounder over the study area was not uniform. Replicate trawl hauls at the same location did not necessarily agree on the abundance or even the presence of this species. We were unable to discern bottom type directly at trawl stations and, therefore, could not correlate abundance or presence of this species with bottom type. Plotting the 1990 station locations at which Bering flounder were absent on the map of sediment classes for the northeast Chukchi Sea (Feder *et al.* 1989; Figure 3) revealed that the bottom type at eight of 16 stations was mixed mud and gravel, two were gravel, four combined gravel and sand and the remaining two were muddy sand. Conversely, this species occurred at stations where the following sediment types were recorded previously: muddy gravel; gravely sand; gravely mud; mud; sandy mud; muddy sand. Thus, the only sediment type excluded from stations where this species was captured was gravel. Other than this apparent avoidance of gravel, sediment type in the study area does not seem to have an obvious influence on the spatial distribution of Bering flounder. In this study, the Bering flounder occurred over a salinity rangeof 29.4 to 33.5 ‰ and was missing at stations exhibiting a salinity range of 29.7 to 33.4 psu suggesting that this salinity range had little or no effect on distribution.

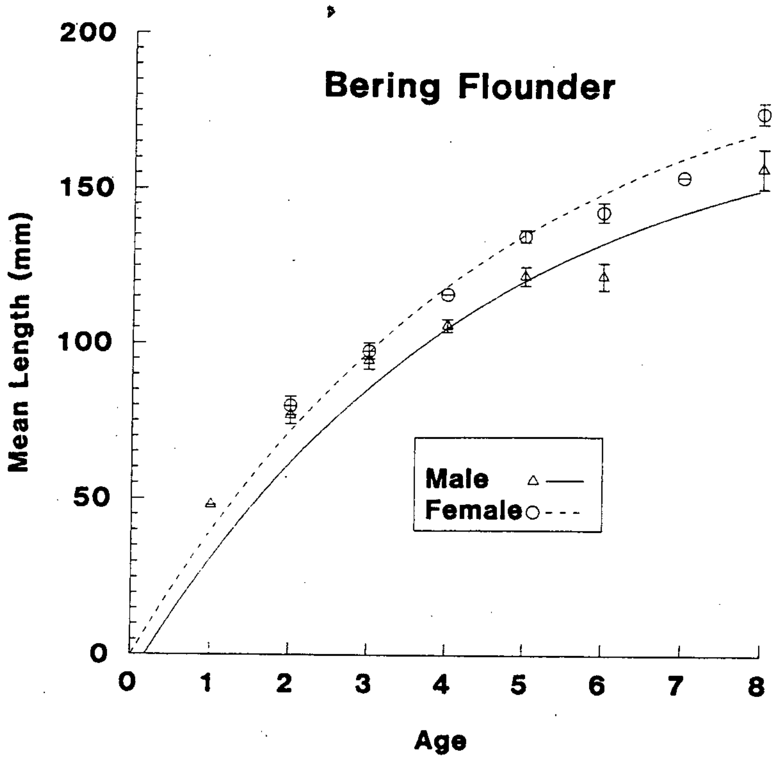

Figure 3. Mean length (SL) at age for male and female Bering flounder from the northeast Chukchi Sea. The von Bertalanffy equation for males is: $L_t = 180\ (1\text{-}e^{-0.230[t+0.185]})$; the corresponding equation for females is: $L_t = 206\ (1\text{-}e^{-0.215[t-0.009]})$. Fish were sampled in 1990.

Although present in the Chukchi Sea (southern part of our study area) in August of 1959, the Bering flounder occurred at extremely low population densities; Pruter and Alverson (1962) caught a total of 289 individuals (<23 kg total) in 59 hauls of 30 min duration each. The highest catch rate Pruter and Alverson reported for Bering flounder was 30 individuals in a 30 min tow using an "eastern otter trawl." In contrast, our 1990 station 9 yielded 587 Bering flounder (20.4 kg) in two 30 min hauls.

Comparisons of 1990 and 1991 biomass and abundance values suggest considerable interannual variation in these parameters. Additional evidence to support this contention may be found by comparing our values with those of Wolotira *et al.* (1977). Using the same 83-112 benthic trawl and the same liner, Wolotira *et al.* (1977) reported a biomass of 4.1 kg/km^2 for Bering flounder in the southeast Chukchi Sea, 2.4 kg/km^2 in Kotzebue Sound and 0.59 kg/km^2 in the northern Bering Sea. In Wolotira's study the starry flounder (*Platichthys stellatus*) was found in far higher biomasses than Bering flounder in both the southeast Chukchi Sea and in Kotzebue Sound. Additional evidence of temporal variability in distribution and abundance of Bering flounder is Andriyashev's (1954) contention that Bering flounder did not occur in the Chukchi Sea before 1933. Taken together, these observations on abundance suggest that the Bering flounder may experience periodic population increases and also periodic mass mortalities due to either direct mortality, recruitment failure or both. Data on age distribution (below) and larval abundance (Wyllie-Echeverria *et al.* Chapter 4) are consistent with this scenario of population fluctuation.

Age, Growth and Population Structure—Our data on length and weight (Table 3, Figure 3) indicate that maximum size in Bering flounder in 1990 approached 200 mm SL and 150 g weight. These sizes correspond to the older fish in the study, ages 9-11. L_∞ values of 211 mm TL (180 mm SL) and 241 mm TL (206 mm SL) were calculated for males and females, respectively, based on mean length at age (Figure 3). Andriyashev (1954) reported the length of the largest specimen from the Chukchi Sea at 150 mm total length. In Pruter and Alverson's (1962) collections, Bering flounder ranged from 140-260 mm, averaging 199 mm total length. They calculated the Bertalanffy parameters for females: L_∞ = 320 mm, k = 0.10, t_0 = -0.41 years. These divergent L_∞ values suggest that conditions for growth in this species were markedly different in the 1930's and 1950's. The small length at age and low biomasses in the 1930's and 1950's led Alverson and Wilimovsky (1966) to conclude that the physical climate of the Chukchi Sea limited population size and depressed normal growth patterns in the Bering flounder.

In our sampling all age classes from 1 to 11 were represented, with age 5 dominating (Figure 3); 75% were ≥ 5 years old. In contrast, the ages of 89 Bering flounder determined by Pruter and Alverson (1962) ranged from 6 to 13 years with 7, 8 and 9 year olds comprising 90% of the population. Thus there is evidence for dramatic shifts in population age structure over time as well as variability in abundance (Figure 1).

Based on the lack of juvenile fishes in their samples, Pruter and Alverson (1962) suggested that this species may not successfully reproduce in the Chukchi Sea. Drift might well carry the larvae to conditions even harsher than those experienced by the adult spawners. Alternatively, the Chukchi Sea population may rely on the drift of pelagic larvae northward on the prevailing surface currents from more southerly locations to maintain population levels. Wyllie-Echeverria *et al.* (Chapter 4) presented evidence that recruitment of Bering flounder larvae to the study area varies interannually. Larvae were relatively abundant in the southern part of the study area in 1990 but entirely missing in 1991. Weingartner (Chapter 2) described temporal variability in the northward flow of Alaska Coastal Water (ACW) from the southern Chukchi Sea caused by changes in wind directions. In 1990 winds were consistently northeastward, increasing the northward flow of the ACW and the advection of larvae from the south. In contrast, 1991 was characterized by more southerly winds which would decrease or reverse the typical northward flow of the ACW. This reversal would prevent the recruitment of Bering flounder larvae to the northeastern Chukchi Sea.

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CHAPTER 7

DISTRIBUTION, ABUNDANCE, AND GROWTH OF ARCTIC COD (*BOREOGADUS SAIDA*) IN THE CHUKCHI SEA[1]

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Abstract. — Distribution, abundance, and growth of Arctic cod from the northeast Chukchi Sea were examined. Arctic cod was the most frequently caught fish by benthic trawl in 1990 and 1991. In 1990, highest abundance and biomass occurred in the southern portion of the study area in Bering shelf water (BSW) followed by Alaska coastal water (ACW) and resident Chukchi water (RCW). In 1991 none of the stations sampled occurred in BSW. Stations with higher abundance and biomass still occurred in the southern part of the study area in RCW.

Environmental conditions in 1990 were more favorable to Arctic cod than 1991. Differences in age distribution recruitment between the two years suggests 1991 was a harsher year. In addition, fish younger than 4 years old were larger in 1990 (1990 age 1 were 122 mm, age 2 129 mm, age 3 173 mm, in 1991 age 1 were 91 mm, age 2 147 mm, age 3 147 mm). Water mass may also influence growth. Older ($\geq$ 3 years) fish at an offshore station in BSW were larger than those at an inshore station in ACW.

INTRODUCTION

Arctic cod, *Boreogadus saida*, is one of the most abundant and widely distributed circumpolar fishes in the Arctic. Along the Alaskan coast, they can be found from the northern Bering Sea through the Chukchi Sea and east to the Canadian border. In the Bering Sea they were found as far south as 60° latitude by Frost and Lowry (1981a), with the more commonly reported southern limit just south of Norton Sound (Pereyra *et al.* 1977, Lowry and Frost 1981). Arctic cod have been found in the Chukchi Sea (Alverson and Wilimovsky 1966, Wolotira *et al.* 1977), however, prior to this study little information was available regarding Arctic cod in the northeastern Chukchi Sea (Walters 1955, Frost and Lowry 1983, Fechhelm *et al.* 1985). Along the northern Alaska coast, most studies have been conducted in the Beaufort Sea and Prudhoe Bay (Cannon *et al.* 1991). Kleinenberg *et al.* (1969) reported finding Arctic cod as far north as 88° north latitude off the Russian coast. Andriyashev (1954) observed Arctic cod near the north pole and hypothesized that they would also occur under the polar ice cap.

In general, Arctic cod abundance and biomass is higher in Arctic waters than in the more southerly Bering Sea (Wolotira *et al.* 1977). Lowry and Frost (1981) hypothesized that fish moved northward every spring and summer with the receding ice edge from the northern Bering Sea and southward in the fall with the advancing ice edge. This annual pattern is consistent with

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their known tolerances for temperatures ranging from -1.8° C (Andiriyashev 1954, Alverson and Wilimovsky 1966) to 6° C (Craig *et al.* 1982). However, Arctic cod have been found inhabiting waters of up to 13.5° C (Craig *et al.* 1982).

Arctic cod contribute significantly to the diets of marine mammals (Frost and Lowry 1980; Lowry *et al.* 1980b; Bradstreet 1982; Finley and Evans 1983) and seabirds (Springer *et al.* 1987). In many areas it is the only abundant food source for these animals and appears to be an important link from lower to upper trophic levels (Bradstreet and Cross 1982). Ringed seal (*Phoca hispida*) abundance has been related to Arctic cod populations and densities by Chapskii (1940). It has been proposed that the primary prey for bulukha whales (Kleinenberg *et al.* 1969) during their summer stay in the Chukchi Sea is Arctic cod. Kleinenberg *et al.* (1969) also related bulukha whale migrations to movement of Arctic cod. Other marine mammals which consume Arctic cod include sei whales [*Balaenoptera borealis* (Tomilin 1957)], killer whales [*Orcinus orca* (Lowry *et al.* 1980b)], ribbon seals [*Phoca fasciata* (Frost and Lowry 1980)], and fin whales [*Balaenoptera physalus* (Klumov 1963)]. Arctic cod was an important prey item for nesting seabirds on Saint Lawrence Island, and on the eastern Chukchi and western Beaufort seashores (Springer and Byrd 1988).

Weingartner's (Chapter 2) review of the hydrography of the northeast Chukchi Sea identifies the water masses and their characteristics and origins. Three primary water masses, Alaska coastal water (ACW), Bering shelf water (BSW), and resident Chukchi water (RCW), are found in the Chukchi Sea. Both BSW and ACW flow north from the Bering Sea. The BSW is a mixture of Bering Sea and Gulf of Anadyr waters with temperatures ranging from 0 to 3° C and salinity 32.5 to 33 practical salinity units (psu). The ACW is formed in coastal areas and mixed with fresher water from Kotzebue Sound. Temperatures of ACW range from 2 to 13° C and salinities are less than 32.2 (psu). The RCW, found offshore in the northern Chukchi Sea, is derived from the upper layers of the Arctic Ocean or shelf water left from the previous winter (Weingartner Chapter 2). The RCW has a temperature less than 1° C and salinity ranges from 32 to 33 psu.

Two other factors which affect the Chukchi Sea are ice cover and melting ice. Ice formation begins in September and October (Lowry *et al.* 1980b) and covers the Chukchi Sea from about November to July (Aagaard 1988). Freezing sea water results in the formation of a highly saline brine which can contribute to the highly saline water of RCW (Weingartner Chapter 2). Ice cover, especially land fast ice, reduces the impact of wind driven surface currents (Aagaard 1988). Melting ice contributes to the fresh water input and may produce an additional water mass (Weingartner Chapter 2). In addition, the ice edge does not melt at a uniform rate, resulting in meltwater embayments (Paquette and Bourke 1981) where upwelling may occur (Hakkinen 1986).

The purpose of this study was to expand our knowledge of Arctic cod abundance, distribution, and age in the northeast Chukchi Sea. We attempt to assess these aspects of Arctic cod biology within the context of biological and physical oceanographic features of the Chukchi Sea.

MATERIAL AND METHODS

Stations in the northeast Chukchi Sea were sampled for fish from August 16 to September 16, 1990 and September 14 to September 23, 1991. A total of 48 stations were sampled in 1990 and 17 stations in 1991. Sampling was done using a NMFS 83-112 survey otter trawl. The net had a 25.2 m headrope, a 34.1 m foot rope set back 7.1 cm from a tickler chain. the cod end was 90 mm stretched mesh with a 33 mm stretched mesh liner inserted in it. Two 30 minute hauls at a trawling speed of approximately 2 knots were taken from each sampling station. The area sampled (m^2) was calculated by multiplying the width of the net opening (measured electronically by a NMFS Scanmar) by the distance trawled. the distance was determined from the ship's position (latitude and longitude) at the beginning and end of each haul. Station locations in table 1 are the end locations of the first haul at the station. Biomass (kg/km^2 trawled) and abundance (number of fish/km^2 trawled) were determined as the average of the two hauls from each station. A subset of captured fish were frozen prior to transport to the lab; 287 individuals were examined from 1990 and 60 from 1991. In addition to biological sampling, CTD information was collected with a Seabird SBE 19.

Fish were measured (total and fork length) to the nearest mm and weighed to the nearest 0.1 g. The fish weight used in all calculations was the total body weight minus the stomach content weight. Otoliths were removed for aging and stored in 50% glycerin.

The annulus on otoliths viewed with transmitted light was defined as the translucent zone, whereas the annulus in burnt sections of otoliths was defined as the dark zone. Age was determined by counting the number of annuli. Otoliths were measured with a calibrated ocular micrometer.

Statistical analyses included t-tests for differences in means (Freund 1979) and F statistics (Neter *et al.* 1990) for slopes and elevations . A Mann-Whitney U test was conducted to detect differences between years in biomass and abundance (Zar 1984). To determine differences in biomass and abundance between water masses with each year, a non-parametic multiple comparison was conducted. When only 2 water masses were present, then a Mann-Whitney U test was conducted.

RESULTS

In 1990 bottom temperature ranged from 12.7° C nearshore by Point Hope decreasing offshore and northward to as low as -1.2° C (maps of temperature and salinity can be found in Weingartner 1994). Salinity was lowest, 29.7 psu, nearshore between Point Hope and Point Lay. It increased both offshore and northward to 33.3 psu. In 1991 bottom temperature ranged from 7° C nearshore by Point Hope decreasing offshore and northward to as low as -1.7° C. Salinity was lowest nearshore at Point Hope and increased offshore and northward to as high as 33.5 psu. In 1990 the sea ice edge was positioned at approximately 74° North while in 1991 it was around 71° 30' North.

Distribution and Abundance.—Arctic cod was the most abundant of the fishes caught in this study; 76% of the total fish catch in 1990, 66% in 1991. In 1990 Arctic cod were present at all 48 stations sampled and ranged in numbers from 10 to 120,000 fish/km^2 (Table 1, Figure 1a). They tended to be most abundant in the southern part of the sampling area off Point Hope, Alaska. Of the 6 stations where abundance was $\geq$50,000 fish/km^2, four occurred in BSW and two in ACW. The BSW had the highest average abundance (59,700 fish/km^2) followed by ACW with 13,400 fish/km^2 and RCW with 8,340 fish/km^2. The BSW abundance was significantly different from ACW ($p < 0.005$) and RCW abundances ($p < 0.001$). There was no significant difference between ACW and RCW abundances ($p > 0.50$).

Arctic cod biomass from 1990 comprised 61% of the total fish biomass. Biomass ranged from 0.45 to 1830 kg/km^2 (Table 1, Figure 1b). Of the nine stations where biomass was $\geq$400 kg/km^2, five where in BSW, two in ACW, and two in RCW. The BSW had the highest average biomass at 864 kg/km^2 followed by RCW at 196 kg/km^2 and ACW at 188 kg/km^2. The BSW biomass was significantly different from RCW ($p < 0.002$) and ACW ($p < 0.010$). There was no significant difference between ACW and RCW biomasses ($p > 0.500$).

Table 1.—Station locations sampled in 1990 and 1991 in the northeast Chukchi Sea. Included are depth (m), bottom temperature (°C), bottom salinity (psu), abundance (number/km^2), and biomass (kg/km^2) of Arctic cod.

Station	**Date**	**Latitude**		**Longitude**		**Depth**	**Bottom**	**Bottom**	**Abundanc**	**Biomass**
#	**d/m/y**	**°**	**'N**	**°**	**'W**	**m**	**°C**	**Salinity (psu)**	**#/km^2**	**kg/km^2**
1	16081990	71	55	168	48	50.4	-1.24	33.31	9090	132
2	17081990	71	33	167	45	46.8			10200	286
3	17081990	71	29	167	02	46.8			39500	1120
4	17081990	71	09	165	54	41.4			17600	382
5	18081990	70	48	164	11	45	-0.19	32.21	5670	94.0
6	21081990	68	23	166	51	18	12.65	29.69	56700	923
7	21081990	68	28	167	16	45	7.09	30.84	2620	27.7
8	21081990	68	29	168	03	54	2.54	32.59	24400	337
9	22081990	68	33	168	45	54	2.11	32.41	120000	1830
10	22081990	68	39	168	47	52.2	2.09	32.44	89700	1710
11	22081990	68	46	168	42	52.2	2.72	32.06	41400	767
12	22081990	68	51	167	56	48.6	2.55	32.26	57000	435
13	23081990	68	52	167	27	45	5.04	31.71	15100	141
14	23081990	68	52	166	28	41.4	10.85	29.64	886	28.5
15	23081990	68	58	166	20	36	10.49	29.78	9.9	0.45
16	24081990	69	06	167	39	46.8	2.75	32.2	22000	213
17	24081990	69	11	168	22	48.6	3.19	32	25900	262
18	24081990	69	12	168	50	50.4	2.21	32.33	97200	1360
19	30081990	69	07	164	54	21.6	10.7	29.45	5660	56.4
20	30081990	69	17	165	41	30.6	8.92	30.34	72300	1110
21	30081990	69	26	166	31	37.8	7.09	32.27	31200	331
22	31081990	69	38	167	18	45	5.83	31.77	22200	142
23	06091990	70	22	162	43	30.6	3.5	31.11	1820	18.6
24	06091990	70	32	163	21	39.6	2.59	31.74	4620	112
25	07091990	70	49	160	28	52.2	0.58	32.58	4970	100
26	07091990	70	56	160	53	52.2			220	7.75
27	07091990	71	09	161	55	46.8	1.02	32.82	2110	19.4
28	08091990	71	34	163	39	43.2	1.07	32.99	264	3.33
29	08091990	71	59	165	22	41.4	1.12	32.26	885	1.52
30	08091990	72	03	166	48	45	0.81	32.39	1270	5.87
31	09091990	71	34	164	56	39.6	0.61	32.25	246	2.33
32	09091990	71	05	163	20	43.2	0.16	32.27	1280	25.6
33	09091990	70	52	161	39	39.6	2.19	31.68	2520	20.2
34	09091990	70	32	161	23	27	3.95	30.95	1430	4.84
35	10091990	69	58	163	15	19.8	5.69	30.35	2880	57.5
36	10091990	69	59	163	32	23.4	5.84	30.33	18700	185
37	10091990	70	26	164	42	43.2	4.25	31.66	6700	86.8
38	11091990	70	45	165	48	41.4	4.37	31.6	18100	355
39	11091990	71	04	167	25	39.6	2.08	32.19	35700	793
40	11091990	70	49	168	40	39.6			747	18.4
41	13091990	70	31	167	38	46.6			1060	47.7

Table 1. continued

Station	Date	Latitude		Longitude		Depth	Bottom	Bottom	Abundanc	Biomass
#	d/m/y	°	'N	°	'W	m	°C	Salinity (psu)	#/km^2	kg/km^2
42	13091990	70	13	166	06	45	5.68	31.84	7140	172
43	14091990	70	04	164	55	39.6	6.47	31.26	13300	247
44	14091990	69	48	164	04	28.8	6.91	29.62	12800	222
45	14091990	69	39	163	18	14.4			1730	20.0
46	14091990	69	33	164	00	48.6	7.52	29.7	12200	71.6
47	15091990	69	37	164	40	27	7.08	30	7740	124
48	16091990	69	42	166	11	41.4	6.49	31.44	11400	167
90-16	14091991	69	00	167	25	47	1.48	31.82	2270	33.8
90-21	16091991	69	23	166	28	39	4.24	30.99	394	10.8
90-22OH	16091991	69	38	167	41	47	-0.38	32.66	8160	114
91-28	17091991	69	46	167	03	47	-1.28	33.18	8920	90.8
91-22OH	17091991	69	40	168	31	51	0.39	32.44	14000	113
91-29	18091991	69	53	167	59	48	0.16	32.44	11600	121
91-27	18091991	70	01	168	48	40	0.17	32.66	4740	44.9
90-27	19091991	71	12	161	54	46	-1.65	33.3	2130	17.9
90-31	19091991	71	36	160	12	51	-1.72	33.48		
91-32	20091991	71	37	159	02	51	-1.73	33.51	3900	42.2
91-33	20091991	71	14	158	40	115	-1.59	33.37	0.00	0.0
91-34	20091991	71	06	158	38	52	-1.38	33.32	3920	42.8
90-23	21091991	70	21	162	53	30	-1.34	33.33	2090	11.8
91-35	21091991	71	59	159	23	27	-1.47	32.27	968	24.9
90-36	22091991	70	01	163	27	38	-1.14	32.21	2140	16.4
90-43	22091991	69	57	164	53	33	-1.21	33.08	5110	50.8
90-06	23091991	68	26	166	38	18	7.09	29.48	15700	220

In 1991 Arctic cod were present at 16 of the 17 stations. Their abundance ranged from 394 to 15,700 fish/km^2 (Table 1, Figure 1c). As in 1990, they tended to be most abundant off Point Hope. However, fish were generally present in fewer numbers at each station in the sampling area; there were no stations in which abundance was $\geq$50,000 fish/km^2. The RCW had the highest average abundance of 6110 fish/km^2 while ACW had an average of 5200 fish/km^2. The BSW was not present at any of the stations sampled. The difference in abundance between ACW and RCW was not significant ($p \leq 0.946$). Arctic cod biomass comprised 47% of the total fish biomass. Biomass ranged from 0 to 220 kg/km^2 (Table 1, Figure 1d). Unlike 1990, none of the stations had a biomass $\geq$400 kg/km^2. The ACW had an average biomass of 88.4 kg/km^2 and RCW had an average of 53.1 kg/km^2. The difference in biomass between the two water masses was not significant ($p \leq 0.946$).

The average biomass for the northeast Chukchi Sea was 304 kg/km^2 in 1990 and 60 kg/km^2 in 1991. The difference in biomass between years was significant ($p \leq 0.001$). The average abundance for the area was 19,540 fish/km^2 in 1990 and 5370 fish/km^2 in 1991. The difference in abundance between years was significant ($p \leq 0.001$).

Length - Weight Relationships.—Fork length (FL) was a linear function of total length (TL), $FL = 2.223 + 0.952\ TL$; $r^2 = 0.998$. Otolith length (OL) as a function of fork length was $OL = -0.143 + 0.041\ FL$; $r^2 = 0.953$ for 1990 fish and $OL = 0.390 + 0.040\ FL$, $r^2 = 0.876$ for 1991 fish (Figure 2). The equations for otolith length and fork length were significantly different between the two years ($p < 0.001$).

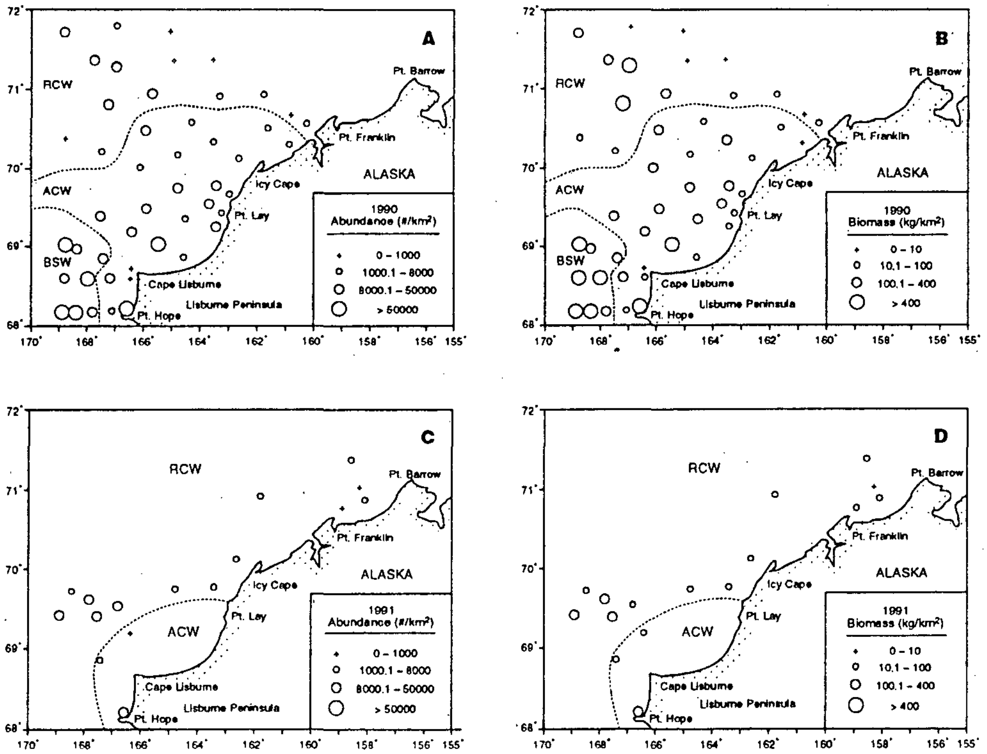

Figure 1. Abundance (fish/km^2) and biomass (kg/km^2) of Arctic cod from the northeastern Chukchi Sea; (A) abundance in 1990, (B) biomass in 1990, (C) abundance in 1991, (D) biomass in 1991.

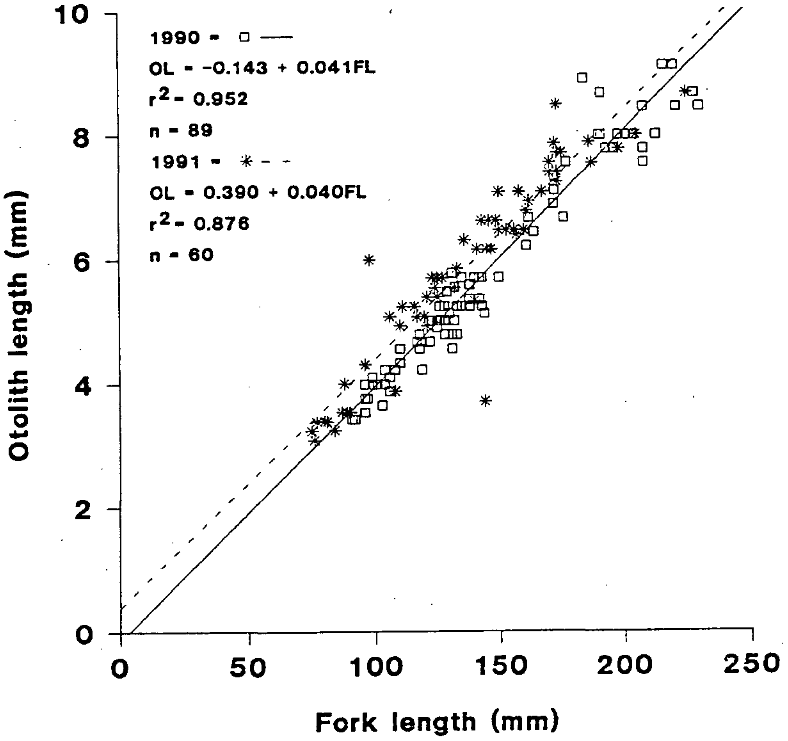

Figure 2. Otolith length (mm) as a function of fork length (mm) for Arctic cod from 1990 and 1991

Weight (W) was a curvilinear function of FL; $W = (4.989*10^{-6}) * FL^{3.072}$; $r^2 = 0.990$ for 1990 fish and $W = (9.233*10^{-6}) * FL^{2.948}$, $r^2 = 0.995$ for 1991 fish. These two regression equations were not significantly different ($p=0.536$) therefore the data were pooled. The equation from the pooled data was $W = (5.398 * 10^{-6}) * FL^{3.056}$; $r^2 = 0.991$ (Figure 3).

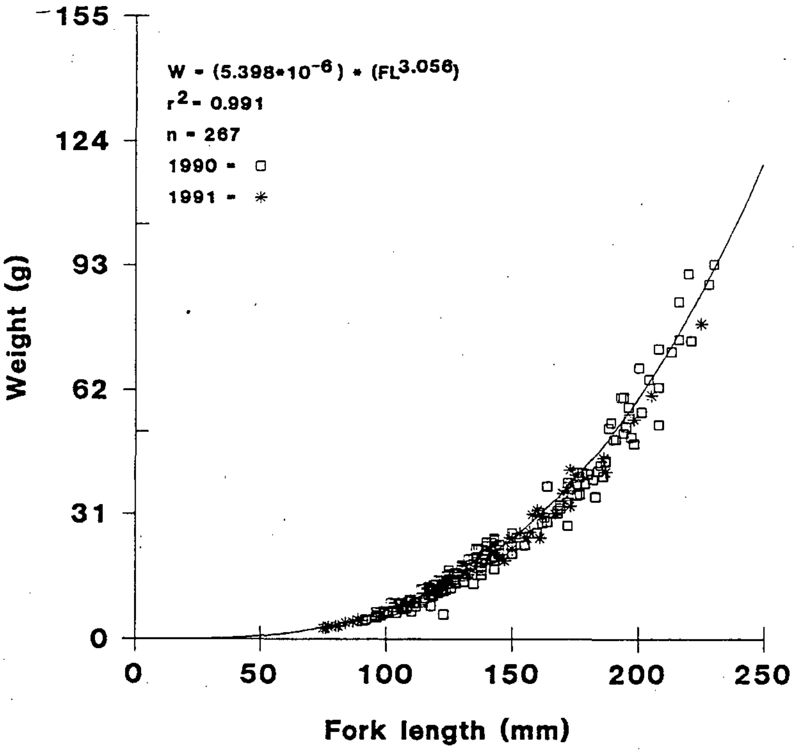

Figure 3. Weight (g) as a function of fork length (mm) for Arctic cod. Data were pooled for the two years of the study.

Age.—Of the fish examined from 1990 the maximum age recorded was one 8 year old female with a FL = 228 mm. In 1991 the oldest fish was a 5 year old male with a FL = 187 mm. There were no age 7 fish for either year and no age 6 fish in 1991. In 1990 61% of the total sample were age 1 fish, while in 1991 only 32% were age 1 (Figure 4). In 1990 78% were less than 3 years old, while in 1991 70% were less than 3. Females and males were equally represented in age-classes 1 and 2 while fish older than 2 years were primarily females (70%) (Table 2).

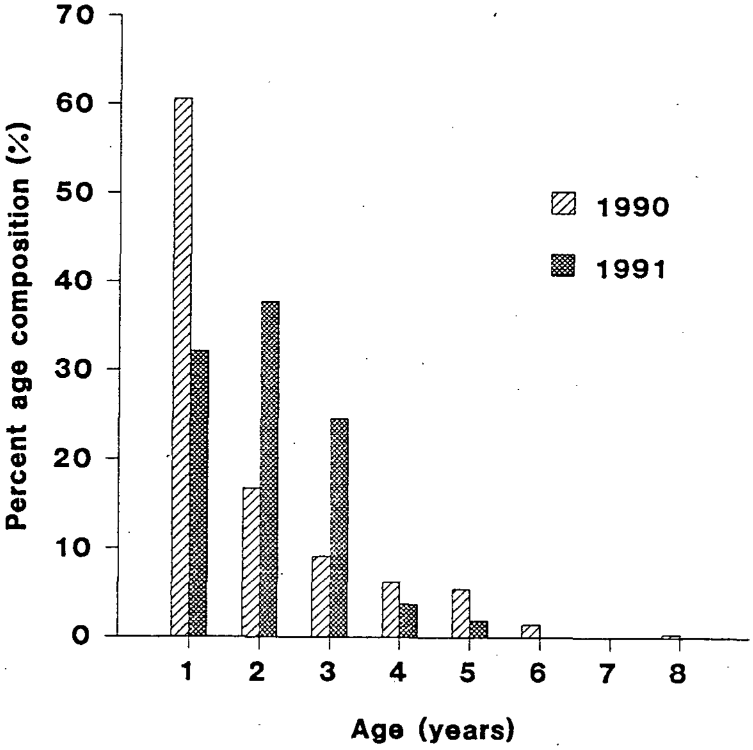

Figure 4. Percent age composition for Arctic cod from both 1990 and 1991 sampling periods.

Table 2.—Sex ratios of Arctic cod from 1990 and 1991 sampling periods.

	1990		1991	
Age	**n**	**% Females**	**n**	**% Females**
1	149	54	15	47
2	41	37	20	55
3	23	70	13	92
4	16	69	2	100
5	14	57	1	0
6	3	33		
8	1	100		

The average fork length at age (Table 3) was significantly larger in 1990 than 1991 for age groups 1 ($p<0.001$), 2 ($p=0.008$), and 3 ($p=0.007$). There was no significant difference between years for the 4 year olds ($p=0.979$) and insufficient data were available for comparing age groups greater than 4 years.

Fish captured in the northern part of the study area (station 31) did not have significantly different fork lengths from those captured in the southern part (station 7) for both fish < 3 years old ($p = 0.465$) and fish ≥ 3 years ($p = 0.944$). However, when inshore fish (station 7) were compared with offshore fish (station 10), offshore fish ≥ 3 years were significantly larger ($p < 0.001$). Fish < 3 years did not differ significantly ($p = 0.246$) in size between the two areas.

Table 3.—Comparison of mean and range of fork length (mm) at age for Arctic cod from the northeast Chukchi Sea.

	This study (1990)			**This study (1991)**			**Frost & (1983)**		**Craig *et al.* (1982)**		
Age	**n**	**$\bar{x}$**	**range**	**n**	**$\bar{x}$**	**range**	**$\bar{x}$**	**range**	**n**	**$\bar{x}$**	**range**
1	127	122	91-161	15	91	75-120	72	45-117	225	84	54-110
2	30	129	99-193	20	147	111-173	116	97-144	137	128	88-177
3	25	173	98-221	13	147	121-198	141	129-160	94	159	120-196
4	17	199	184-220	2	199	172-225	171	161-180	19	180	129-203
5	15	189	160-230	1	187	187			9	209	153-250
6	1	216	216						4	240	198-247
8	1	228	228								

DISCUSSION

Abundance and Distribution.—Studies relating Arctic cod to physical parameters have been done only in the inshore environment. No relationships have been determined for offshore habitats. Moulton and Tarbox (1987) found Arctic cod in the inshore Beaufort Sea were more concentrated along the transition of cold (<- 1° C), high salinity (28-32 psu) marine bottom water and warm (2 - 9° C, low salinity (6 - 27 psu) coastal surface water. Our data (not restricted to inshore) did not follow a similar trend as the highest concentrations of Arctic cod were in the southern offshore part of the study area by Point Hope in 2 to 3° C (bottom temperatures) BSW. The -1° bottom isotherm was farther north off of Point Franklin (Weingartner Chapter 2). As the BSW is known to have a higher abundance of zooplankton compared to ACW and RCW (Springer *et al.* 1989), Arctic cod may be more attracted to it for food. Moulton and Tarbox (1987) reported high concentrations of copepods and mysids in the transition layer as well as Arctic char and Arctic cisco.

Wolotira *et al.* (1977) conducted a study in the Southeast Chukchi Sea in 1976 utilizing the same net type as ours. Arctic cod biomass in their northernmost stratum, occupied by ACW (determined by examining their temperature and salinity data), was 12.3 kg/km^2. This was considerably lower than that found in the northeast Chukchi Sea where the average biomass was 25 times more in 1990 and 5 times more in 1991. Average biomass for ACW was 15 times more in 1990 and 7 times more in 1991. The differences between these two studies, separated by 13 years, may be the result of extreme interannual differences in oceanographic conditions.

Interannual differences in Arctic cod abundance and biomass were evident between 1990 and 1991. In addition, time of year may have influenced the abundance and biomass particularly if Lowry and Frost's (1981) hypothesis of annual migration is correct. Wolotira *et al.* (1977) conducted their study during September to October while ours was in August and September.

Environmental Conditions Influencing Fish Growth.—Environmental conditions determine the growth and survival of fishes. Warmer years in the Chukchi Sea tend to be more favorable to the growth and abundance of some fish than cold years (Springer *et al.* 1984). Arctic cod may fall into this category as evidence by the differences in length of 1, 2, and 3 year old fish between 1990 and 1991. In 1990 the sea ice edge in our study area was farther north than in 1991. The prevailing wind direction in 1990 was from the south, whereas in 1991 the dominant wind direction was from the north. These conditions resulted in 1990 being warmer than 1991 and presumably more conducive to growth and survival. In addition, Weingartner (Chapter 2) linked warm surface temperatures with increased northward flow from the northern Bering Sea which may bring a greater abundance of pelagic prey than would otherwise be resident in the Chukchi Sea. This situation is reflected in the recruitment of Arctic cod to the age-1 year class. In 1990 the percentage of age-1 fish in the samples was nearly twice that of 1991. Our mean length at age data (Table 3) also support the contention that 1990 was more favorable for growth than 1991.

Mean fork length-at-age in this study was greater than reported in previous studies (Craig *et al.* 1982; Frost and Lowry 1983). This suggests that growth conditions in the study area were better during the years preceding this study than in the years preceding the previous studies. In addition, the significant difference in length at age of fish < 4 years old in this study indicates that 1990 was better for growth than 1991. The difference in mean length at age for older fish between offshore and inshore may be related to water masses. The BSW has higher concentrations of dissolved nutrients and chlorophyll than ACW (Walsh *et al.* 1989) and is a major source of zooplankton for the Chukchi Sea (Springer *et al.* 1989). As station 10 was located in BSW, there may have been a higher concentration of prey items contributing to greater growth than at station 7 which was located in ACW.

Age.—Of the northern gadids, Arctic cod appear to have the shortest life span. Walleye pollock (*Theragra chalcogramma*) live to 28 years (McFarlane and Beamish 1990), Atlantic cod (*Gadus morhua*) to 16 years (Fleming 1960), Pacific cod (*Gadus macrocephalus*) to 12 years (Craig *et al.* 1982), Greenland cod (*Gadus ogac*) to 11 years (Mikhail and Welch 1989), and saffron cod (*Eleginus gracilis*) live to 9 years (Wolotira *et al.* 1977). The maximum observed age of Arctic cod in previous studies was 7 years (Bradstreet *et al.* 1986). Our study suggests that Arctic cod may live to eight years. Only one fish was determined to be this age and the possibility of observer errors in aging individual otoliths may have been present. However, two readers independently read the otolith, and both agreed to the assessment of age 8. Even with this unusually old individual, Arctic cod exhibit the shortest longevity of northern gadids studied.

Arctic cod spawning has been reported to occur under the ice from late November to early February (Craig *et al.* 1982) and in some instances as late as March (Rass 1968). Aronovich *et al.* (1975) found the incubation period of the eggs could be prolonged by extended subzero winter water temperatures. An extended spawning and temperature-dependant development could lengthen the time period in which larval fish appear. Wyllie-Echeverria *et al.* (Chapter 4) observed newly hatched larvae as late as mid-July. These events, either singularly or together, may result in a wide range of lengths at age which would explain the large variability in lengths at age found in this and other studies. Another source of variability was collection date. Arctic cod in 1990 were collected nearly a month later than those in 1991.

Life History Strategy.—Species employing *r* selection reproductive strategies generally occur in environments that are unstable or unpredictable with the possibility of high mortality rates. In these environments an investment of resources in producing as many offspring as early in the life cycle as possible would be an advantage (Adams 1980). Craig *et al.* (1982) concluded that Arctic cod exhibited *r* strategy traits: small body size, relatively short life span, early maturity, rapid growth, and large numbers of offspring. Our data supports the *r* selected life strategy traits of relatively short life span and small size.

Due to the unpredictable population size of *r* selected species, Arctic cod may exert a regulatory effect on its predators (Craig *et al.* 1982). In years where environmental conditions were not conducive to population growth of Arctic cod there would subsequently be fewer fish (or lower biomass) available for consumption by marine mammals and seabirds, possibly resulting in lower reproductive success of these predators.

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CHAPTER 8

FOOD HABITS OF FOUR DEMERSAL CHUKCHI SEA FISHES[1]

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Abstract.—Four common Chukchi Sea fishes, taken during August-September, 1990-1991, were examined for food habits. The species studied were Arctic cod, *Boreogadus saida*, Arctic staghorn sculpin, *Gymnocanthus tricuspis*, Bering flounder, *Hippolglossoides robustus*, and saffron cod, *Eleginus gracilis*. All four species occurred in abundance in the northeast Chukchi Sea. Schoener dietary overlap indices on the same species from different stations indicated considerable differences in the diets between stations. Therefore, examination of interspecific dietary overlap was limited to those stations where two or more species were analyzed from the same tows. Highest dietary overlap occurred between Arctic and saffron cod, and negligible overlap occurred between the above two species and the staghorn sculpin near Point Hope. Arctic cod preyed primarily on planktonic and epibenthic organisms, saffron cod consumed epibenthic and benthic fauna, the staghorn sculpin consumed polychaetes and mollusks, and Bering flounder took fish and crustaceans. The diets of these fishes were not substantially different from those reported for closely related species studied elsewhere. Differences in the diets between stations are probably at least partially related to the distributions of water masses originating elsewhere, in the northern Bering Sea and Arctic Ocean.

INTRODUCTION

Fish are a major link in the Arctic food chain between herbivores and apex consumers. Arctic cod (*Boreogadus saida*) is one of the most abundant fish in the Arctic (Lonne and Gullksen, 1989; Borkin *et al.* 1987) and is an important food for a variety of marine mammals and birds (Lonne and Gullksen, 1989; Frost and Lowry, 1984). Saffron cod (*Eleginus gracilis*), Bering flounder (*Hippoglossoides robustus*) and staghorn sculpins (*Gymnocanthus tricuspis*) are also consumed by marine mammals in the Chukchi Sea (Lowry *et al.* 1980b). Information on the diets of these fishes in the Chukchi Sea is therefore central to understanding trophic relationships between primary and apex consumers in the Arctic food web. This paper presents information on the diets of the above four fish in the eastern Chukchi Sea north of Point Hope.

METHODS

The fish samples were collected in August-September, 1990 and 1991, as outlined in Smith *et al.* (Chapter 5). Station locations where fish for stomach analysis were collected are

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shown in Figure 1. The fish for stomach analysis were identified, weighed to the nearest g, total length was measured to the nearest mm, and the stomachs removed. Material in the stomachs was identified to the lowest taxonomic category possible and wet weights of each taxon obtained to the nearest mg on a Kahn electrobalance.

The index of relative importance as defined by Brodeur and Pearcy (1990) was calculated for the taxa at each station:

$$iri = f(\%n_i + \%w_i)$$

where f is the frequency of occurrence, $\%n_i$ is the percent number of prey item i in the stomachs and $\%w_i$ is the percent weight of prey item i in the stomachs.

The Shannon-Weiner measure of niche breadth (dietary evenness) was computed for each taxa (Brodeur and Pearcy, 1990). It is essentially a measure of diversity expressed by the formula:

$$H' = -\Sigma p_i Log(p_i)$$

where H' is the diversity index, p_i is the proportion by weight or number of prey item i in the stomachs. Dietary evenness is the ratio of the diversity in the stomachs to the maximum possible diversity:

$$H'max = log(r)$$
$$J = H'/H'max$$

where J is the evenness, H'max is the maximum possible diversity and r is the total number of taxa.

Niche overlap was computed using the Schoener (1968) index as discussed in Linton *et al.* (1981):

$$Ro = 1 - 0.5(\Sigma|p_{ij} - p_{ik}|)$$

where Ro is the overlap index, p_{ij} is the proportion by weight of prey item i in predator j and p_{ik} is the proportion by weight of prey item i in predator k.

RESULTS

The average length of fish at each station ranged from 76 to 160 mm, and weight ranged from 9 to 53 g (Table 1).

Fish for stomach analysis were selected to include the entire size range of specimens collected by the trawls. If the trawls contained high numbers of small specimens, the average size of individuals in the subsample for stomach analysis was significantly greater than that of the whole sample. The average length of Arctic cod in the whole sample at Stations 7 and 91-32 was 110.2 mm and 106 mm respectively, the average length of staghorn sculpin was 84.5 mm, 75.6 mm, 65.5 mm, and 78.8 mm at Stations 10, 35, 90-06, and 90-36, respectively, and the

Figure 1 (Chapter 8)

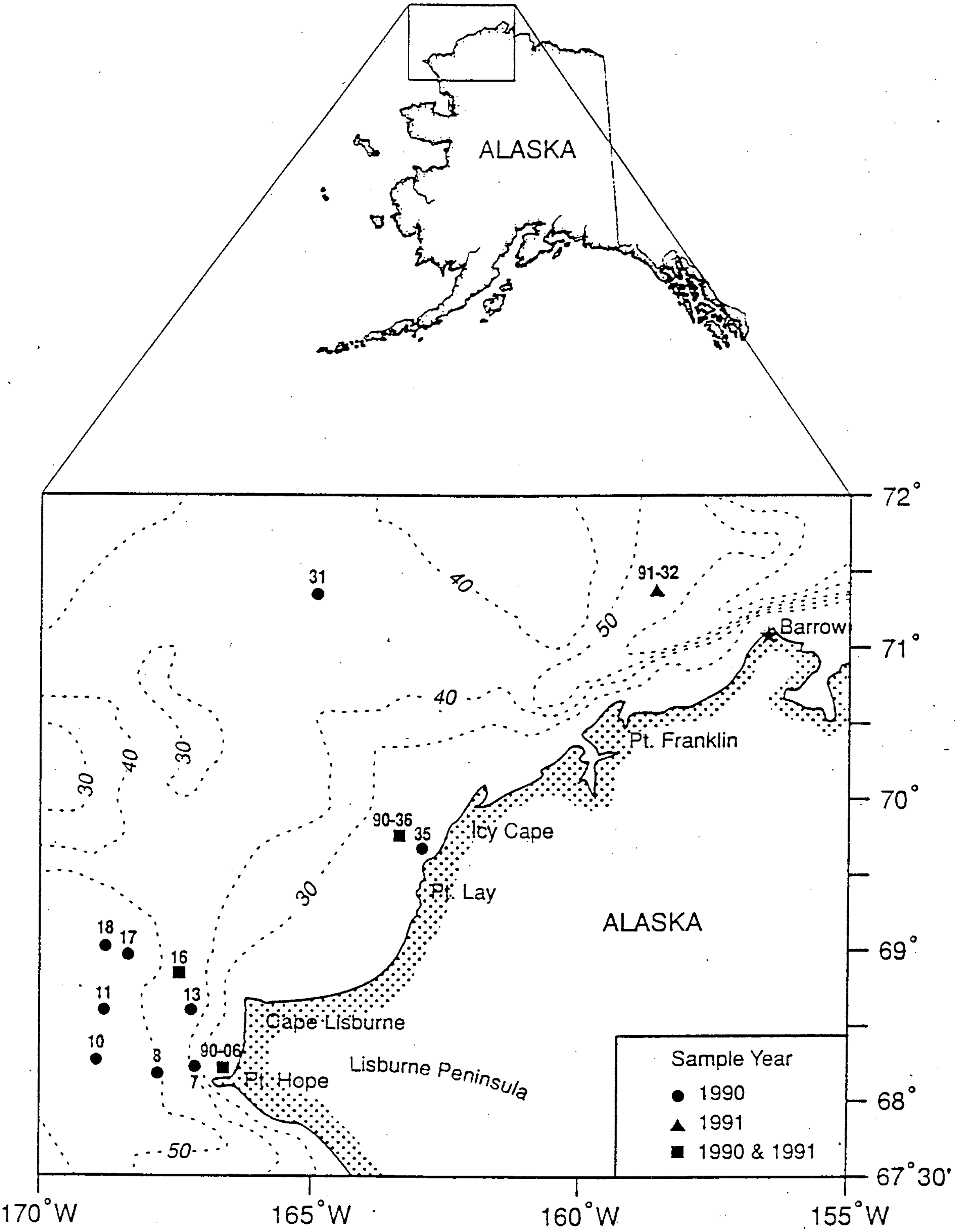


Figure 1. Station locations in the northeast Chukchi Sea from which fish were collected for stomach analysis. Dashed lines are depth contours in meter.

average length of saffron cod at station 90-06 was 130.7 mm. There were no significant differences in the average length of Bering flounder taken in the tows and selected for stomach analysis. The majority of fish had been feeding prior to capture.

Table 1.—The average length and weight, and the number of fish with full and empty stomachs in the subsamples of four demersal fish taken at various stations in the northeast Chukchi Sea.

	Station Number	Average Length (mm)	Average Weight (g)	Number With Food	Number Empty
Arctic Cod	13	125.3	20.0	20	0
	18	159.9	39.5	19	4
	31	116.7	16.9	21	1
	7	124.4	20.9	24	2
	90-06	143.8	29.4	30	2
	91-32	142.1	26.2	9	0
Arctic staghorn sculpin	8	99.1	17.5	18	0
	10	103.0	26.2	25	1
	11	86.6	17.4	20	0
	17	84.8	15.3	20	0
	18	102.2	22.3	9	0
	35	107.2	28.3	25	7
	90-06	76.1	8.9	25	2
	90-36	94.5	24.2	24	0
Bering flounder	8	118.6	35.2	49	23
	11	139.7	52.6	22	2
	16	128.9	41.8	38	14
	17	126.5	35.5	29	0
	18	128.2	39.1	19	1
Saffron cod	90-06	152.9	47.0	24	0

Schoener's (1968) test for species overlap was applied to single species to assess the effect of different locations on the diets. The overlap values varied from 0.005 to 0.598 (Tables 2 - 4) with highest values tending to occur at stations in close proximity to one another. Such variations in overlap indices for a single species from different stations indicates that these fish are generalists, capable of exploiting a broad spectrum of prey, depending on prey availability at particular locations. Since the overlap indices in Tables 2 through 4 are so different and vary markedly from 1, overlap measures to compare different species can be applied only in those cases where the species were taken at the same stations. Thus, interspecific overlap was examined only between Arctic cod, staghorn sculpin and saffron cod at Station 90-06 and between Bering flounder and staghorn sculpin at Stations 8, 11, and 17. There was insufficient material on staghorn sculpin from Station 18 to produce meaningful overlap values. Overlap between Bering flounder and staghorn sculpin at Stations 8, 11, and 17 was 0.05, 0.02, and 0.13, respectively. Overlap between Arctic cod and saffron cod was 0.425; overlap between Arctic cod and staghorn sculpin and between saffron cod and staghorn sculpin was 0.024. Overlap is considered significant at values is excess of 0.6 (Brodeur and Pearcy, 1990). Thus, even between such similar species as saffron cod and Arctic cod, overlap at the same station was insignificant.

Table 2.—Matrix of dietary overlap indices for Bering flounder from various stations in the northeast Chukchi Sea during 1990.

	Station				
Station	**8**	**11**	**16**	**17**	**18**
8	1.000	0.280	0.547	0.547	0.458
11		1.000	0.157	0.169	0.158
16			1.000	0.483	0.480
17				1.000	0.360
18					1.000

Table 3.—Matrix of dietary overlap indices (Schoener, 1968) for Arctic staghorn sculpin from various stations in the northeast Chukchi Sea during 1990 and 1991.

	Station						
Station	**8**	**10**	**11**	**17**	**35**	**90-06**	**90-36**
8	1.000	0.333	0.242	0.293	0.028	0.117	0.007
10		1.000	0.217	0.220	0.052	0.085	0.021
11			1.000	0.297	0.026	0.194	0.033
17				1.000	0.070	0.305	0.041
35					1.000	0.302	0.186
90-06						1.000	0.011
90-36							1.000

Table 4.—Matrix of dietary overlap indices for Arctic cod from various stations in the northeast Chukchi sea during 1990 and 1991.

	Station					
Station	**91-32**	**90-06**	**13**	**18**	**31**	7
91-31	1.000	0.035	0.003	0.138	0.065	0.096
90-06		1.000	0.010	0.034	0.027	0.034
13			1.000	0.264	0.005	0.496
18				1.000	0.253	0.305
31					1.000	0.181
7						1.000

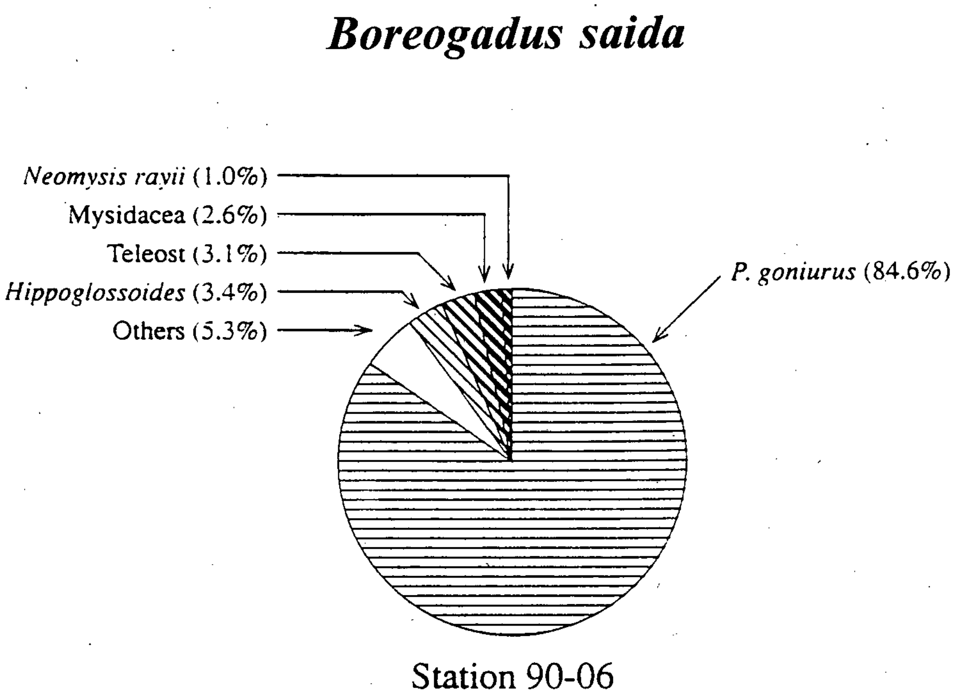
Relative importance indices indicate that *Pandalus goniurus* was a substantial component of the diets of both saffron cod and Arctic cod (Figure 2). However, saffron cod were taking a substantial number of crangonid shrimps and benthic amphipods while Arctic cod were taking epibenthic mysids and fishes. In general, a substantial portion of the Arctic cod diet consisted of pelagic organisms. *Calanus* sp. was a dominant component of the diet at Stations 7, 13 and 18 and the pelagic amphipod *Parathemisto libellula* was dominant at Station 91-32 (Figure 3).

The infaunal cumacean genera *Eudorella* and *Leucon* were important in the diet at Stations 7 and 13; almost all of the cumaceans consisted of pelagic stage adult males. The unknown food category (Stations 13 and 18) consisted of tissue, possibly belonging to larvaceans or pteropods. Decapod zoeae were important to the diets of Arctic cod at Stations 31 and 7. The "Other" category consisted of many taxa which were either taken infrequently, or were too small to contribute substantially to the diet. In Arctic cod they included benthic amphipods (*Protomedeia* spp., *Rhachotropis oculata*, *Anonyx* spp., *Boeckosimus* sp. and *Maera* sp.), pelagic amphipods (*Hyperia* sp. and *Hyperoche medusarus*), mysids (*Mysis oculata* and *Pseudomma truncatum*) and fishes (*Pungitius* sp., Pleuronectidae). The "Other" category in the saffron cod diet included polychaetes (Polynoidae, *Nephtys* sp.) and infaunal stages of cumaceans (*Diastylis* spp.). Thus, while both cod species consumed epibenthic taxa, the saffron cod tended to take more benthic prey and the Arctic cod more pelagic prey.

Staghorn sculpin at Station 90-06 were consuming primarily polychaetes and gastropods (Figure 4). The gastropods were not identified; identifiable polychaetes consisted of Flabelligeridae, Ampharetidae and *Pectinaria* sp. The "Other" category consisted of benthic amphipods (*Ericthonius* sp., *Ischyrocerus* sp.), a cumacean (*Diastylis bidentata*), an isopod and some bivalves. Staghorn sculpin at Station 90-36 were consuming primarily euphausiids (*Thysanoessa raschii*), a shrimp (*E. gaimardi*) and a benthic amphipod. This is the only station where they consumed primarily Crustacea. At the remaining two stations, Station 10 and 35, the diet included primarily polychaetes (*Nephtys* sp., Opheliidae, Flabelligeridae) and *Echiurus echiurus*.

The Bering flounder selected for stomach analysis were all collected at stations near Point Hope. Therefore, our data on the relative importance of prey taxa reflects prey availability over a small portion of the total study area. Bering flounder were consuming mainly fish; the most important identifiable fish was *Lumpenus* sp. (Figure 5). Other teleost families included zoarcids, agonids, cottids and gadids. Benthic and epibenthic crustaceans comprised most of the rest of the diet. The infaunal amphipod *Byblis* was important at Station 8. The infaunal crangonid *Argis lar* and epibenthic hippolytids (*Spironticaris* sp., *Eualus gaimardi*) were the dominant shrimp in the diet, and pagurid crabs were important at Station 16.

The Shannon-Weiner statistic is a measure of dietary evenness. In the absence of data on prey populations, the Shannon Weiner statistic is sometimes considered a measure of niche breadth (Brodeur and Pearcy, 1990). The values for Bering flounder and *Gymnocanthus* were higher than for saffron and Arctic cod because the former were consuming fewer species in more similar amounts by number and weight than the latter (Table 5).



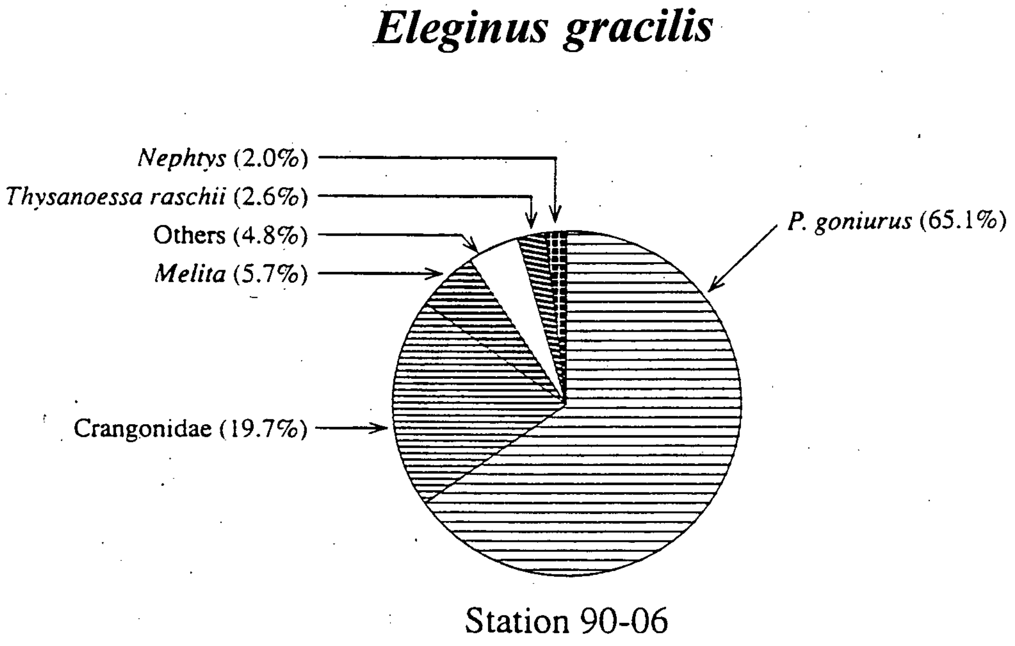


Figure 2. Index of relative importance of major taxa in the diet of Arctic cod (upper) and saffron cod (lower) from Station 90-06 in the northeast Chukchi Sea collected during 1991.

Boreogadus saida

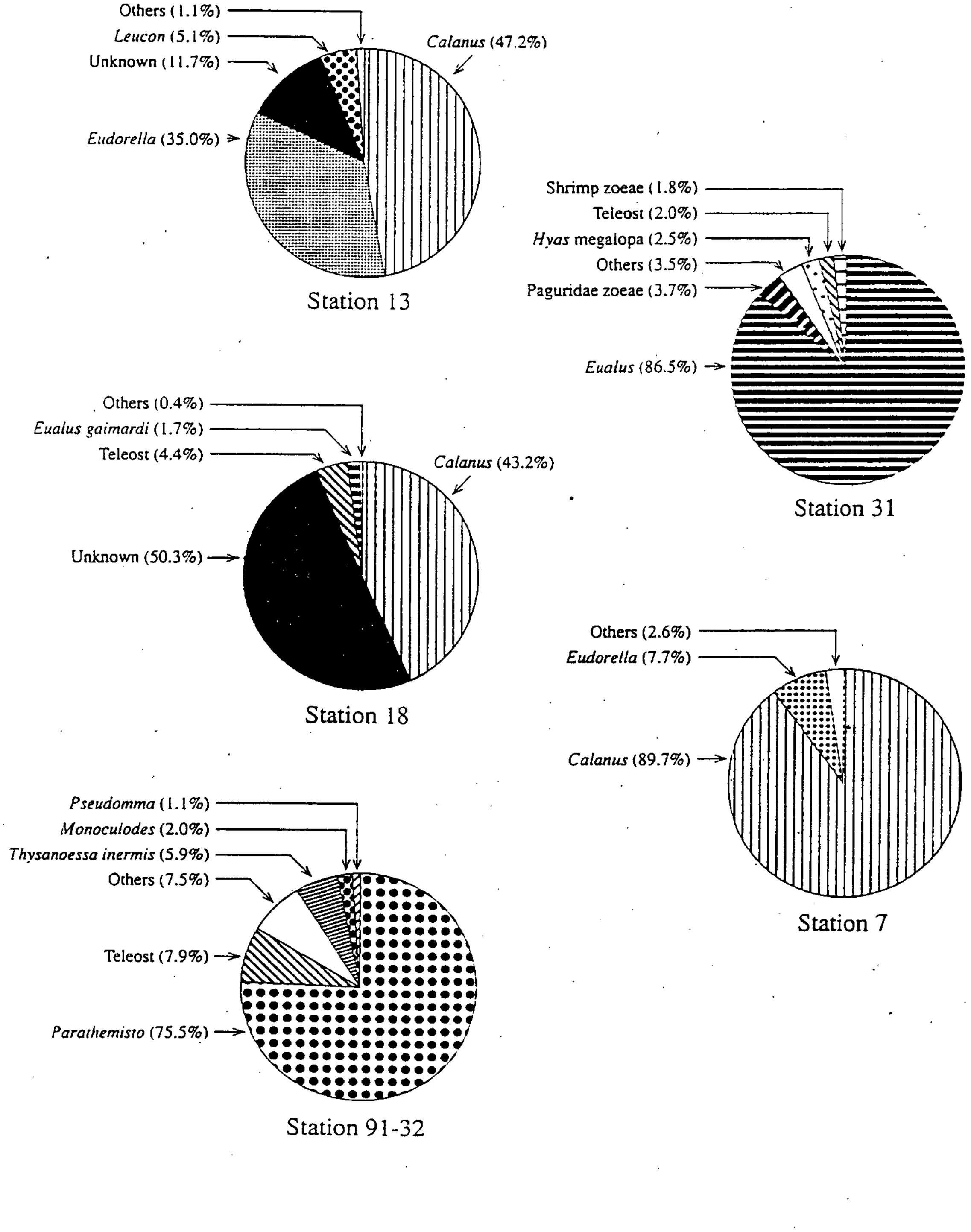


Figure 3. Index of relative importance of major taxa in the diet of Arctic cod collected from four stations in the northeast Chukchi Sea during 1990 and 1991.

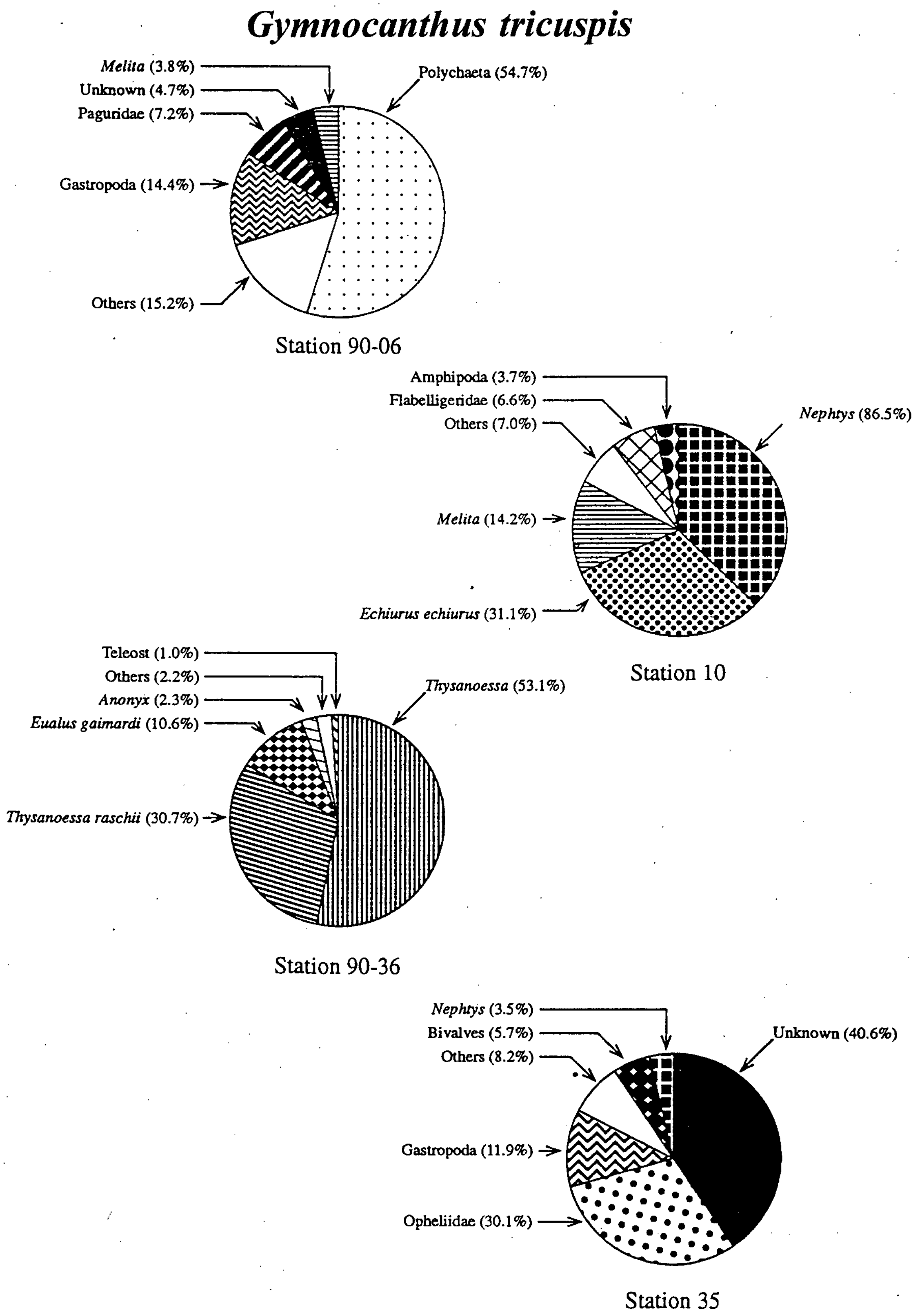


Figure 4. Index of relative importance of major taxa in the diet of Arctic staghorn sculpin collected from four stations in the northeast Chukchi Sea during 1990.

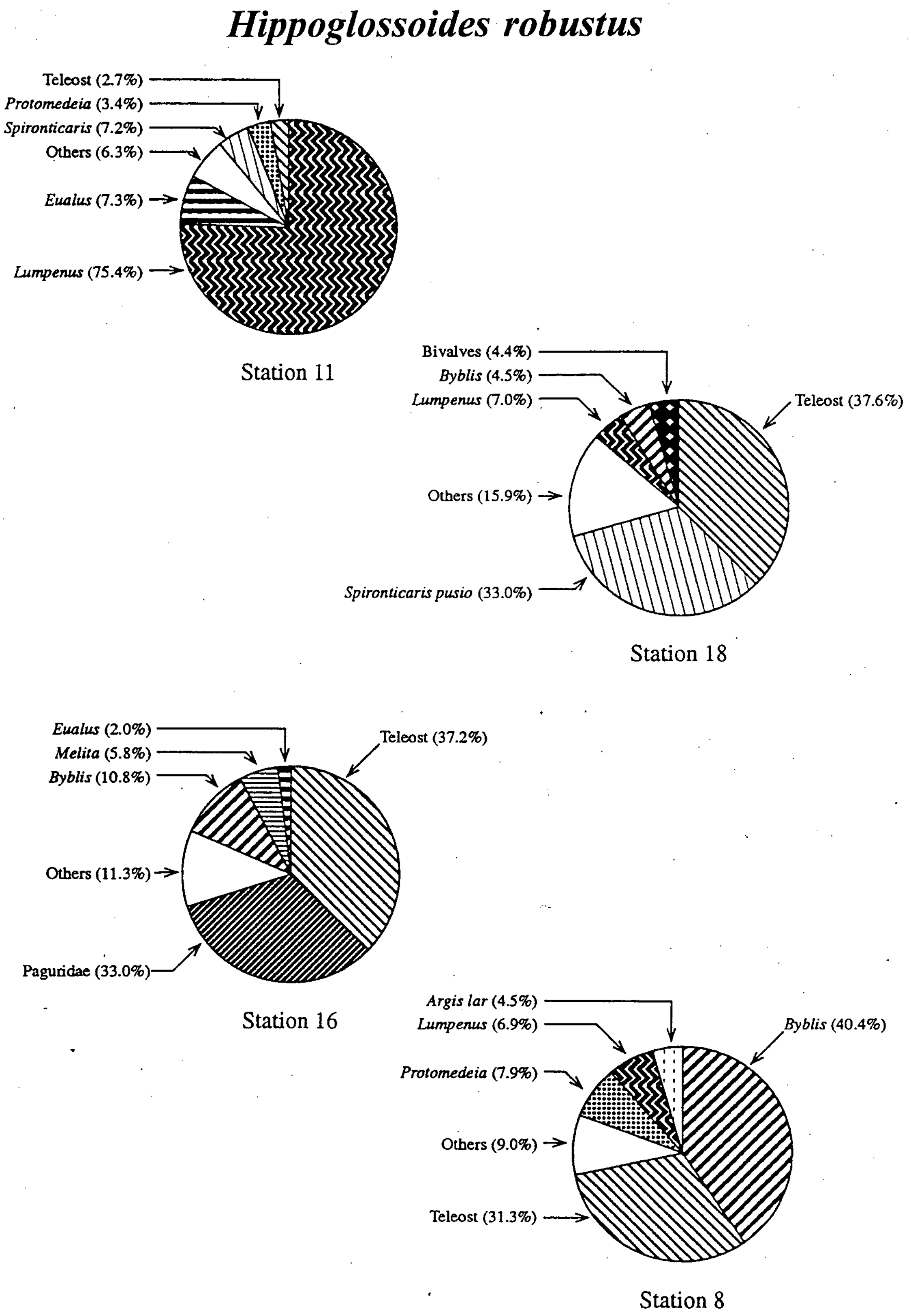


Figure 5. Index of relative importance of major taxa in the diet of Bering flounder collected from five stations in the northeast Chukchi Sea during 1990 and 1991.

Table 5.— Shannon-Weiner evenness statistic for diets of four predator species from the northeast Chukchi Sea.

Predator Taxon	**N**	**Total no. prey taxa in diet**	**Evenness by weight**	**Evenness by number**
Bering flounder	157	18	0.61	0.76
Arctic staghorn sculpin	166	21	0.71	0.29
Arctic cod	123	32	0.02	0.16
Saffron cod	24	15	0.02	0.02

DISCUSSION

In general, the diets of the fish studied here do not differ substantially from those reported elsewhere. Arctic cod consume primarily epontic amphipods and plankton during the ice-covered period, thus obtaining much of their energy through primary consumers feeding on ice algae blooms (Lonne and Gulksen, 1989). During summer they feed primarily on plankton in the Beaufort and northern Chukchi Seas and on epibenthic shrimp and gammaridean amphipods in the northern Bering Sea (Lowry and Frost, 1981). The diet of Arctic staghorn sculpin in our study area is similar to that of *Gymnocanthus pistilliger*, near the Kamchatka Peninsula which feeds primarily on polychaetes and *Echiurus* (Tokranov, 1985). *Hippoglossoides platessoides* feed primarily on mollusks, fish, crustaceans and polychaetes (Macdonald and Green, 1986), however, ophioroids can be a dominant prey item in Arctic regions where alternative prey is in low abundance or absent (Berestovskiy, 1989). Flathead sole less than 25 cm in length from the eastern Bering Sea feed primarily on small crustaceans such as mysids, gammaridean amphipods and crangonid shrimp (Livingston *et al.* 1986).

Previous research in the northern Bering and southern Chukchi Sea has demonstrated the profound influence of different water masses and their associated properties on carbon production rates and the composition of both benthic and planktonic communities (Walsh *et al.* 1989; Greibmeier *et al.* 1988; Springer *et. al.*, 1989; Naumenko and Dzhangil'din, 1987). The organic carbon and plankton advected northward with the major water masses from the northern Bering Sea (Coachman *et al.* 1975) influence species distribution, abundance and biomass, thus impacting the diets of fish, perhaps as far north as Point Franklin. Thus, an understanding of the factors influencing the diets of Arctic cod, Bering flounder and Arctic staghorn sculpin in the Chukchi Sea requires an understanding of processes occurring in the Chirikov Basin, a region of the northern Bering Sea bounded by Siberia and Alaska, St. Lawrence Is., and the Bering Strait.

Water in the Chirikov Basin is divided into three water masses, the Anadyr, Bering Shelf and Alaska Coastal water (Coachman *et al.* 1975). The characteristics and distribution of these water masses are described by Weingartner (Chapter 2). Intense summer phytoplankton blooms are often observed in the western and central Chirikov Basin, where upwelling and mixing of Anadyr and Bering Shelf water result in elevated nutrient levels in the photic zone (Hansell *et al.* 1989). The advection of carbon originating from blooms in the Chirikov Basin through the Bering Strait appears to result in elevated chlorophyll, zooplankton and benthic stocks in the southern Chukchi Sea (Greibmeier *et al.* 1988; Springer *et al.* 1989; Naumenko and Dzhangil'din, 1987). The frontal system between Bering Shelf and Alaska Coastal water can be followed northward toward Cape Lisburne (Weingartner, Chapter 2) and is particularly apparent when examining the horizontal distribution of isohaline and isothermal contours in the bottom water off Point Hope and Cape Lisburne. Presumably, zooplankton, particulate organic carbon and the remaining nutrients are advected northward along with Coastal and Bering Shelf water, thus impacting feeding conditions for fish north of Point Hope.

The impact of northward transport of food is suggested by the diets of Arctic cod near Cape Lisburne and Point Hope. Calanus were a dominant taxa in Arctic cod stomachs at Stations 7, 13, and 18. Highest concentrations of Calanus marshallae in the southern Chukchi Sea have been associated with the frontal region near the 32.4 psu isohaline contour (Springer *et. al.*, 1989). These copepods were probably being concentrated in the frontal region and transported northward past Point Hope and Cape Lisburne, where they were consumed by cod. Calanus were absent from Arctic cod stomachs at Station 90-06, which is east of the frontal zone in Alaska Coastal water, where Calanus are in low concentrations or absent. The presence of saffron cod, a neritic species, at Station 90-06 is another indication that Alaska Coastal water is influencing community composition there.

The frontal region near Point Hope and Cape Lisburne (Weingartner, Chapter 2) apparently also impacts the benthic community. Cluster and principal coordinate analysis on abundance data revealed two distinct benthic communities, a coastal and an offshore group, in the Point Hope - Cape Lisburne region (Feder *et al.* 1989). The offshore group occurred in the frontal region near Point Hope and Cape Lisburne and includes Stations 7, 8, 10, 11, 13, 16 and 18 in our study (Figure 1). The offshore community was dominated by benthic suspension feeders, in particular the amphipod Byblis gaimardi and juvenile specimens of the barnacle Balanus crenulatus (Feder *et al.* 1989). Such organisms tend to be most abundant in places such as frontal regions where elevated primary production results in a high flux of organic carbon to benthic consumers (Grebmeier *et al.* 1988). Byblis was an important prey organism in Bering flounder stomachs at Stations 16 and 18, and dominant at Station 8. Some of the fish consumed by Bering flounder may also have been feeding on Byblis or Balanus. Since we have no information on the distribution and abundance of shrimp in the study area, little can be said concerning water column processes which may be affecting their importance in diets of Bering flounder. Benthic biomass in the offshore group was dominated by polychaetes and Echiurus echiurus (Feder *et al.* 1989), the dominant prey items in Arctic staghorn sculpin at Station 10.

The potential effects of water masses or the source of carbon in the diets of fish north of Cape Lisburne is problematic since stomach analysis was done on fish from only four stations and almost nothing is known of the abundance and distribution of epifaunal invertebrates. Arctic staghorn sculpin at Stations 90-36 and 35, near Icy Cape, were feeding primarily on *T. raschii*, Opheliidae, gastropods and bivalves. Parathemisto libellula, dominating Arctic cod diets at Station 91-35, may be a resident population in Chukchi Sea water or they may have been advected south with Arctic water. The frontal system in the Pt. Franklin area (Weingartner, Chapter 2) may be a fairly persistent feature separating water masses originating in the northern Bering and southern Chukchi Seas from Resident Chukchi or Arctic water masses. If the above is true, substantially different epibenthic and planktonic communities would be expected on either side of the frontal zone and such differences would undoubtedly be reflected in the diets of fish inhabiting the different water masses.

ACKNOWLEDGMENTS

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CHAPTER 9

FISHES AND FISH ASSEMBLAGES OF THE NORTHEASTERN CHUKCHI SEA, ALASKA

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Abstract.—Distribution, abundance, and the structure and stability of bottom fish assemblages in the northeastern Chukchi Sea, Alaska, and their relationship to general oceanographic features were determined. Fishes were collected with an otter trawl at 48 stations in 1990. In 1991 eight of these stations were resampled and 8 additional stations were occupied. Cluster analysis was used to determine fish assemblages. Stepwise multiple discriminant analysis and principal coordinate analyses were used to relate assemblages to oceanographic features. A total of 66 species in 14 families were identified. Gadids made up 83% and 69% of the abundance in 1990 and 1991, respectively. An additional 15% in 1990 and 28% in 1991 were made up of cottids, pleuronectids, and zoarcids. The number of species, species diversity (H), and evenness (V') formed a general pattern of being greater inshore than offshore and greater in the southern area than in the northern area. There were significant differences in ranks of species, species diversity, and evenness at three of eight stations sampled both years. Cluster and discriminant analyses of the 1990 data yielded three along-shore and three off-shore associations. The northern off-shore association had the fewest species, lowest diversity and evenness, and least abundance whereas the two southern associations had the highest. Discriminant and principal coordinate analyses suggest bottom salinity and percent gravel are primary factors influencing association arrangement.

INTRODUCTION

There have been many studies on the distribution and abundance of demersal fishes inhabiting the temperate and tropical seas, primarily in connection with commercially important species. Rarely have the fishes been studied beyond the compilation of species lists for given areas (Colvocoresses and Musick 1984). Survey data has been used, however, to examine the relationships between environmental factors and species distributions, or in more limited cases, to examine the relationships between environmental factors and fish associations. From these studies a number of environmental factors have been identified as important, temperature, salinity, sediment type, being the primary factors. When sampling transected the continental shelf and slope changes in fish species and associations have been primarily related to depth. For example, Overholtz and Tyler (1985) examined the species catches of surveys conducted at different depths in the Georges Bank area of the northwestern Atlantic and found six species associations which were consistent over a number of years. Off Vancouver Island Fargo and Tyler (1991) sampled at depths of 18-240 m and found four species assemblages related to depth. Merrett *et al.* (1991)

sampled depths of 2,230 - 4,787 m in the eastern North Atantic and found that the number of species decreased with depth and different species dominated the catches at different depths.

Jahn and Backus (1976) used salinity and temperature characteristics to define water masses in the Atlantic and related Slope Water, Gulf Stream, northern and southern Sargasso Sea waters and related mesopelagic fishes to these water masses. They concluded that the Slope Water and Gulf Stream faunas were distinct and different from the other two water masses. In another study of the area McKelvie (1985) also found fish associations but concluded they were not distinct from one another, rather there was a gradation between the various faunas. Mahon and Smith (1989) also found that salinity and temperature were important factors in determining fish associations on the Nova Scotian shelf but also determined that depth, and three characteristics of sediment were important factors in determining associations. They concluded, however, that the associations were more related to depth than to other attributes and there were no clear boundaries between the associations.

Some studies indicate sediment type is an important factor determining fish associations whereas others indicate sediment interacts with depth to determine fish associations. Scott (1982) found the distributions of a number of groundfish species on the shelf of Nova Scotia to be related to bottom sediment type, some species were highly specific to sand and gravel while others were broadly related to mud and silt. These relationships were complicated, however, because of the interrelationship between depth and sediment type. Day and Pearcy (1968) sampled depths of 40 - 1,829 m in the northwest Pacific off Oregon and found four demersal fish associations distributed by depth with little overlap; each was characterized by two or three abundant species. They also found that sediment type varied from 100% sand on the upper shelf to a silt clay on the lower slope and that the average sediment type was different for each species association. Species-groups and sediment type, however, did not exactly coincide; two sediment types were found in the depth range of several groups of species. Off the coast of Oregon at depths ranging from 70 to 102 m Pearcy (1978) found both a shallow and deep demersal assemblage. He found, however, an interaction between depth and sediment type where there was a clear separation of the effects of depth but not with sediment type. Pearcy (1978) concluded depth was the primary factor with sediment type of secondary importance in determining the distribution of associations.

Few studies have been conducted in arctic areas and little reported about distribution and species composition of demersal fishes inhabiting these waters. An exception is the northeastern Chukchi Sea where three trawl surveys have occurred (Alverson and Wilimovsky 1966; Frost and Lowry 1983; Fechhelm *et al.* 1985). These studies, however, were spatially limited and not adequately comprehensive to examine the number of species present in the northeast Chukchi Sea, their abundance, distribution, factors influencing distribution, or the existence of species associations. These exploratory studies, however, were important first steps in determining factors influencing the distribution and abundance of fishes in arctic waters.

The purpose of this study was to determine the distribution and abundance of demersal fishes, species assemblages and the relationship of these assemblages to oceanographic features in the northeastern Chukchi Sea, Alaska. Because of differences in the hydrographic and sediment structure, and the presence of invertebrate associations (Feder *et al.* 1990; Feder *et al.* Chapter 10) we hypothesized that there would be onshore-offshore and north-south differences in abundance and biomass, and the associations would be related to water mass characteristics.

THE STUDY AREA

The physical features of northeast Chukchi Sea have been well described by Weingartner (Chapter 2) and Feder *et al.* (Chapter 10) and we only summarize those aspects pertinent to the two hypotheses previously presented. The northeast Chukchi Shelf is relatively shallow and gradually increases to depths of 30 to 50 m offshore over most of the area (Figure 1). The bottom sediments are poorly sorted with a trend of relatively coarse sediments on the inner shelf between Pt. Hope and Pt. Barrow with muds containing various proportions of gravel and sand offshore (Sharma 1979; Naidu 1987). Sediments in the more northerly offshore region contain a higher percentage of water and lower percentage of gravel than the more southern offshore area (Feder *et al.* 1990).

There are a several water masses in the Chukchi Sea during the open water season (Weingartner, Chapter 2). In the study area, however, there are primarily two, the Alaska Coastal Water (ACW) and the Resident Chukchi Water (RCW). The ACW is nearshore and characterized by relatively warm, low salinity water. It is a mixture of Bering Shelf Water (BSW) and freshwater from river discharge along western Alaska, primarily the Yukon River. The RCW is characterized by relatively cold, high salinity water and is seaward of the ACW. It is either advected onshore from the upper layers of the Arctic Ocean and/or is remnant ACW and BSW from the previous winter. The ACW and RCW masses are separated by a bottom front which is generally between the 25 m and 40 m isobaths which intersects the coast between Icy Cape and Pt. Franklin (Johnson 1989; Feder *et al.* 1990; Weingartner Chapter 2).

Feder *et al.* (Chapter 10) examined the distribution of infaunal and epifaunal mollusks of the study area. They found that infaunal molluscan abundance and biomass were greater north of the front. Additionally, they identified six infaunal associations, three associated with more inshore waters and three offshore. Abundance and biomass of the epifaunal molluscs tended to be greater inshore than offshore. There was also an inshore-offshore epifaunal mollusc assemblage pattern but the pattern was not as clear as that formed by the infaunal molluscs.

METHODS AND MATERIALS

The sampling area was located in the area northeast of Pt. Hope (north of approximately 68° 20'N latitude), east of the international boundary (168° 58'W longitude) and limited in northward extent by weather and sea ice conditions. Forty eight stations were occupied along 11 transects perpendicular to shore between 16 August and 16 September, 1990. Nearshore stations were established nearer one another than further offshore to increase the probability of having two stations inshore of the historical position of the bottom front. Between 16 and 23 September, 1991, 16 stations were occupied of which eight had been sampled in 1990 to estimate interannual variability (Figure 1; station locations, depths, temperatures, and salinities are given in Smith *et al.*, Chapter 5). Weather conditions dictated the general areas in which sampling could be conducted and stations were numbered to reflect the sampling sequence.

Each station location was determined using a Global Positioning System. Fish were sampled from a chartered fishing vessel equipped with a National Marine Fisheries Service standard 83 - 112 survey otter trawl which had a 25.2 m head rope, a 34.1 m footrope equipped with a tickler chain, and a codend of 8.9 cm stretched mesh into which a 3.2 cm stretched mesh liner was inserted. To estimate variability in the catch at each station two half hour long trawls were conducted. Because of weather conditions and torn nets, however, only one trawl was made

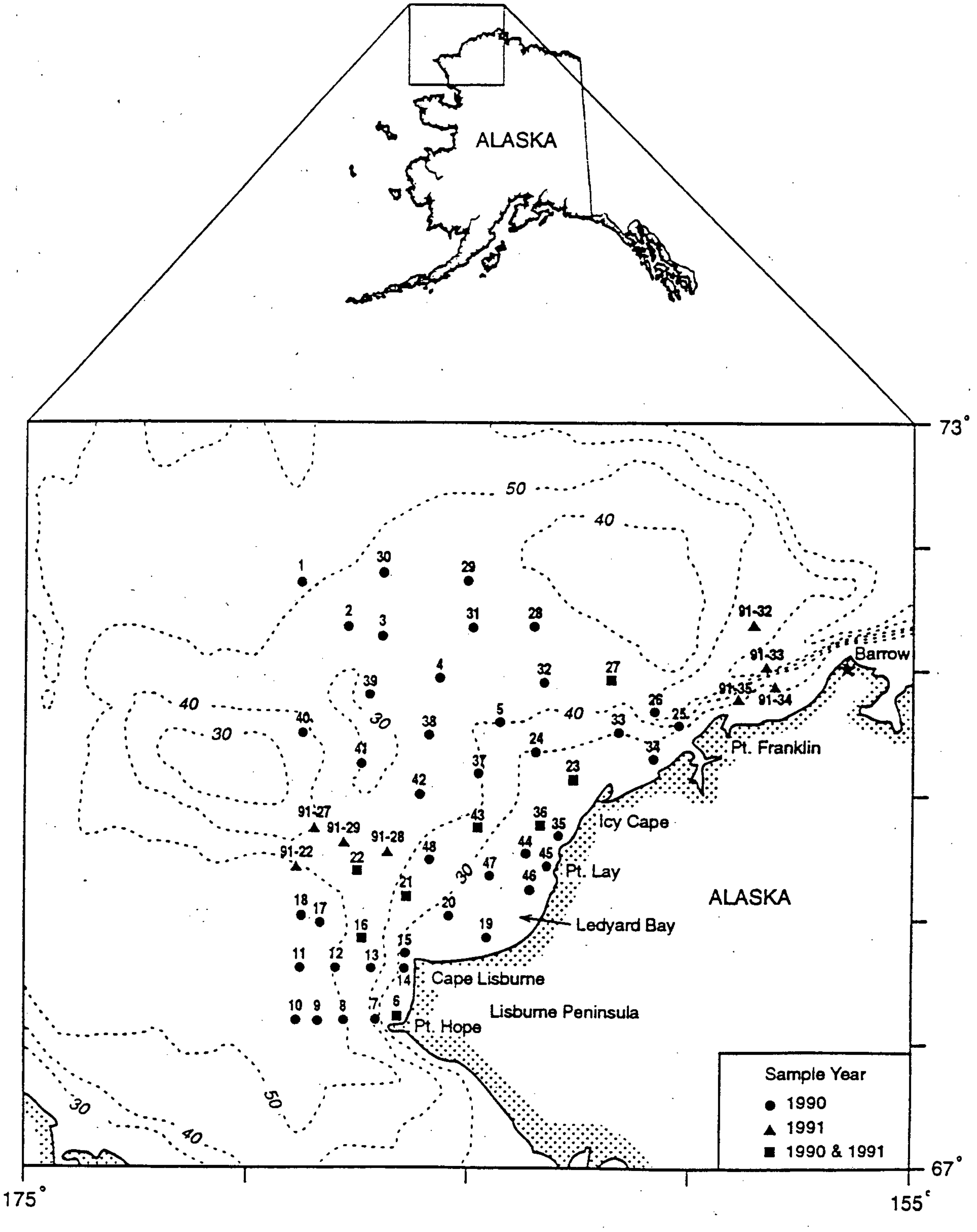

Figure 1. General location of stations sampled for demersal fishes in the northeastern Chukchi Sea, Alaska, during August and September 1990 and 1991. Specific locations for stations are given in Smith *et al.* (Chapter 5).

at station 31 in 1990 and stations 16, 91-33, 91-34, and 91-35 in 1991. Fish abundance (fish/km^2) and biomass (g/km^2) were determined by the area swept method; we noted the boat's location when the net reached bottom and when the trawl left the bottom upon retrieval. Additionally, the width of the trawl's wings and height of the headrope above the footrope were determined with a Scanmar electronic mensuration unit. Upon the trawl's retrieval the entire catch was weighed in the net with an electronic load cell (4,536 kg capacity), fish were sorted to the lowest taxonomic category possible, counted, placed in baskets, and weighed with a mechanical platform scale (81.6 kg capacity).

To investigate diversity, we used the number of species for richness (S) and calculated Shannon's index (H) (Pielou 1977) using abundance and total unique species of both trawls combined at each station. Shannon's index was calculated as:

$$\mathbf{H} = \frac{n \log n - \sum_{i=1}^{k} f_i \log f_i}{n}$$

where n = total number of fish, f_i = number of individuals in species *i*, and k = the number of species (Zar 1984). "Evenness" was estimated following Pielou with the equation

$$\mathbf{V'} = \frac{\mathbf{H}}{\ln \mathbf{S}}$$

where V' = measure of evenness, H = Shannon's diversity index, and S = the number of species present.

Determination of fish associations and their relationship to physical oceanographic conditions was established in a two staged process. The first stage used cluster analysis of species abundance followed by discriminant function and principal coordinate analyses using environmental data. Cluster analysis was used to determine fish associations. Following the recommendation of Clifford and Stevenson (1975), the most commonly occurring species (21, each of which made up >0.1% of the abundance) were chosen based on a preliminary examination of abundance data; they made up 99.6% of the total abundance and 98% of the biomass. Abundance was usually the mean of two trawls except for a few stations in which only one trawl was made. Prior to calculating similarity indices, abundance (X) was transformed (ln[X+1]) to normalize the data (Clifford and Stevenson 1975). The similarity indices were calculated as 1 - D where D is the Bray-Curtis dissimilarity index (Clifford and Stephenson 1975) adapted from Lance and Williams (1967). The algorithm for D is

$$\mathbf{D} = \frac{\sum_{i=1} |(X_{1j} - X_{2j})|}{\sum_{i=1}^{n} (X_{1j} + X_{2j})}$$

where *n* = number of individuals in species *i* and *j* = number of stations. Similarity takes on values from zero to one where one indicates identical species composition between two stations. Following Clifford and Stevenson (1975) a range of similarity indices was used to determine major groupings and a preliminary inspection of the data suggested groupings could be distinguished with indices of 50 - 60% and these were used as our reference for examining the dendograms.

Multiple discriminant function analysis (DFA) and principal coordinate analysis (PCA) were used to evaluate the relationship between fish associations and the environmental parameters. The PCA was used to validate the results of the DFA and to determine if other variables could be influencing our groupings. First a linear stepwise multiple discriminant analysis was performed using both BMDP and SPSS. To control for multicollinearity we eliminated one of any pair of variables with $-0.8 > r > 0.8$. Mud, bottom temperature, epifaunal biomass, and invertebrate infaunal biomass were highly correlated with gravel, bottom temperature, epifaunal abundance, and infaunal invertebrate abundance, respectively, and were therefore not included in the analyses. Three subsets of the data were used to evaluate the relationship between oceanographic conditions and fish associations based on abundance. The variables composing the first data set, depth, bottom salinity and temperature, were determined at each station with a Seabird SBE 19 internally recording conductivity-temperature-depth recorder following trawling. Due to a malfunction, however, salinity and temperature could not be recovered for 7 of the 48 stations sampled in 1990. The variables in the second data set consisted of sediment type (arc sine transformed percent of mud, sand, and gravel), which was assigned to each station from those stations sampled nearest to each of ours by Feder *et al.* (1989). The third data set contained infaunal and epifaunal mollusc biomass and abundance, from Feder *et al.* (Chapter 10) and again the data from those stations nearest ours were assigned to each of our stations. Data on sediment type, biomass, and abundance of invertebrates were provided by Dr. H. M. Feder, Institute of Marine Science, University of Alaska Fairbanks.

Three approaches were taken to examine the congruity between years for the eight stations sampled both years. First, species ranks at each site sampled both years were compared using the Wilcoxon signed ranks test (Siegel and Castellan 1988). Our hypothesis was that if there were nonsignificant differences between years, then interannual variability was minimal. If significant ($p \leq 0.05$) differences existed between years at the stations then interannual variability grossly affected taxon structure. Second, species richness and diversity were compared between years for those stations occupied in both 1990 and 1991. Lastly, the dates from those stations resampled in 1991 were combined with the 1990 data set and fish associations redetermined as previous described. If there is congruity between years, those stations sampled in both years should classify together.

RESULTS

Abundance and Biomass.—A combined total of 66 species were in 14 families found for 1990 and 1991 (Table 1). In 1990 two species of gadids made up 82% of the abundance and 69% of the biomass. Members of the cottid, pleuronectid, and zoarcid families made up an additional 15% of total abundance in 1990 and 28% in 1991. The fishes displayed four patterns of abundance in 1990: (1) Arctic cod (*Boreogadus saida*), the most dominant species, made up 76.1% of total fish abundance and 61.3% of total biomass; (2) four moderately abundant species (*Myoxocephalus verrucosus*, *Eleginus gracilis*, *Gymnocanthus tricuspis*, and *Hippoglossoides robustus*) collectively made up 12.3% of abundance and 15.8% of biomass (Table 1); (3) 16 species which occurred occasionally made up 5.9% of the abundance and 13.7% of the biomass; and (4) 35 species which were rare made up only 0.5% of the abundance and 1.8% of the biomass in 1990 (Table 1). The fish in the first two categories made up over 88.4% and 77.1% of the total abundance and biomass, respectively.

Table 1.—Species abundance (fish/km^2), biomass (g/km^2) and the percent (%) of each fish species collected in the northeastern Chukchi Sea during 1990 and 1991. The top 21 species are labeled 1 to 21.

	1990				**1991**			
Species	**Abundance**	**(%)**	**Biomass**	**(%)**	**Abundance**	**(%)**	**Biomass**	**(%)**
COTTIDAE (SCULPIN)								
# *Icelus spatula*	x	(*)	12	(*)	0	(0.00)	0	(0.00)
# *I. SPINIGER*	x	(*)	10	(*)	0	(0.00)	0	(0.00)
Cottidae sp.	0	(0.00)	0	(0.00)	5	(0.05)	272	(0.20)
21 *Artediellus* sp.	26	(0.10)	280	(0.06)	0	(0.00)	0	(0.00)
A. pacificus	2	(0.01)	47	(0.01)	0	(0.00)	0	(0.00)
7 *A. scaber*	141	(0.55)	583	(0.12)	197	(2.28)	704	(0.51)
Blepsias bilobus	1	(*)	169	(0.03)	0	(0.00)	0	(0.00)
Enophrys diceraus	5	(0.02)	188	(0.04)	130	(1.50)	1106	(0.81)
4 *Gymnocanthus tricuspis*	783	(3.06)	9070	(1.84)	494	(5.71)	5228	(3.81)
20 *Hemilepidotus papilio*	28	(0.11)	571	(0.12)	9	(0.11)	414	(0.30)
Megalocotus platycephalus	15	(0.06)	944	(0.19)	10	(0.12)	944	(0.72)
# *Microcottus sellaris*	x	(*)	12	(*)	0	(0.00)	0	(0.00)
3 *Myoxocephalus* sp.	1573	(6.15)	49167	(9.99)	90	(1.05)	1295	(0.94)
M. polyacanthocephal	1	(.01)	167	(0.03)	0	(0.00)	0	(0.00)
M. quadricornis	6	(0.02)	442	(0.09)	0	(0.00)	0	(0.00)
6 *M. verrucosus*	238	(0.93)	12604	(2.56)	1033	(11.95)	35017	(25.51)
Myoxocephalus sp. 2	0	(0.00)	0	(0.00)	108	(1.25)	4550	(3.31)
Myoxocephalus sp. 1	0	(0.00)	0	(0.00)	2	(0.02)	318	(0.23)
# *Nautichthys pribilovius*	x	(*)	12	(*)	4	(0.05)	15	(0.01)
# *Triglops forficata*	x	(*)	20	(*)	0	(0.00)	0	(0.00)
T. pingeli	137	(0.54)	1698	(0.35)	131	(1.52)	1294	(0.94)
		(11.56)		(15.46)		(25.61)		(37.29)
PLEURONECTIDAE (FLOUNDERS)								
5 *Hippoglossoides robustus*	486	(1.90)	17406	(3.54)	25	(0.29)	940	(0.68)
Pleuronectes aspera	20	(0.08)	746	(0.15)	101	(1.17)	1505	(1.10)
P. proboscidea	5	(0.02)	181	(0.04)	0	(0.00)	0	(0.00)
# *P. sakhalinensis*	x	(*)	12	(*)	0	(0.00)	0	(0.00)
P. quadrituberculatus	18	(0.07)	2467	(0.50)	16	(0.19)	2016	(1.47)
Platichthys stellatus	2	(0.01)	1365	(0.28)	0	(0.00)	0	(0.00)
Reinhardtius hippoglossoides	2	(0.01)	85	(0.02)	0	(0.00)	0	(0.00)
# *Hippoglossus stenolepis*	x	(*)	256	(0.05)	0	(0.00)	0	(0.00)
		(2.11)		(4.59)		(1.65)		(3.25)
ZOARCIDAE (EELPOUTS)								
11 *Lycodes palearis*	133	(0.52)	4802	(0.98)	24	(0.27)	536	(0.39)
14 *L. polaris*	83	(0.33)	7780	(1.58)	0	(0.00)	0	(0.00)
15 *L. raridens*	67	(0.26)	8078	(1.64)	71	(0.82)	5241	(3.82)
L. turneri	8	(0.03)	580	(0.12)	0	(0.00)	0	(0.00)
L. rossi	4	(0.02)	137	(0.03)	0	(0.00)	0	(0.00)
Lycodes sp. Y	0	(0.00)	0	(0.00)	8	(0.09)	92	(0.07)
lycodes sp. X	0	(0.00)	0	(0.00)	8	(0.09)	92	(0.07)
Lycodes sp.	0	(0.00)	0	(0.00)	4	(0.04)	112	(0.08)
# *Gymnelus hemifasciatus*	x	(*)	12	(*)	0	(0.00)	0	(0.00)
G. viriis	1	(*)	30	(0.01)	30	(0.35)	72	(0.05)
		(1.16)		(4.37)		(1.66)		(4.48)
PSYCHROLUTIDAE								
Eurymen gyrinus	x	(*)	31	(0.01)	1	(0.01)	17	(0.01)

Table 1. continued

	1990				1991			
Species	Abundance	(%)	Biomass	(%)	Abundance	(%)	Biomass	(%)
AGONIDAE (POACHERS)								
# *Aspidophoroides bartoni*	1	(*)	24	(*)	0	(0.00)	0	(0.00)
A. olriki	2	(0.01)	85	(0.02)	0	(0.00)	0	(0.00)
16 *Podothecus acipenserinus*	57	(0.22)	1077	(0.22)	24	(0.28)	147	(0.11)
# *Occella dodecaedron*	x	(*)	11	(*)	0	(0.00)	0	(0.00)
Pallasina barbata	0	(0.00)	0	(0.00)	2	(0.02)	9	(0.01)
STICHAEIDAE (PRICKLEBACK)								
Chirolophis snyderi	0	(0.00)	0	(0.00)	1	(0.01)	57	(0.04)
13 *Lumpenus fabrichii*	90	(0.35)	1122	(0.23)	52	(0.61)	102	(0.07)
# *L. medius*	1	(*)	38	(0.01)	0	(0.00)	0	(0.00)
Stichaeus sp.	0	(0.00)	0	(0.00)	2	(0.02)	48	(0.03)
S. punctatus	2	(0.01)	107	(0.02)	1	(0.01)	28	(0.02)
Eumesogrammus praecisus	1	(0.01)	61	(0.01)	3	(0.04)	151	(0.11)
GADIDAE (COD)								
1 *Boreogadus saida*	19456	(76.06)	301878	(61.34)	5728	(66.27)	63913	(46.56)
2 *Eleginus gracilis*	1642	(6.42)	38769	(7.88)	255	(2.95)	7150	(5.21)
17 *Gadus macrocephalus*	44	(0.17)	1869	(0.38)	0	(0.00)	0	(0.00)
8 *Theragra chalcogramma*	138	(0.54)	1883	(0.38)	0	(0.00)	0	(0.00)
		(83.19)		(69.98)		(69.22)		(51.77)
CYCLOPTARIDAE (LUMPSUCKERS)								
# *Eumicrotremus andriashevi*	x	(*)	11	(*)	31	(0.34)	753	(0.55)
E. orbis	4	(0.02)	116	(0.02)	2	(0.02)	112	(0.08)
LIPARIDAE (SNAILFISH)								
Liparis sp.	1	(*)	34	(0.01)	4	(0.05)	373	(0.27)
L. tunicatus	10	(0.04)	373	(0.08)	0	(0.00)	0	(0.00)
18 *L. gibbus*	44	(0.17)	442	(0.90)	17	(0.20)	2408	(1.75)
OSMERIDAE (SMELTS)								
19 *Osmerus mordax*	32	(0.13)	1903	(0.39)	13	(0.15)	129	(0.09)
10^*Mallotus villosus*	133	(0.52)	710	(0.14)	1	(0.01)	6	(*)
HEXAGRAMIDAE (GREENLINGS)								
Hexagrammos stelleri	4	(0.01)	151	(0.03)	0	(0.00)	0	(0.00)
CLUPEIDAE (HERRING)								
12 *Clupea harengus pallasi*	126	(0.49)	17469	(3.55)	1	(0.01)	57	(0.04)
AMMODYTIDAE (SANDLANCES)								
Ammodytes hexapterus	0	(0.00)	0	(0.00)	5	(0.06)	10	(0.01)
ANARHICHADIDAE (WOLFFISH)								
# *Anarhichas orientalis*	1	(*)	61	(0.01)	0	(0.00)	0	(0.00)

x - Less than 0.49
* - Less than 0.01%
# - Found at only 1 station in 1990
^ - Found at only 1 station in 1991

These trends are generally reflected in the 1991 data. For example, the two gadids made up 69% of total abundance and 52% of total biomass (Table 1). There are, however, some notable exceptions. In 1990 Bering flounder made up 2% of the abundance and nearly 4% of the biomass but in 1991 this species was nearly absent, making up 0.3% of the abundance and

0.7% of the biomass. In contrast ,*M. verrucosus* during 1990 made up 0.9% of abundance and 2.6% of biomass, but in 1991 this species made up 12% of abundance and 26% of the biomass (Table 1).

There was a tendency for abundance and biomass of all species combined to be greatest in the southern part of the study area, intermediate off the Pt. Lay area, and lowest in the northern part of the study area (Figure 2). In 1990 the greatest abundance occurred at station 19 (118,800 fish/km^2) and greatest biomass at station 20 (1,591 kg/km^2) in Ledyard Bay (Figure 2). The lowest abundance (16 fish/km^2 at station 26) and biomass (2.1 kg/km^2 at station 29) both occurred off Pt. Franklin. Of the 17 stations sampled from Ledyard Bay and southward seven had abundances greater than 50,000 fish/km^2 but no station north of the area had an abundance this large. In contrast, of those stations with an abundance of less than 10,000 fish/km^2, 14 of 17 stations were off Icy Cape and northward, 6 of 14 stations off the Pt. Lay area, and only one south of Ledyard Bay. Biomass also reflected this general trend (Figure 2).

In 1991 abundance and biomass estimates were low over the entire study area with no trend of higher abundance or biomass in the southern area (Figure 2). Additionally, biomass and abundance estimates differed widely from those found at the eight stations previously sampled in 1990, three (stations 16, 21, and 22) of which differed significantly ($P<0.05$) between the two years (Table 2). Species in common between years at these three stations varied from 6.7% to 42.1% and for those that were present in both years sampled, abundance varied substantially. For example, at station 22, Arctic cod was 2.4 times as abundant in 1990 as in 1991 but Bering flounder was 23 times as abundant in 1991 as in 1990. Similar observations can be made for those stations in which there were no significant differences. For example, the number of species in common varied from 20% to 60%. Differences in the catch between years at these stations also varied extensively and at station 6, which had the largest number of species both years, Arctic cod was four times as abundant in 1990 as in 1991 (Table 2). The opposite was true for *Enophrys diceraus* which was 32 times more abundant in 1991 than in 1990.

Table 2.—Estimated abundance (fish/km^2) of demersal fishes collected at stations sampled in the northeastern Chukchi Sea during both 1990 and 1991. Species sequence is based on the overall abundance of 1990 (Table 1).

	Station 6		**Station 16**		**Station 21**		**Station 22**	
Species	**1990**	**1991**	**1990**	**1991**	**1990**	**1991**	**1990**	**1991**
B. saida	56373.8	14183.5	22386.5	2273.4	32184.6	196.8	20475.3	8527.7
G. tricuspis	324.8	0.0	0.0	27.1	630.5	0.0	0.0	568.8
M. verrucosus	0.0	3793.9	265.4	0.0	54.8	0.0	0.0	0.0
E. diceraus	59.4	1932.8	11.6	0.0	0.0	0.0	0.0	0.0
Myoxocephalus sp.	0.0	0.0	712.2	0.0	599.4	0.0	608.9	0.0
L. aspcsa	40008	1520.2	0.0	0.0	0.0	0.0	0.0	0.0
H. robustus	0.0	37.5	1113.5	0.0	229.7	0.0	254.8	10.8
L. raridens	0.0	102.4	0.0	54.1	0.0	0.0	1061.0	0.0
Myoxocephalus sp.2	0.0	1621.1	0.0	0.0	0.0	0.0	0.0	0.0
L. palearis	0.0	37.5	492.1	162.4	199.8	0.0	416.1	0.0

Table 2. continued

	Station 6		Station 16		Station 21		Station 22	
Species	**1990**	**1991**	**1990**	**1991**	**1990**	**1991**	**1990**	**1991**
L. fabricii	22.1	651.8	147.3	0.0	129.8	0.0	128.0	0.0
T. pingeli	0.0	519.1	0.0	0.0	27.4	0.0	0.0	0.0
C. harengus	221.8	18.8	10.7	0.0	804.1	0.0	26.0	0.0
G. macrocephalus	830.6	0.0	102.7	0.0	0.0	0.0	62.5	0.0
NUMBER OF OTHER SPECIES	2853.2	1474.2	226.7	0.0	321.6	0.0	551.6	135.6
TOTAL	61293	28939	25625	2516	35568	393	24075	9367
Wilcoxon Z		0.580		-2.959		-3.411		-2.859
P Value		0.562		0.003		0.001		0.004
Number of Species	19	24	15	4	15	1	17	8
Number of Species in Common Both Years		13		3		1		8
Total Number of Species Both Years Combined		32		17		15		19
% Common		40.6%		17.6%		6.7%		42.1%
SW Diversity	0.47	1.83	0.62	0.40	0.52	---	0.74	0.40

Table 2. continued

	Station 23		Station 43		Station 36		Station 27	
Species	**1990**	**1991**	**1990**	**1991**	**1990**	**1991**	**1990**	**1991**
B. saida	3180.0	2379.4	13684.7	5090.2	19104.8	2139.4	3017.3	2180.3
G. tricuspis	1163.1	1016.2	170.6	189.8	246.7	702.2	0.0	0.0
M. verrucosus	0.0	0.0	0.0	11.0	574.3	0.0	0.0	0.0
E. diceraus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Myoxocephalus sp.	6.0	55.9	0.0	11.0	0.0	0.0	0.0	0.0
L. aspcsa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H. robustus	0.0	0.0	66.8	88.2	0.0	33.4	0.0	0.0
L. raridens	0.0	0.0	550.5	22.0	0.0	0.0	0.0	34.6
Myoxocephalus sp.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L. palearis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L. fabricii	0.0	0.0	43.0	111.0	0.0	11.1	0.0	0.0
T. pingeli	57.8	111.8	375.4	22.2	49.1	11.1	0.0	0.0
C. harengus	0.0	0.0	34.1	0.0	0.0	0.0	0.0	0.0
G. macrocephalus	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NUMBER OF OTHER SPECIES	28.9	86.3	178.0	88.2	49.0	100.3	0.0	251.1
TOTAL	5219	5690	15263	5877	20751	3966	3017	2465

Table 2. continued

	Station 23		Station 43		Station 36		Station 27	
Species	**1990**	**1991**	**1990**	**1991**	**1990**	**1991**	**1990**	**1991**
Wilcoxon Z		0.76 5		- 0.80 6		0.03 1		0.67 7
P Value		0.44 4		0.42 0		0.97 5		0.49 8
Number of Species	7	9	14	13	8	10	1	5
Number of Species in Common Both Years		6		9		4		1
Total Number of Species Both Years Combined		10		18		14		5
% Common		60%		50%		28.6%		20%
SW Diversity	1.01	1.25	0.53	0.54	0.38	1.18	---	0.37

Species Richness, Diversity, and Assemblage Structure.—Families contributing the most species were Cottidae (21), Zoarcidae (10), Pleuronectidae (8), Stichaeidae (6), and Agonidae (5) (Table 1). The remaining families contributed only 16 additional species. Nearly 45% of the species were represented by a single specimen, while 55% were represented by >10 individuals.

Species richness was greatest south of Icy Cape and lowest in the north. The most species per station (19) were recorded at stations 6 (Pt. Hope), 45 (Pt. Lay), and 48 (Ledyard Bay) in 1990 and at station 6 (23 species) in 1991 (Figure 3). The fewest species (2 and 3) occurred at four stations in the most northern area (stations 28 through 32). There was a tendency for these stations south of Icy Cape to have 11 or more species with those stations north to have 10 or less; the majority of the latter had fewer than 8 species. There was interannual variability in the number of species found at a station (Table 2). Species ranks were significantly ($P<0.05$) different at three stations just northeast of Cape Lisburne between 1990 and 1991. At these stations there were between 15 and 17 species in 1990 but in 1991 the number varied from 1 to 8 species (Table 2). In the north there was one species found at station 21 in 1990 but five in 1991.

For species diversity there was a trend of higher diversity inshore than offshore and in the southern part of the study area than the northern (Figure 3). Those stations with a species diversity of >0.90 occurred south of a line from northeast of Pt. Franklin south-westward. The greatest species diversity (1.99) occurred at station 45 off Pt. Lay with two stations off Cape Lisburne (15 and 14) nearly as large (1.56 and 1.87, respectively). Nearly all stations with a diversity of >1.0 occurred along shore from Pt. Franklin to Pt. Hope. The smallest species diversity occurred at station 39 (0.02) west of Pt. Franklin. Stations 3 and 29 just north of station 39 also had very low (0.07) diversity indices. Like species richness, there was considerable interannual differences in species diversity. The greatest interannual difference occurred at station 6 followed closely by station 36 (Table 2). Evenness followed the same pattern as species diversity indices (Figure 3).

Cluster analysis of fishes collected in 1990 formed six associations at a similarity level of 0.5 - 0.6, three near shore and three offshore, with one station (15) not classifiable (Figure 4).

Two clusters formed an association (I) off the Lisburne Peninsula. A second association (II) was formed by one cluster which bisected the northern offshore association (VI). Interestingly association II was more closely related to association I off Lisburne Peninsula than the association it bisected. The northern offshore association (VI) consisted of two relatively distant clusters while the northern inshore association (III) consisted of two closely related clusters, one of which was made up of two stations. The central offshore association (IV) was formed by two clusters. Finally, there was the central onshore association (V) in Ledyard Bay which consisted of four closely related and two distantly related stations. Cluster analysis was also repeated without Arctic cod, the most abundant species, and similar results were obtained.

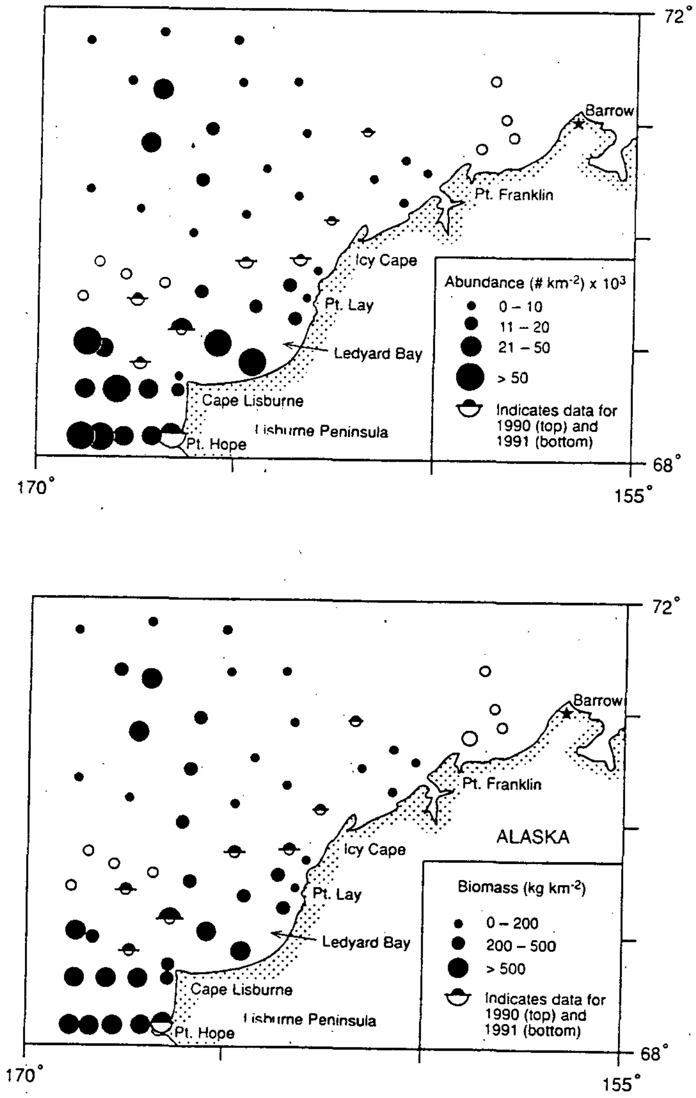

Figure 2. Relative abundance (fish/km^2) and biomass (kg/km^2) estimates of benthic fishes at 48 and 16 stations sampled during 1990 and 1991, respectively, in the northeastern Chukchi Sea, Alaska.

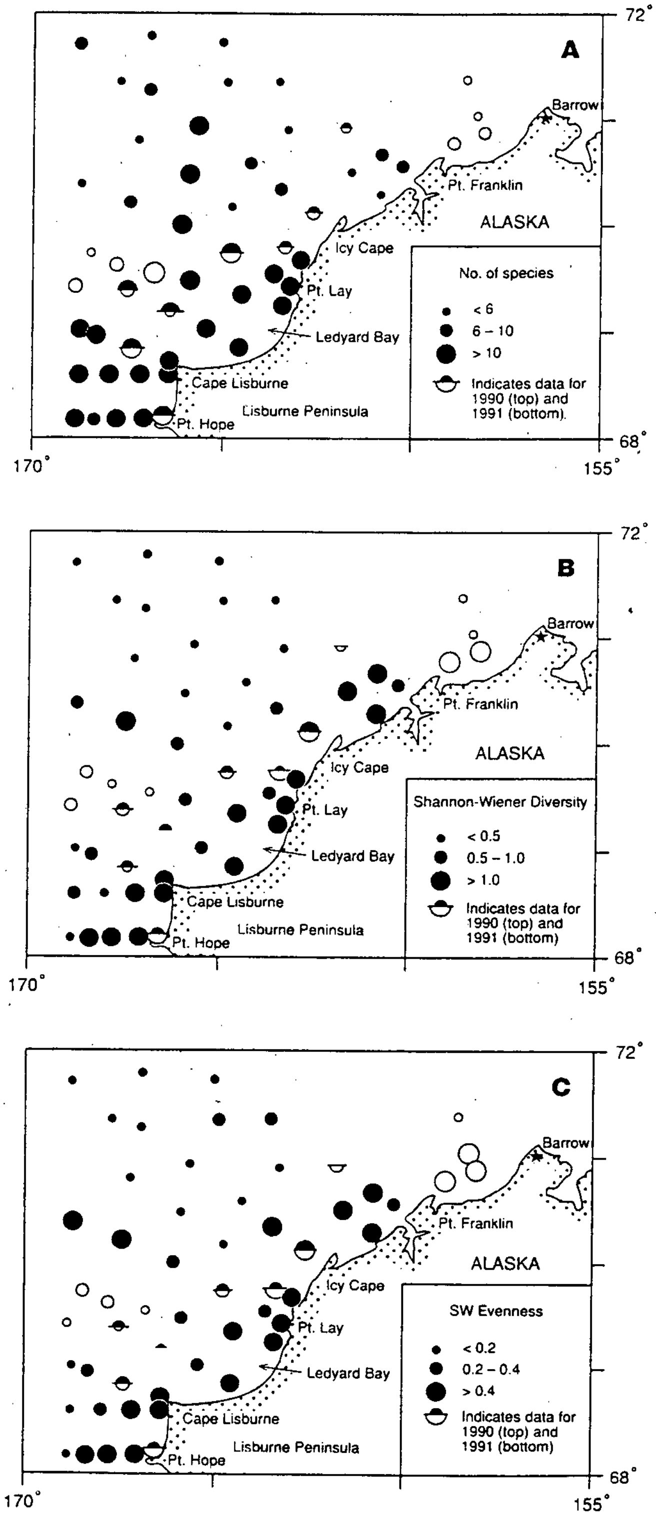

Figure 3. Relative richness (number of species), species diversity (Shannon index), and evenness of behthic fishes at 48 and 16 stations sampled during 1990 and 1991, respectively, in the northeastern Chukchi Sea, Alaska.

Even though the six fish assemblages and the unclassified station were composed of different species and abundances, the associations all had a common feature, in each Arctic cod made up over 90% of the abundance (Table 3). The most distinctive assemblage was VI from the northern area which had the fewest species, lowest abundance, and least diversity and evenness. This compares to either associations I or V which had much higher values for all of these measures. The top five species characterizing this association, in order of abundance were Arctic cod, *L. raridens*, *M. verrucosus*, *G. tricuspis*, and *C. harengus pallasi*. Association I had the most species, the top five of which were Arctic cod, *Myoxocephalus* sp., *H. robustus*, *G. tricuspis*, and *L. palearis*.

Table 3.—Estimated mean abundance (fish/km^2), number of species, Shannon diversity, and evenness found in the six fish associations for the 21 most abundant species determined from the cluster analysis using the Bray-Curtis similarity index.

	Group					
Species	**1**	**2**	**3**	**4**	**5**	**6**
Boreogadus saida	43733	16419	5280	8172	16096	6100
Eleginus gracilis	684	2	170	19	10956	0
Myoxocephalus sp.	3391	49	44	2	4492	0
Gymnocanthus tricuspis	1005	87	889	156	2618	7
Hippoglossoides robustus	1599	72	0	61	15	3
Myoxocephalus verrucosus	178	0	429	177	773	9
Artediellus scaber	20	0	0	11	1061	4
Theragra chalcogramma	69	0	0	26	861	0
Triglops pingeli	70	3	120	59	722	0
Mallotus villosus	437	0	0	40	0	0
Lycodes palearis	453	0	0	7	0	0
Clupea harengus pallasi	195	0	0	139	323	0
Lumpenus fabricii	235	18	2	14	141	0
Lycodes polaris	260	64	2	0	6	0
L. raridens	76	7	4	284	13	5
Podothecus acipens	60	0	18	5	280	0
Gadus macrocephalus	21	0	1	6	273	0
Liparis gibbus	129	2	0	15	29	0
Osmerus mordax	0	0	0	0	258	0
Hemilepidotus papilio	89	0	0	13	0	0
Artediellus sp.	80	0	0	0	20	0
NUMBER OF SPECIES	20	10	11	18	18	6
SHANNON DIVERSITY	0.35	0.05	0.37	0.25	0.72	0.02
EVENNESS	0.27	0.05	0.35	0.20	0.57	0.02

The objective of the discriminant analysis was to determine the extent the cluster analysis groupings using Bray-Curtis similarity matrix, based on abundance, could be differentiated using environmental variables. Bottom salinity and percent gravel were the key factors which separated assemblage groups, the first axis accounting for 72% and the second axis 28% of the variation (Table 4). Bottom salinity showed the strongest association with axis 1 whereas percent gravel was strongest in axis 2. The different associations outlined in the cluster analysis are readily apparent on the plot of the two ordination axes (Figure 5). The lines superimposed on Figure 5 enclose stations of similar environmental conditions. There is relatively little overlap of groups III and V, the former characterized by low salinity and high gravel whereas the latter is intermediate in salinity and gravel (Figure 5). Stations 14 and 15 classified together, having the lowest salinity and percent gravel of the groups. There is overlap at the peripheries of groups I and VI suggesting a gradation in environmental conditions. Group VI is more saline but consists of a wide range of percent gravel.

Our data clustered into six groups and one unclassified station. Based on the first two of seven probabilities (Mahalanobis D-square) of association in the discriminant analysis, 33 of 41 (80.5 %) station classifications using bottom salinity and percent gravel agreed with our cluster analysis groupings based on abundance of each species. To emphasize the different classification of the eight stations and overlap between associations, the ordination is replotted (Figure 5, lower panel) but stations are coded with symbols used in the cluster analysis. The superimposed lines again enclose stations of similar hydrographic conditions.

Table 4.—Discriminate function analysis of environmental factors with Chukchi Sea fish abundance as the class criterion.

	STANDARDIZED DISCRIMINANT FUNCTION COEFFICIENTS	
Dependent	**1st Axis**	**2nd Axis**
Bottom Salinity	0.94189	0.48469
Percent of Gravel	-0.14688	1.04905
Percent Variance	71.81	28.19
Eigenvalue	1.887	0.741

Principal component analysis, which includes all environmental data, qualitatively supports the discriminant analysis but also suggests other variables are important determinants of fish associations (Table 5). In the first dimension, which accounts for 31.8% of the variance among stations, high loadings occur for bottom salinity, depth, and gravel. An additional 27.8% of the variation is accounted for by the second dimension in which epifaunal and infaunal abundances, and gravel have high loadings. The third dimension, which accounts for an additional 15.6% of variation, has high loadings on gravel and sand.

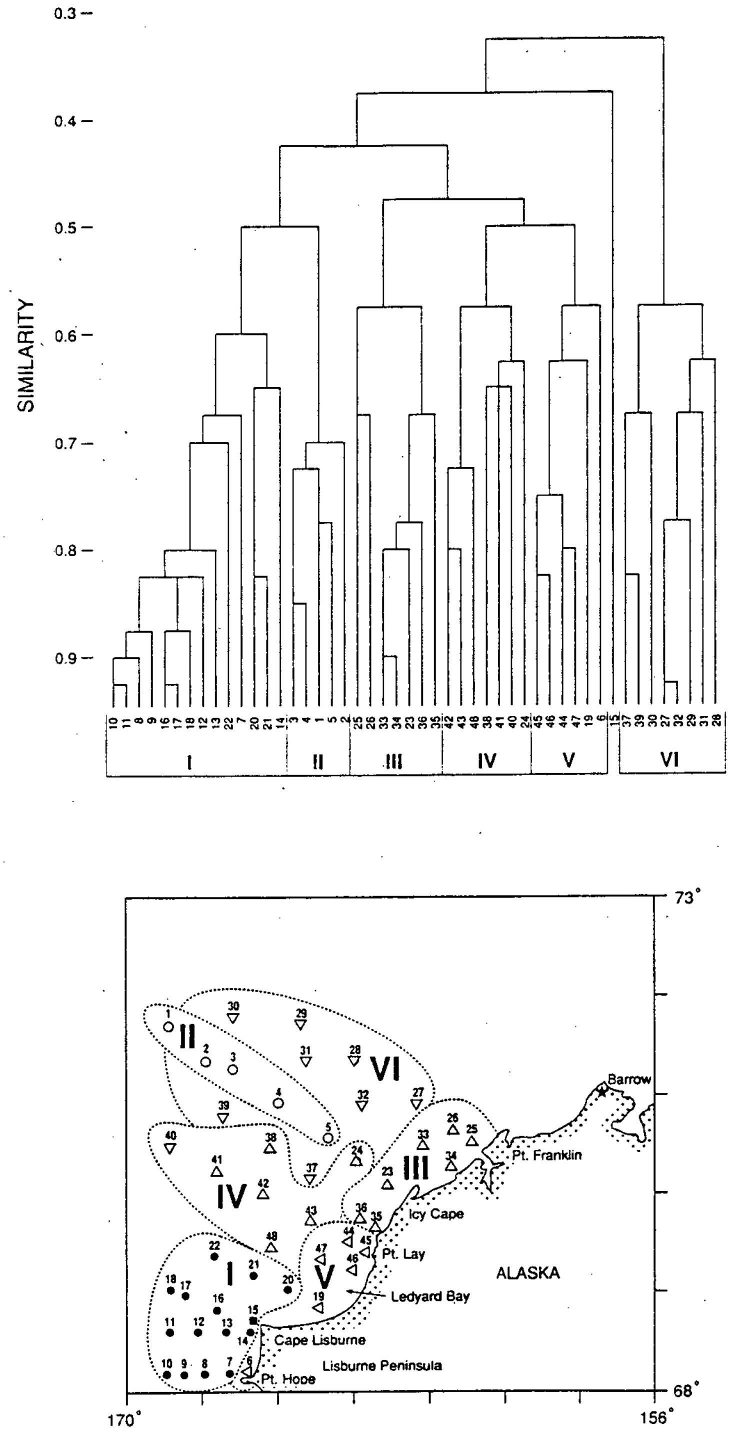

Figure 4. Similarity dendogram and demersal fish associations for fishes captured in the northeastern Chukchi Sea, Alaska, during 1990. The decision criteria for determining association was a similarity index of 0.5 - 0.6.

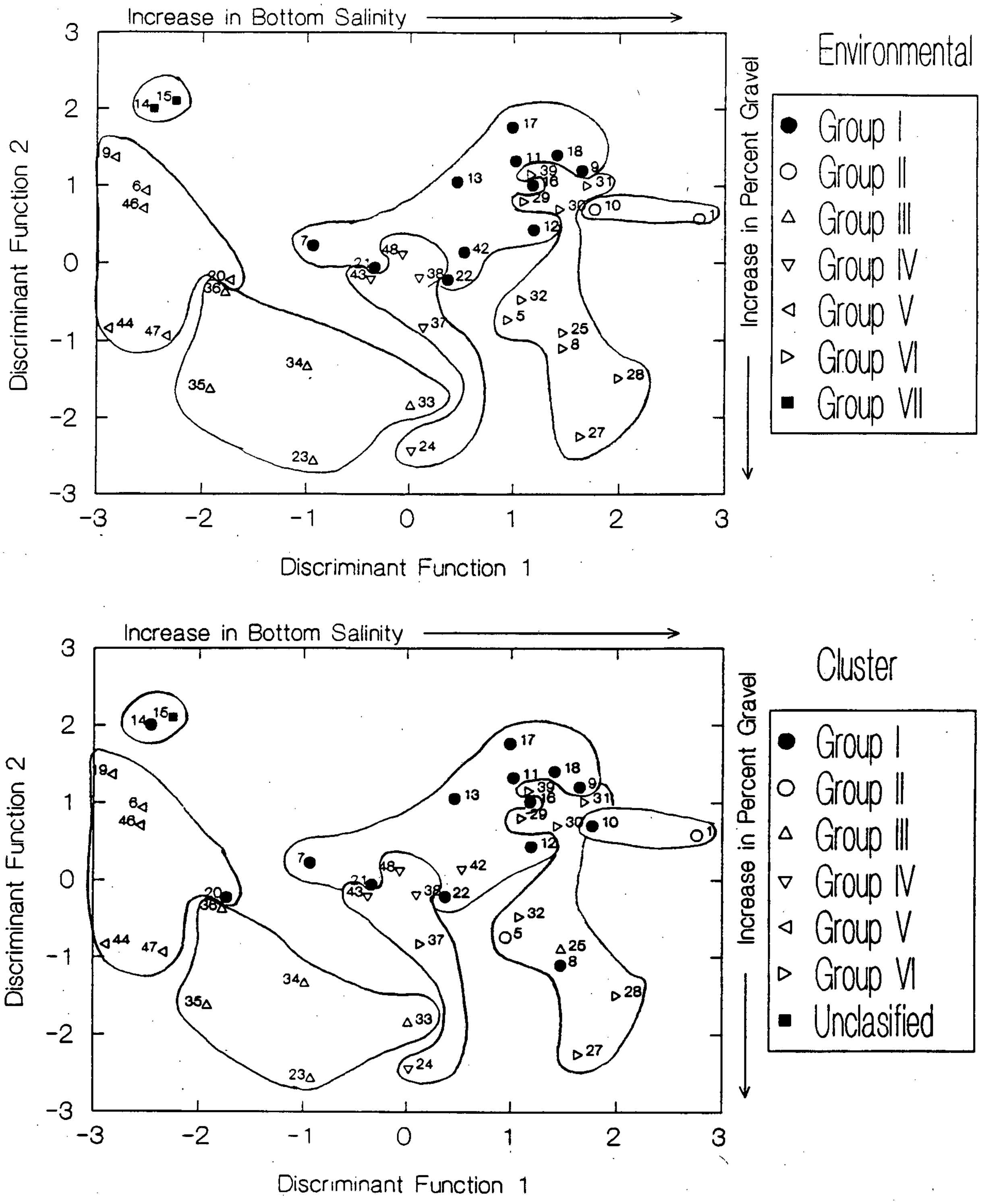

Figure 5. Station groupings formed in the discriminant function analysis based on environmental data. To demonstrate the differences in classification of eight stations, station associations of the upper panel are reploted in the lower panel with symbols used for the associations determined in the cluster analysis of Figure 4.

Table 5.—Results of the principal component analysis using both environmental factors, and infaunal and epifaunal abundance.

Variable	PC1	PC2	PC3
Sand	0.563	-0.451	-0.643
Gravel	0.663	-0.421	0.771
Depth	-0.796	0.398	-0.238
Bottom salinity	-0.882	0.118	0.105
Epifaunal abundance	0.461	0.861	0.060
Infaunal abundance	0.318	0.880	0.040
Cumulative variance	0.371	0.649	0.805
Eigenvalue	2.596	1.951	1.095

DISCUSSION

Based on sediment distribution, hydrography, and infaunal and epifaunal molluscs of the area, we hypothesized that there would be differences in abundance and biomass of fishes occupying the different water masses in the northeastern Chukchi Sea and that fish communities would relate to infaunal and eipfaunal invertebrate communities previously identified. We found that abundance and biomass of fishes are generally arranged in an onshore-offshore and north-south configuration. Further, species richness decreased from south to north. The distribution of fish associations was also related qualitatively to the infaunal and epifaunal mollusc associations found by Feder *et al.* (Chapter 10), i.e., the several nearshore and offshore fish associations were similarly distributed as the mollusc associations..

The total of 66 species, 56 in 1990 and an additional 10 species in 1991, collected in this study is considerably more than has been collected in previous studies in the area. The total number of species varied from only one (Arctic cod) at station 27 to 19 species at stations 6, 45, and 48 in 1990. In 1991 only one (Arctic cod) was found at station 21 with 24 species occurring at station 6. A common feature between the other studies and ours was the dominance of Arctic cod. In a trawl survey west of Pt. Barrow and western Beaufort Sea, Frost and Lowry (1983) found 19 species, with Arctic cod, Canadian eelpout (*Lycodes polaris*), twohorn sculpin (*Icelus bicornus*), and hamecon being the most common taxa. Fechhelm *et al.* (1985) surveyed primarily the along-shore waters of the area with several offshore stations sampled and captured 29 species with a trend of lower catch/unit effort (CPUE) from south to north and greater offshore than onshore. Fechhelm *et al.* found that, in addition to Arctic cod, the other most common species were capelin and Arctic flounder (*Liopsetta glacialis*). The number of species we collected, however, is somewhat similar to that collected by Alverson and Wilimovsky (1966) in the southeastern Chukchi Sea whose sampling extended as far north as Cape Lisburne. Alverson and Wilimovsky (1966) identified 52 species of which Arctic cod, capelin (*Mallotus villosus*), and Bering flounder were most common. They also commented that there was no "definite" pattern in abundance of the top 10 species.

The number of species we found (66) in the northeastern Chukchi Sea is comparable to other areas. Day and Pearcy (1968) found 67 species representing 21 families offshore of central Oregon in depths of 40 to 1,829 m. In contrast, Pearcy (1978) sampled seven stations off Oregon found between 19 and 35 species at depths of 74 to 195 m. Fargo and Tyler (1991) report more than 50 species of groundfish in Hecate Strait, British Columbia. Oviatt and Nixon (1973) found 99 species in Narragansett Bay, 10 of which accounted for 91% of the catch. Merrett *et al.* (1991) found 43 species in 15 families at depths of 2,230 to 4,787 m in the eastern North Atlantic. In contrast to numbers of species, species diversity indices seem to be somewhat lower than that reported for other areas and more in the range observed in areas stressed by anthropogenic sources. Diversity indices in our study varied from 0.20 (station 18 but was zero at other stations previously mentioned where only Arctic cod were found) to 1.87 (station 14 off Cape Lisburne) and 1.99 (station 45 off Pt. Lay). Percy (1978) found diversity (H_e) ranging from 0.7 to 2.47. Oviatt and Nixon (1973) found that species diversity indices varied from about 1.5 in January to 3.0 in September. In a polluted estuary of the Port of Boston Haedrich and Haedrich (1974) calculated indices which varied from 0.33 in August to 1.03 in March. Bechtel and Copeland (1970) investigated diversity in relation to pollutants in Galveston Bay, found indices to vary from 0.89 in February to 1.59 in July with some sites as low as 0.022 - 0.091. Because of the differences in effort and area covered, however, it should be cautioned that these comparisons of species numbers and diversity are qualitative.

At first inspection it appears that abundance and biomass is comparable to that found in more southern areas (Table 6). For example, in 1990 abundance ranged from 366 fish/km^2 (station 26) to 131,000 fish/km^2 (station 9) and biomass ranged from 2 kg/km^2 (station 29) to 2,228 kg/km^2 (station 9). Arctic cod, however, made up the majority of abundance and biomass in the study area and the proportion varied extensively. Abundance of Arctic cod made up a low of 0.23% and biomass 0.18% at station 15 off Cape Lisburne to a high of 100% at station 27 northwest of Pt. Franklin. Thus, even though total abundance and biomass seems comparable to other studies (Table 6), it consists primarily of Arctic cod and abundance and biomass of the remaining species is very low.

Table 6.—Standing crop, abundance (fish/km^2) and biomass (kg/km^2) for fishes from other representative studies.

Area	Abundance	Biomass	Authors
Norton Sound Nearshore	-----	320	Wolotira *et al.*, 77
Norton Sound Offshore	-----	159	Wolotira *et al.*, 77
Bering Sea Nearshore	-----	639	Wolotira *et al.*, 77
Bering sea Offshore	-----	351	Wolotira *et al.*, 77
Narragansett Bay	8,400	9,000-30,000	Nixon & Oviatt 73
Continental Oregon	14,000-40,000	900- 2,200	Pearcy 78
Coral Reef	-----	58,000	Bardach 59
Kelp Forest	-----	33,000-37,000	Quast 68
Embayment	-----	335,000	Nixon & Oviatt 73
Chukchi Sea	366-13,100	2.1- 2,229	Current Study

There is a qualitative similarity in the distribution of fish abundance, biomass, and associations to the epifaunal molluscs (Feder *et al.* Chapter 10). Feder *et al.* found abundance and biomass of epifaunal molluscs highest at stations along the coast with very high values adjacent to Pt. Hope and north of Cape Lisburne. High infaunal abundance and biomass, however, occurred north of and adjacent to the bottom front associated with the Alaska Coastal Current and along the coast north of Icy Cape and adjacent to or north of Cape Lisburne. Feder *et al.* also described six infaunal and five epifaunal assemblages. Significant to the current study, we found several nearshore and offshore fish assemblages which were configured somewhat similarly to the epifaunal mollusc assemblages found by Feder *et al* (Chapter 10).

The qualitative similarities between our study and that of Feder *et al.* (Chapter 10) suggests that there are common variables influencing the distribution of organisms inhabiting the area. In our study the results of the multivariate analyses using environmental data yielded similar patterns of classification; 80% of the stations were classified similarly in the discriminant analysis on salinity and percent gravel as they had been classified in the cluster analysis. Moreover, the principal component analysis accounted for 75% of the variation in station classification with heavy loadings on bottom salinity and percent gravel. The principal component analysis also suggests other variables are important, besides heavy loadings on bottom salinity and gravel, there were heavy loadings on depth, and infauna and epifaunal abundance. Other studies have found relationships between sediment type (Scott 1982), salinity and temperature (Jahn and Backus 1976; Mahon and Smith 1989), depth (Day and Pearcy 1968; Fargo and Tyler 1991), and organic matter (Oviatt and Nixon 1973). The influences of these factors are difficult to discern, undoubtedly due to their varying in concert and interactions between them. As an example, Fargo and Tyler (1991) found associations related to depth and sediment type where sediment type was different for each species association. Species-associations and sediment type, however, did not exactly coincide; two sediment types were found in the same depth range of species-associations. They suggested that faunal similarities were maintained in regions of sediment transition and factors other than sediment type governed distribution of associations. Similarly Pearcy (1978) found a clear separation of the effects of depth but not sediment for two associations, one shallow and one deep. There was, however, an interaction between depth and sediment type where the shallow assemblage showed a high similarity between stations of different sediment types. Although Pearcy did not find a significant relationship between sediment type and total abundance, he did find a significant relationship with particular flatfish species. For example, higher catches of the slender sole (*Lyopsetta exilis*) were found on clay/silt sediments and low catches on sandy sediments. In contrast the Pacific sandab (*Citharichthys sordidus*) showed the opposite relationship. Although depth has been found to be a factor influencing fish associations, in our case it seems surprising that it entered the principal component analysis; the depth profile of the study area is characterized as gradual and shallow except for off Pt. Franklin (Figure 1).

If the associations we identified were a constant feature of the area and unaffected by the variation in hydrography, we would expect to find no significant (statistical) differences between years in species ranks at stations sampled both years. Additionally, those stations resampled in 1991 would also classify in the same association when included with the 1990 data. Three of the 8 stations sampled both years were significantly (Table 2) different between years in species rankings. These three stations also classified with other associations when the data from those stations resampled in 1991 are combined with the 1990 and similarities are recalculated. At those stations which were not significantly different between years there still were considerable differences in abundance between years (Table 2). For example, there were an estimated 61,000 fish/km^2 at station 6 in 1990 but only 29,000 fish/km^2 in 1991.

The age structure of Arctic staghorn sculpin and Bering flounder, and interannual differences in the Alaska Coastal Current (ACC) suggest there is considerable instability in the hydrography of the northeastern Chukchi Sea. Whether our observed assemblages and their location are permanent features of the area is unclear. Smith *et al.* (Chapter 5) found that 42% of the Arctic staghorn sculpin sampled in 1990 consisted of fish older than four years. In 1991 the number of fish in these age categories represented only 9% of the total. For Bering flounder in 1990 Smith *et al.* (Chapter 6) found that ages ranged from 1 to 11 with age class 5 dominating. This differs considerably with Pruter and Alverson (1962) who found ages ranging from 6 to 13 with ages 7 through 9 making up 90% of the total number of fish. Finally, the strong coherence between wind directions and direction of the ACC (Weingartner, Chapter 3) causes periodic southerly reversals of the ACC (Johnson 1989; Weingartner Chapter 3) which can be prolonged. This in turn causes considerable variation in the flow into the Chukchi Sea and potential transport of adult and larval fishes into the area. This could cause, in part, a lack of coherence in fish associations between years.

Although considerable instability in the areal distribution and abundance of fish species and therefore associations is suggested, this may not lead to different associations and their locations. Overholtz and Tyler (1985) concluded that, even though some assemblages changed dramatically in species richness and relative abundance, the spatial integrity of each complex remained constant over time. Similarly there were seasonal changes in species associations on the Scotian Shelf but they were relatively constant over nine years within seasons (Mahon and Smith 1989). Colvocoresses and Musick (1984) examined nine years of trawl data from the Middle Atlantic Bight. The distributional patterns were largely structured by temperature on the inner- and mid-shelf and by depth on the outer shelf and shelf break. They also found there was sedimentary and topographical uniformity of the inner- and mid-shelf with no strong species group-sedimentary relationships. Temporally, as with Mahon and Smith (1989), they found good geographic definition in both autumn and spring groups with overlap between groups. The groups which made up the communities differed between seasons but simultaneously had much in common. Colvocoresses and Musick also found relationships between groups and depth, and shifts in the groups with changes in temperature. For example, the geographic extent of the associations varied between years depending on the southward extent of the cooler 8° C water. They concluded that the fish behave as a group in response to environmental variation.

The fish associations found in this study were depicted as having clear assemblage boundaries, each of which has a characteristic assemblage of species and proportions of each species, that are related to sediment type and hydrographic features. Although other characteristics may be determinants, as indicated by the principal coordinate analysis, the associations should undoubtedly be thought of as gradual shifts in species and proportions over transitional areas of these features as evident in the ordination plots (Figure 5). This is similar to the mesopelagic fishes of McKelvie (1985) who concluded that the associations were best interpreted as a gradation between faunas. The area could be viewed as a transition zone between the fish communities of northern Bering Sea and the southern Chukchi Sea, and the Arctic Ocean in which fishes of the northeastern Chukchi Sea are a mixture of the two fish communities. In this view the presence of the different species, their abundance and biomass vary, shifting somewhat offshore/onshore or northerly/southerly, with the shifts in the hydrographic structure of the area.

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CHAPTER 10

DISTRIBUTION OF MOLLUSKS IN THE NORTHEASTERN CHUKCHI SEA[1]

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Abstract.—Infaunal and epifaunal mollusks of the northeastern Chukchi Sea were sampled, and one hundred and thirty-nine molluscan taxa identified. The pattern of spatial distribution of molluscan species was determined by cluster analysis which resulted in six infaunal and five epifaunal station groups. Species characterizing various faunal groups are defined. Stepwise multiple discriminant analysis was applied to correlate benthic biological associations with environmental variables. Delineation of infaunal groups was mainly due to percentage of sand and bottom salinity while epifaunal groups were separated by percent gravel and bottom temperature. An increase in abundance and biomass of infaunal mollusks occurred adjacent to, and north and northwest of an identified bottom front between the Bering Shelf and Resident Chukchi Water, and Alaska Coastal Water. Epifaunal molluscan abundance and biomass were highest near the coast. Mollusks, especially smaller species and the juvenile stages of larger species, represent a food resource for bottom-feeding predators in the study area.

Key words: Chukchi Sea, mollusk, benthic, infauna, epifauna, bottom front, bottom - feeding predators, cluster analysis, discriminant analysis.

INTRODUCTION

Limited quantitative information is available for marine mollusks of the Chukchi Sea north of 68° 21' latitude and east of 170° 00' west longitude (Figures 1 and 2). However, an investigation of the infauna of this region by Feder *et al.* (1990) indicated that this group is an important one comprising approximately 20% of the abundance, 36% of the wet weight, and 40% of the carbon biomass of infauna collected. Studies by Stoker (1978, 1981) in the northeastern Chukchi Sea examined distribution, abundance, and biomass data for mollusks in conjunction with other infaunal organisms. Both Stoker (1978) and Feder *et al.* (1990) include interpretations of total infaunal distributions based on environmental parameters. The abundance and distribution of bivalves in the western Chukchi Sea are discussed in Filatova (1957). The distributional ecology of bivalves in the adjacent western Beaufort Sea is presented in Carey *et*

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[1] In press with Arctic for publication.

al. (1984). Qualitative reports on molluscan fauna in the general area are included in MacGinitie (1955) for the Point Barrow region, Ingham *et al.* (1972) and Mann (1977) in the eastern Chukchi Sea, and Frost and Lowry (1983) in the western Beaufort Sea. Supplemental information on the composition and general distribution of selected mollusks in these northern latitudes is also available from feeding investigations on walrus and bearded seals (Johnson *et al.* 1966; Fay, 1982; Lowry et *al.* 1980a, b). Additionally, a number of studies include information for molluscan fauna in the southeastern Chukchi Sea. Sparks and Pereyra (1966) present data from 1959 on the composition and relative abundance of mollusks south of Point Hope, although they include some data from stations north of Cape Lisburne. A trawl survey conducted in 1976 provides quantitative data on the epifauna, inclusive of mollusks and demersal fishes, in the area between Bering Strait and Point Hope (Wolotira *et al.* 1977; Feder and Jewett, 1978; and Jewett and Feder, 1981). Qualitative and quantitative sampling for epifauna and demersal fishes was conducted in 1982 in shallow waters (<15 m) in the Kivalina region, south of Point Hope (Blaylock and Erikson, 1983; Blaylock and Houghton, 1983). Information on infauna, inclusive of mollusks, is included in multi-year studies in the northern Bering and southern Chukchi Seas by Feder *et al.* (1985), Grebmeier (1987, 1992), Grebmeier *et al.* (1988, 1989), and Feder *et al.* (1990a,b).

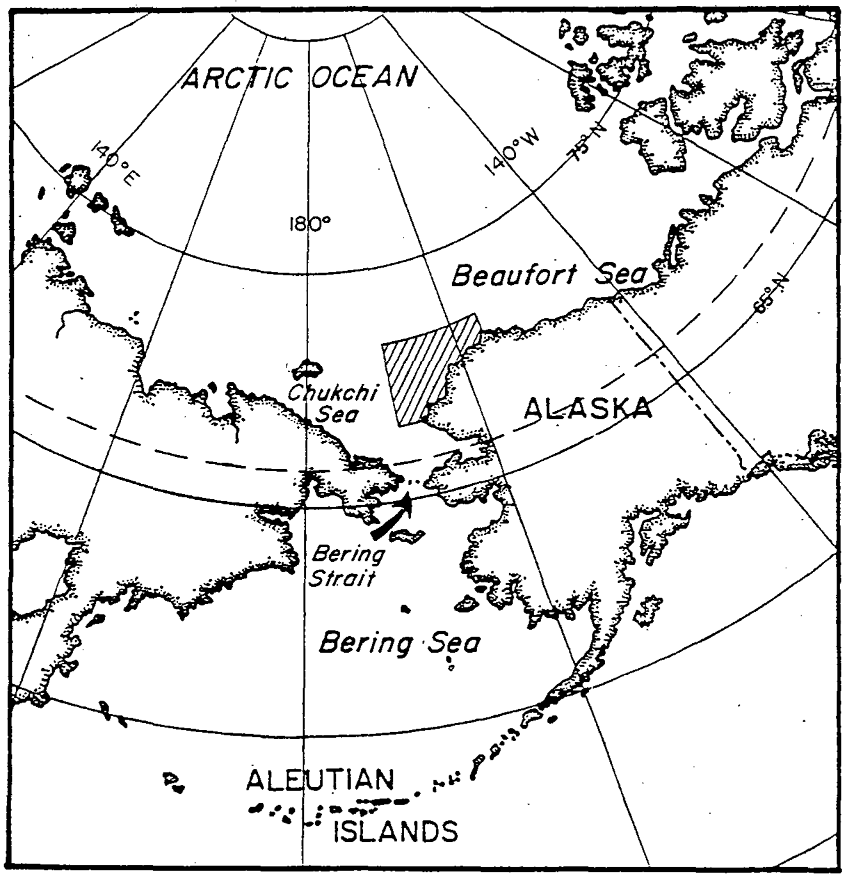

Figure 1. Location of the study area (cross hatched).

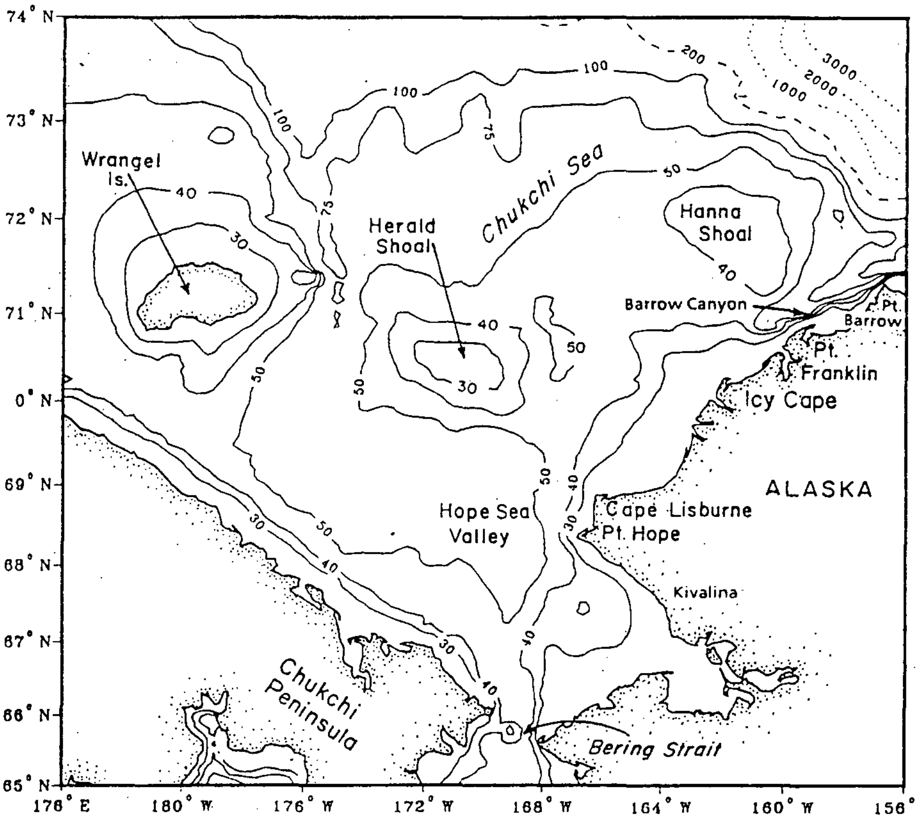

Figure 2. Bathymetry of the Chukchi Sea.

Taxonomic literature on mollusks of the northeastern Chukchi Sea is scattered among many sources. Because most mollusks within the study area are widely distributed in arctic and boreal seas, taxonomic descriptions are primarily included in publications relating to areas adjacent to the Chukchi Sea. MacGinitie (1959) describes the molluscan fauna near Point Barrow; Macpherson (1971) summarizes the gastropods, chitons, and scaphopods from the Canadian Archipelago; Bernard (1979) and Lubinsky (1980) provide useful descriptions of the bivalve fauna of the western Beaufort Sea and the eastern Canadian arctic, respectively. Mollusks from adjacent Japanese waters (including the Okhotsk and western Bering seas) are described in Okutani *et al.* (1988, 1989), and reference to these and other mollusks is also found in Pavloskii (1955). Foster (1981) and Baxter (1987) summarize the composition and distribution of molluscan fauna throughout Alaskan waters.

In this paper we consider the infaunal and epifaunal mollusks of the northeastern Chukchi Sea, and relate their abundance and biomass values to environmental parameters, and consider the importance of mollusks as food for benthic predators in the study area.

THE STUDY AREA

The northeastern Chukchi Sea is relatively shallow, with depths ranging between 30 and

60 m over most of the region (Figure 2). In general, bottom depth varies smoothly, although there are several important bathymetric features which influence both the flow and distribution of water masses. These features include (1) Barrow Canyon which strikes northeastward across the continental shelf and slope west of Point Barrow, (2) Hope Sea Valley, a broad, 55 m deep depression which trends northwestward from Point Hope, (3) Hanna Shoal to the west of Barrow Canyon, and (4) Herald Shoal in the center of the Chukchi Basin. The two shoals have minimum depths of about 25 m.

Circulation features and water-mass properties of the Chukchi Sea are discussed by Coachman *et al.* (1975), Walsh *et al.* (1989), Johnson (1989), and Weingartner (Chapter 2). Chukchi Sea waters reflect a combination of both advective and *in situ* processes with the most important of these being the northward advection of waters through Bering Strait. This flow bifurcates offshore of the Lisburne Peninsula. One branch transports Bering Shelf Water (BSW) northwestward through the Hope Sea Valley but also northward along the eastern flank of Herald Shoal. This water mass is characterized by low temperatures (-1° to 2°C), high salinity (>32.5/psu) and relatively high nutrient and particulate organic carbon (POC) concentrations (Grebmeier *et al.* 1988; Walsh *et al.* 1989). In summer and fall, part of the northeastward flowing branch forms the Alaska Coastal Current (ACC) and consists primarily of Alaska Coastal Water (ACW). This water mass, which is heavily influenced by coastal freshwater discharge from the Yukon River and numerous smaller drainages along the western coast of Alaska, consists of relatively warm (>2°C) and dilute (<31.8/psu) water, with a high sediment load but low concentrations of nutrients and POC (Grebmeier *et al.* 1988). The Alaska Coastal Current flows inshore of and parallel to the 30 and 40 m isobaths and exits the Chukchi Sea through Barrow Canyon. A third water mass, Resident Chukchi Water (RCW), is either advected onshore from the upper layers of the Arctic Ocean and/or is ACW and BSW remnant from the previous winter when its salinity was increased and temperature decreased due to freezing processes. As noted by Johnson (1989) and Weingartner (Chapter 2), a bottom-intersecting front paralleling the 30 and 40 m isobaths is typically observed in summer and fall months. The front extends northward from the Lisburne Peninsula to about 71°N and then bends eastward toward Icy Cape and Pt. Franklin. ACW lies inshore of this front while BSW, RCW, and mixtures of these water masses lie offshore and to the north of the front (Johnson, 1989). Because ACW is less dense than BSW or RCW, ACW may also be observed at the surface and offshore of the bottom front. Year-long current meter records from 1991/92 and a fall 1992 hydrographic survey identified a persistent northward flow of BSW along the east flank of Herald Shoal (Weingartner, unpublished). Coachman and Shigaev (1992) and Whitledge *et al.* (1992) speculate that a fraction of the water flowing north along the Lisburne Peninsula is ultimately derived from the vicinity of Wrangel Island in the northwest Chukchi Sea. This high-salinity, nutrient-rich water is advected into the southeastern Chukchi Sea along the Siberian coast by the Siberian Coastal Current. They suggest that nutrients within this current supplement those derived from the Bering Sea to enhance annual primary production in the southcentral Chukchi Sea and contribute POC to the northeastern shelf (Grebmeier *et al.* 1988; Walsh *et al.* 1989). Occasionally, wind-induced reversal of the normal northeastern water flow along the coast is accompanied by upwelling (Wiseman and Rouse, 1980: Johnson, 1989). As discussed later, all the above observations have important effects on the distribution, abundance, and biomass of mollusks in the northeastern Chukchi Sea.

In the northeastern Chukchi Sea, the inner shelf between Point Hope and Point Barrow is carpeted by relatively coarse sediments. Further seaward are muds containing various proportions of gravel and sand (Naidu, 1987). Sediments of the more northerly offshore region have a higher percentage of water and lower percentage of gravel than the southern offshore area (Feder *et al.* 1990a). All sediments are very-poorly to extremely-poorly sorted. The central portion of the northeastern Chukchi Sea receives the major proportion of clayey sediments of Yukon River origin. Sediment is displaced from the Bering Sea via the net northward flow of water masses presumably as a nepheloid layer (McManus and Smyth, 1970). Sea ice covers the Chukchi Sea from November through June and can affect the benthos by ice gouging (Grantz *et al.* 1982; Carey, 1991). Polynyas can occur from Cape Lisburne to Point Barrow, generally extending seaward from just beyond the landfast ice (Stringer and Groves, 1991).

MATERIALS AND METHODS

Infaunal mollusks, and conductivity, temperature and depth (CTD) data, were collected in August-September 1986 at 37 stations in the study area (Figure 3a). Five replicate samples using a 0.1 m^2 van Veen grab were taken at each station. Epifaunal mollusks and associated physical oceanographic data were collected in August 1990 at 48 stations at similar depths to the 1986 collection, as part of a fish survey in the northeastern Chukchi Sea (Figure 3b; Smith *et al.* unpublished). Epifauna was obtained using a NMFS 83-112 otter trawl. The net had a 90 mm mesh cod end and a 32 mm stretched liner. Effective opening width of the net was 17.0 m. Two 30-minute tows were taken at each station. Sediment data are from Naidu (1987) and Feder *et al.* (1990a).

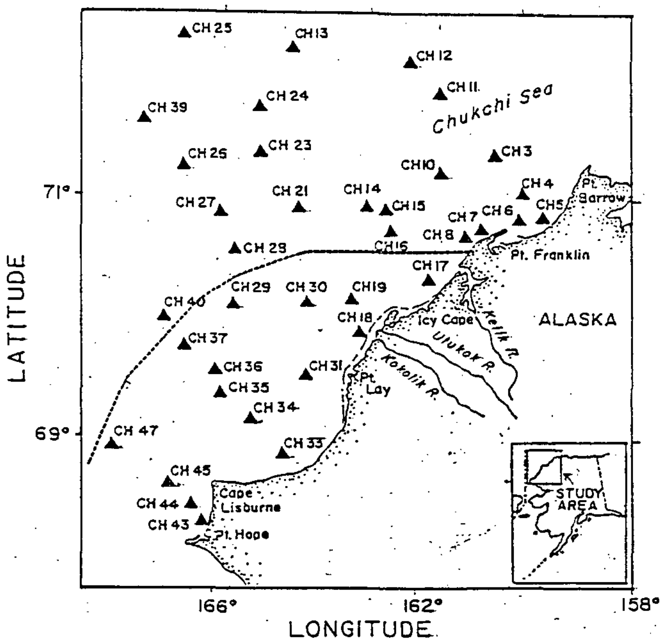

Figure 3a. Location of the infaunal sampling stations occupied in the northeastern Chukchi Sea by Feder *et al.* (1990a). Dashed line represents a bottom frontal zone that separates Bering Shelf and Resident Chukchi Water, offshore and to the north, from Alaska Coastal Water, inshore of the front.

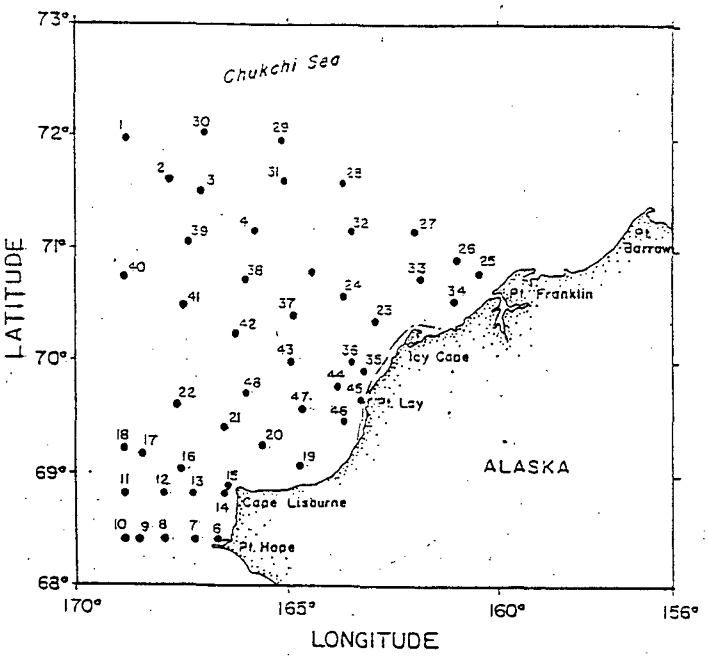

Figure 3b. Location map showing epifaunal sampling stations occupied in the northeastern Chukchi Sea in 1990 by Smith *et al.* (unpublished).

Specimens were identified to species or lowest possible taxon. Voucher specimens are deposited in the University of Alaska Museum Aquatic Collection, Accessions 1993-3 (specimens collected in 1986) and 1992-16 (specimens collected in 1991). Photographs of nine species, which are common in the study area, but have not been well illustrated in the literature, are included in this paper.

The 1986 infaunal collection of Feder *et al.* (1990a) extended farther north than the epifaunal sampling of 1990 (Smith *et al.*Chapter 5). Infaunal and epifaunal samples were collected by different gear types. Each infaunal sample represented a localized area while epifaunal data were derived from samples taken over a variable distance. Consequently, it was necessary to establish new station numbers for the epifaunal studies in August 1990. Thus, it was not technically possible to pool and analyze all molluscan data. Infauna and epifauna are treated separately here with some integrations of data included in the discussion.

Data used in the classification of stations consisted of taxon abundance values (infauna: ind/m^2; epifauna: ind/km^2). One species, (*Neptunea heros*) was eliminated in the epifaunal multivariate analysis because its high abundance and ubiquitous occurrence overwhelmed the variations among other species considered dominant. In order to normalize data, a log transformation (*ln* [X+1]) was applied prior to cluster analysis. The Czekanowski similarity coefficient was used for clustering (Bray and Curtis, 1957; Boesch, 1977). Top-ranked taxa in each station group and percent fidelity of these taxa to stations in each station group are presented. Stepwise multiple discriminant analysis (Davies, 1971), using the BMDP7M and SPSS Discriminant programs, was applied to biological data to correlate station group separation by cluster analysis with environmental variables. Such an analysis has been used elsewhere to test a biological model (e.g., station groups), with environmental parameters (Flint, 1981; Shin, 1982; Weston, 1988). Environmental variables used were sediment variables [particle size parameters, organic carbon (C), nitrogen (N), and C/N values], and bottom temperature and salinity. The percentage values for sediment grain-size distribution were arcsine transformed. Wet-weight values of infauna were converted to carbon by applying conversion values of Stoker (1978) determined for taxa in the same region. Only wet-weight values were used for the epifaunal analyses. Standard discriminant function coefficients are presented. These coefficients indicate the relative contribution of the variables in calculating the discriminant scores on each function, and are commonly used as measures of the relative importance of the variables in discriminating among groups (Green, 1971; Green and Vascotto, 1978). Infaunal stations were segregated into a northern and a southern group by the frontal zone identified by Johnson (1989), Feder *et al.* (1990a), and Weingartner (Chapter 2) and the differences between mean abundance and carbon biomass values for each group tested statistically. Statistical analysis of these data consisted of *t*-tests utilizing SYSTAT (Wilkinson, 1990). Prior to analysis, a square root transformation was applied to the data (Sokal and Rolf, 1969; Zar, 1974).

RESULTS

General.—Approximately 75 and 62 mollusk taxa were identified from the grab and the trawl samples, respectively. These taxa included 52 bivalves, 83 gastropods, three polyplacophorans, and one cephalopod. One hundred and thirty nine molluscan taxa were identified. All taxa are listed in Appendix I, along with comments on taxonomy.

Infauna.—Abundance values for the 37 stations sampled in 1986 ranged from 16 to 880 ind.m^{-2} with a mean of 248 ind/m^2. Biomass ranged from 0.007 to 15.02 gC/m^2 with a mean of 3.04 g C/m^2. Highest abundance and biomass values generally occurred north of and adjacent to the bottom front identified by Johnson (1989), Feder *et al.* (1990a) and Weingartner (Chapter 2) (Figures 4a,b). Some high values were also recorded adjacent to Point Hope and north of Cape Lisburne. At stations north and west of the bottom front, mean infaunal molluscan carbon biomass ($\bar{X}$=3.97; S.D.=3.48) was significantly higher (P=0.01) than at the southern stations ($\bar{X}$=1.72; S.D.=1.53).

Protobranch bivalves dominated infaunal abundance and biomass, and were widely distributed. *Nucula tenuis* was present at 29 stations, primarily where muddy substrate prevailed. Other protobranch species, *Nuculana radiata, Yoldia hyperborea*, *Y. scissurata*, and *Y. myalis*, were more localized in their distribution. Three species of heterodont bivalves (*Astarte montagui, A. borealis*, and *Cyclocardia ovata*) also had high abundance and biomass values but more patchy distributions. The heterodont bivalve *Macoma calcarea* was widely distributed (present at 24 stations), but mainly dominated infaunal abundance and biomass within the muddy, northern offshore region and stations just north of Cape Lisburne. The heterodont bivalves *Astarte montagui*, *A. borealis* and *C. ovata* were more common in gravelly substrates, while *Thyasira gouldi* (present at 25 stations), was most abundant off Point Hope at Station 44.

Although a few gastropod taxa were relatively common, compared to bivalves, they were far less abundant. The relationship between small gastropod species collected in the study area and sediment parameters is not known. The opisthobranch gastropods *Cylichna alba* and *Retusa obtusa* were present at 19 and 11 stations, respectively. Common prosobranch gastropods included *Tachyrhynchus erosus* and the trochids, *Solariella varicosa* and *S. obscura.* Turridae, mostly unidentified species of *Oenopota*, were occasionally common.

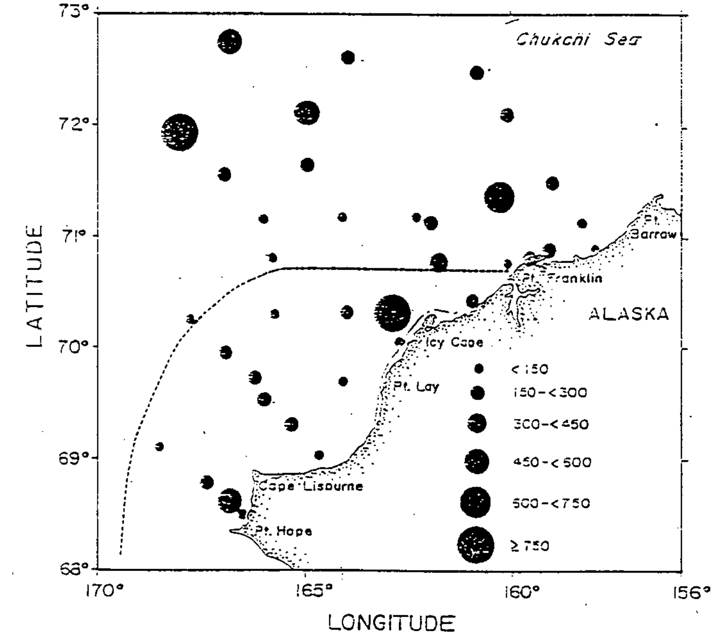

Figure 4a. Abundance (ind/m^2) of infaunal mollusks in the northeastern Chukchi Sea. Dashed line represents a bottom frontal zone that separates Bering Shelf and Resident Chukchi Water, offshore and to the north, from Alaska Coastal Water, inshore of the front.

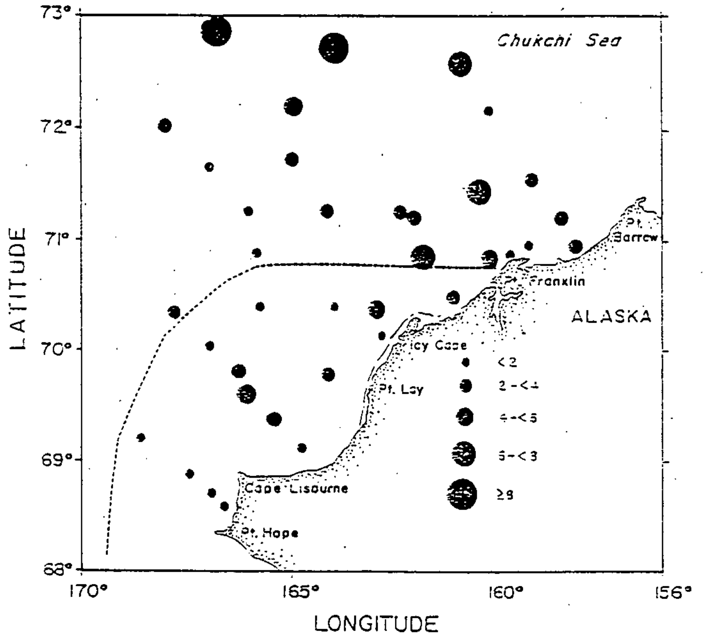

Figure 4b. Carbon biomass (gC/m^2) of infaunal mollusks in the northeastern Chukchi Sea. Dashed line represents a bottom frontal zone that separates Bering Shelf and Resident Chukchi Water, offshore and to the north, from Alaska Coastal Water, inshore of the front.

From the recurrence of stations in the cluster analysis of abundance data (Figure 5), six station groups were determined (Figures 5 and 6). One station adjacent to Point Hope, Station 43, and one station north of Cape Lisburne, Station 33, were not classified based on the distinct faunal composition of each of these stations (Table 1). The dominant fauna (present in 50% or more of stations in a station group) characterizing each station group and the percent occurrence of dominant taxa at stations comprising the groups are included in Table 1. Abundance varied from 42 ind/m^2 within inshore Group VI to 388 ind/m^2 in northern offshore Group I; carbon biomass varied from 0.9 gC/m^2 within inshore Group IV to 5.4 gC/m^2 in Group I (Table 2). The highest abundance and carbon biomass occurred within offshore Station Group I. The largest numbers of *N. tenuis* and *M. calcarea* were found within Group I; abundance of both of these species was considerably less at Groups II and III, the other offshore groups. Group III comprised a mixture of taxa characteristic of inshore and offshore stations, and had the second highest carbon biomass value for station groups. Group IV, extending northwest of Cape Lisburne, was distinguished by large numbers of the bivalve *Thyasira gouldi* with most other taxa in low abundance. Group VI, a sandy-gravelly inshore site just south of Icy Cape, had one of the lowest number of taxa and lowest abundance of mollusks, as well as total infauna (Feder *et al.* 1990a); also, the lowest carbon biomass of infaunal mollusks occurred within this station group. This station group was the only one at which the protobranch bivalve *Y. scissurata* occurred. Substrate at inshore Group V, north of Group VI, comprised a higher percentage of gravel, and had the highest number of taxa of all groups.

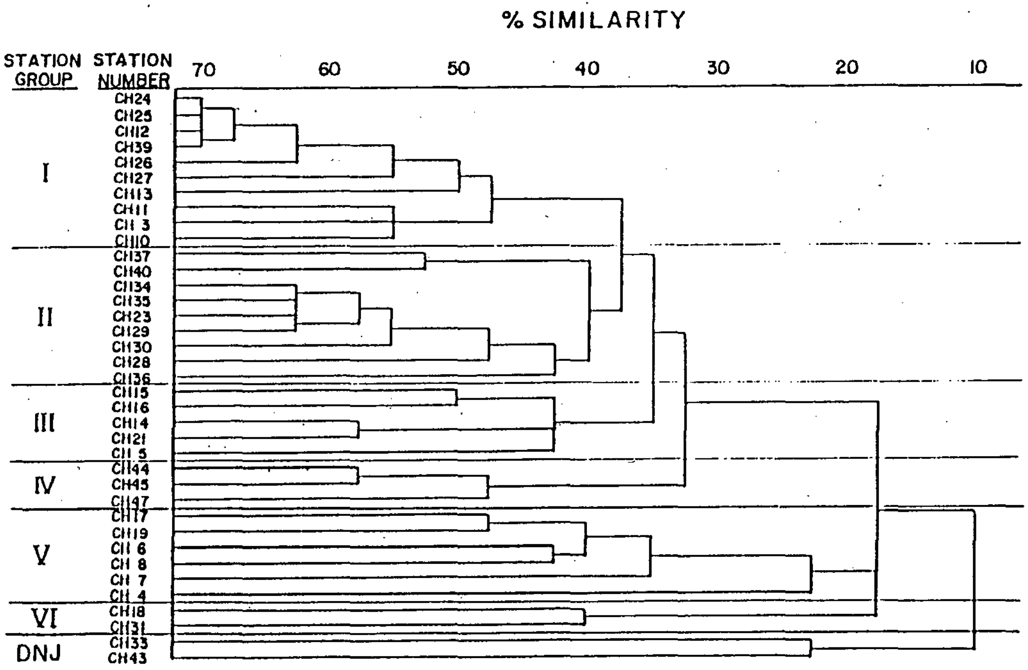

Figure 5. Dendogram showing grouping of stations based on a cluster analysis of infaunal molluscan abundance data. DNJ=Did not join any group.

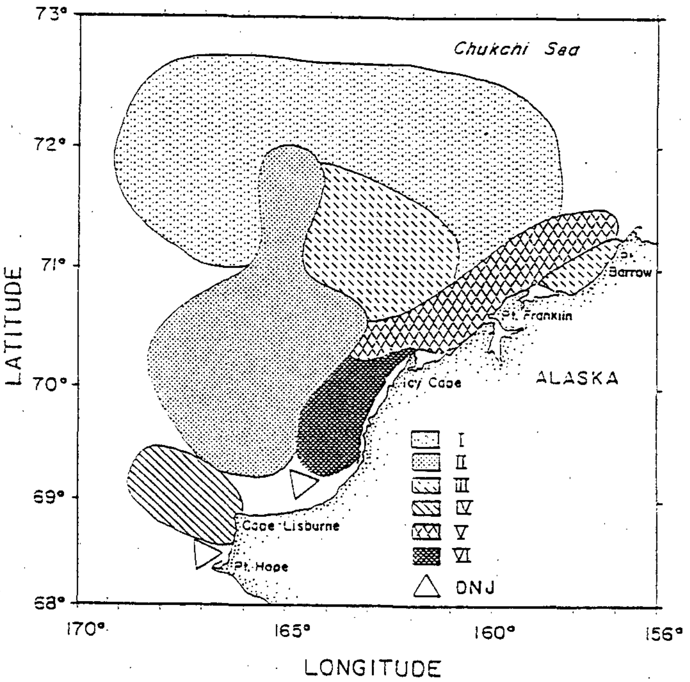

Figure 6. Infaunal molluscan assemblages in the northeastern Chukchi Sea based on cluster analysis.

Table 1.—Infaunal molluscan abundance dominants within six stations groups and two stations not classified. Taxa occurred at 50% or more of the stations within a station group. DNJ= Did not join a station group.

Station Group	Stations in Group	Taxa	Abundance (ind/m^2)	% Occurrence in Group[1]
I	3 10 11	*Nucula tenuis*	196	100
	12 13 24	*Macoma calcarea*	88	100
	25 26 27	*Thyasira gouldi*	17	90
	39	*Yoldia hyperborea*	14	80
		Nuculana radiata	14	50
		Retusa obtusa	11	90
		Mysells sp.	8	60
		Cylichna alba	8	70
II	23 28 29	*Nucula tenuis*	98	100
	30 34 35	*Thyasira gouldi*	14	89
	36 37 40	*Macoma calcarea*	6	56
		Tachyrhynchus erosus	5	89
		Solariella varicosa	4	78
		Cylichna alba	4	56
III	5 14 15	*Nucula tenius*	70	100

Table 1. continued

Station Group	Stations in Group	Taxa	Abundance (ind/m^2)	% Occurrence in Group[1]
III cont.	16 21	*Astarte montagui*	16	100
		Cyclocardia ovata	10	100
		Astarte borealis	9	80
		Solariella obscura	6	100
		Cylichna alba	5	80
		Oenopota sp.	5	100
		Propebela sp.	5	60
IV	44 45 47	*Thyasira gouldi*	105	67
		Nucula tenius	65	100
		Nuculana radiata	57	100
		Retusa obtusa	8	67
		Tachyrhynchus erosus	3	67
		Polinices pallidus	3	100
V	4 6 7 8	*Cyclocardia ovata*	123	83
	17 19	*Astarte montagui*	29	100
		Liocyma viride	25	83
		Yoldia myalis	14	50
		Mysella sp.	13	83
		Ainopsida serricata	8	50
		Musculus spp.	7	100
		Hiatella arctica	5	50
		Polinices pallidus	4	100
VI	18 31	*Yoldia scissurata*	12	100
		Thyasira gouldi	5	50
		Macoma calcarea	4	100
		Clinocardium ciliatum	4	100
		Liocyma viride	3	50
		Liocyma fluctuosa	2	50
		Natica clausa	2	50
		Tellina lutea	2	50
		Cylichna alba	2	100
DNJ	33	*Musculus* spp.	26	
		Cylichna alba	4	
		Nucula tenuis	2	
		Yoldia myalis	2	
		Oenopota spp.	2	
DNJ	43	*Musculus* spp.	10	
		Hiatella arctica	6	

Table 1. continued

Station Group	Stations in Group	Taxa	Abundance (ind/m^2)	% Occurrence in Group[1]
DNJ cont.		(no other molluscan taxa were present)		

[1]The value for each taxon in the column of % Occurrence in Group is based on the number of stations at which the particular taxon occurs.

Table 2.—Number of taxa, abundance, and biomass of infaunal taxa, by station group.

Station Group	Number of Taxa	Abundance (ind/m^2)	Wet Weight Biomass (g/m^2)	Carbon Biomass (gC/m^2)
I	44	388	147	5.4
II	35	168	51	1.8
III	46	201	134	3.5
IV	13	260	20	0.9
V	50	300	70	2.9
VI	15	42	43	0.28

Table 3 shows the results of multiple discriminant analysis of the environmental conditions relative to infaunal station groups determined by multivariate analysis. The discriminant functions (DF) 1 and 2 contribute nearly 85% of the total separation among the groups ($P \leq 0.001$), and 76% of the stations were classified correctly according to station group. Only these functions are considered further in the interpretation. After the final step in the discriminant analysis, F statistics between pairs of station groups showed significant differences ($P \leq 0.003$) in all comparisons except one (Group I vs Group III). Nevertheless, the comparison between the latter two groups was marginally significant ($P=0.06$). The low negative value along the DF 1 is due to percent sand (Figure 7). The high positive value along DF 2 is the result of bottom salinity (Figure 7). The centroid of Group VI is well separated from the other groups along the axis of DF 1. Also, the centroids of Groups II, IV, and V are separated from Groups I and III along DF 1. The centroid of Group IV is well separated from the other groups along the axis of DF 2. Also, the centroids of Groups I, III, and V are separated from Groups II and IV along the axis of DF 2. The separation of inshore Group VI from the other groups is due to the higher percentage of sand at the Group VI stations. Alternatively, offshore Groups I, II and III, and southern inshore Group IV off Cape Lisburne are distinguished by the lower percentage of sand (i.e., presence of more mud) within stations of these groups. The low bottom salinity for Group IV differentiates it from the other station groups. The highest salinity occurs at stations of northern offshore Groups I and III, and northern inshore Group V, which separates them from the other groups.

Table 3.—Results of the discriminant analysis of the environmental conditions among the six infaunal station groups. *Significance at P ≤ 0.001.

Discriminant Function	1	2	3
Percent separation	48.73	35.95	15.31
Cumulative percent separation	48.73	84.69	100.00
Test of significance			
Chi-squared value	87.88*	49.99*	18.11
Degrees of freedom	15	8	3

Variables and Standardized Discriminant Function Coefficient			
Percent sand	-0.82	0.29	-0.53
Salinity	0.26	1.00	-0.18
OC/N	-0.26	0.49	0.89

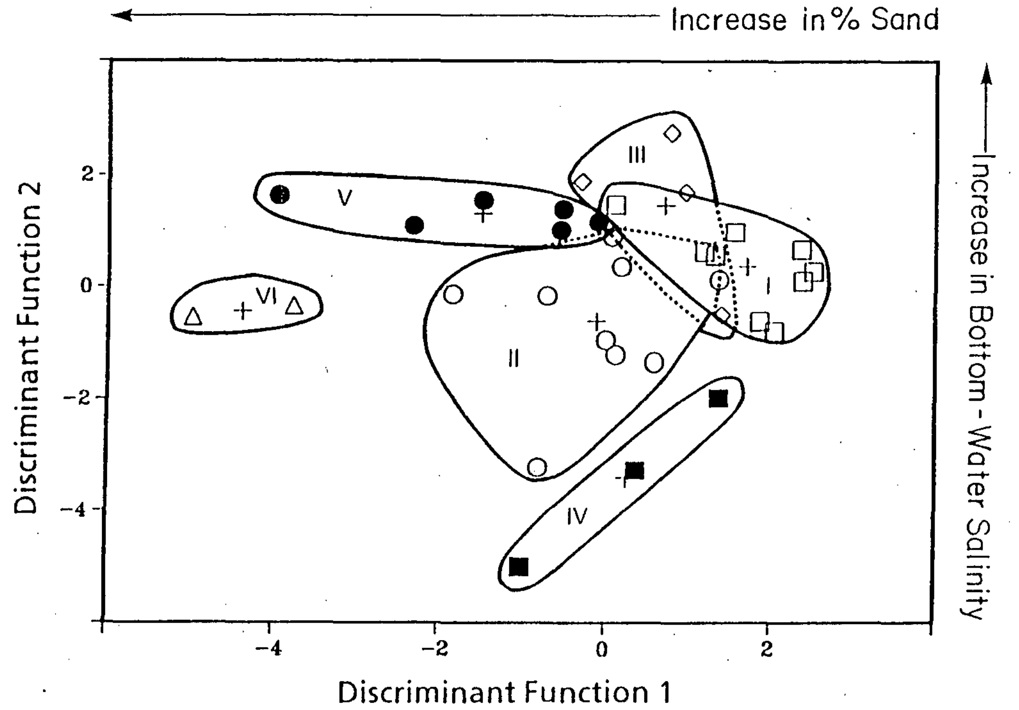

Figure 7. Station and station group plot from stepwise multiple discriminant analysis of molluscan infauna utilizing environmental variables. + = the centroids of the station groups. Sediment values used in the analysis based on dry weights.

Epifauna.—Abundance values from the 48 stations sampled in 1990 varied from 170 to 71,817 ind/km^2 with a mean of 4,227 ind/km^2. Wet-weight biomass ranged from 0.29 to 47.28 kg/km^2 with a mean of 6.42 kg/km^2. Abundance and biomass were highest at stations nearest the coast, with particularly high values west and north of Cape Lisburne and near Point Franklin (Figures 8a and 8b).

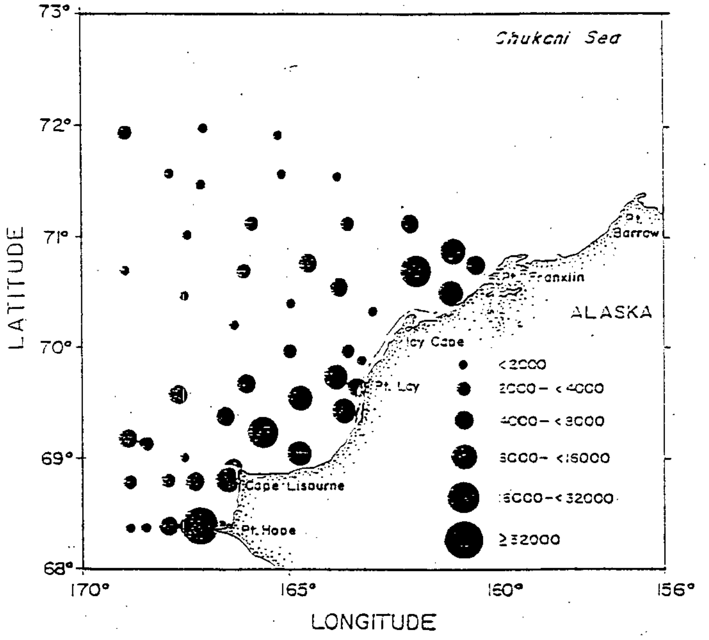

Figure 8a. Abundance (ind/m^2) of epifaunal mollusks in the northeastern Chukchi Sea.

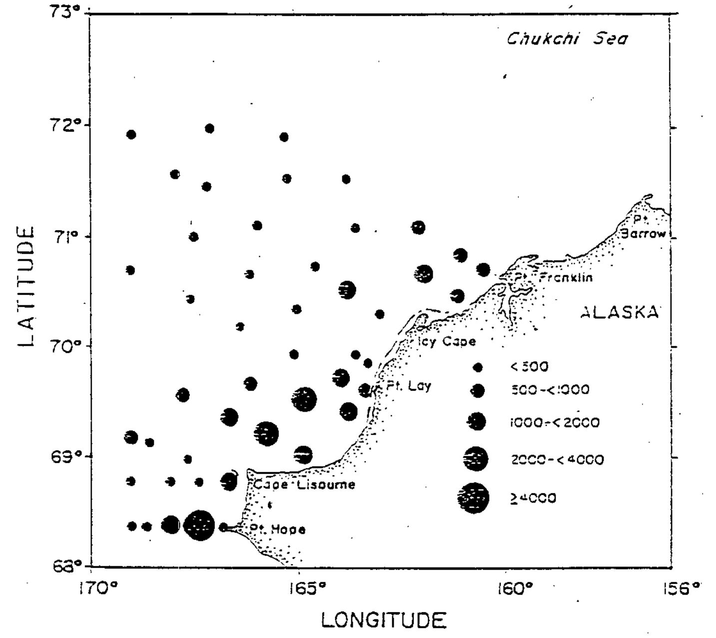

Figure 8b. Biomass (kg/km^2) of epifaunal mollusks in the northeastern Chukchi Sea.

Gastropods made up the greatest portion of the molluscan epifauna in abundance and biomass. The gastropod *Neptunea heros* (Figure 9a) occurred at all stations, and was typically the most abundant mollusk present. Two other species of *Neptunea, N. ventricosa* (Figure 9b), and *N. borealis* (Figure 9c), were nearly as common, occurring at 35 and 45 of the stations, respectively. Other common neptunids included *Volutopsius deformis*, *V. stefanssoni* (Figure 10a), *V. fragilis* (Figure 10b), *Beringius stimpsoni* (Figure 11a), and *Plicifusus kroyeri*. Also generally common were buccinids [*Buccinum angulosum*, *B. polare*, *B. scalariforme*, *B. solenum* and *B. tenellum* (Figure llb, c)] and naticids (*Polinices pallidus* and *Natica clausa*). The internal-shelled prosobranch *Onchidiopsis* had a wide distribution, but whether one or more species was present is uncertain.

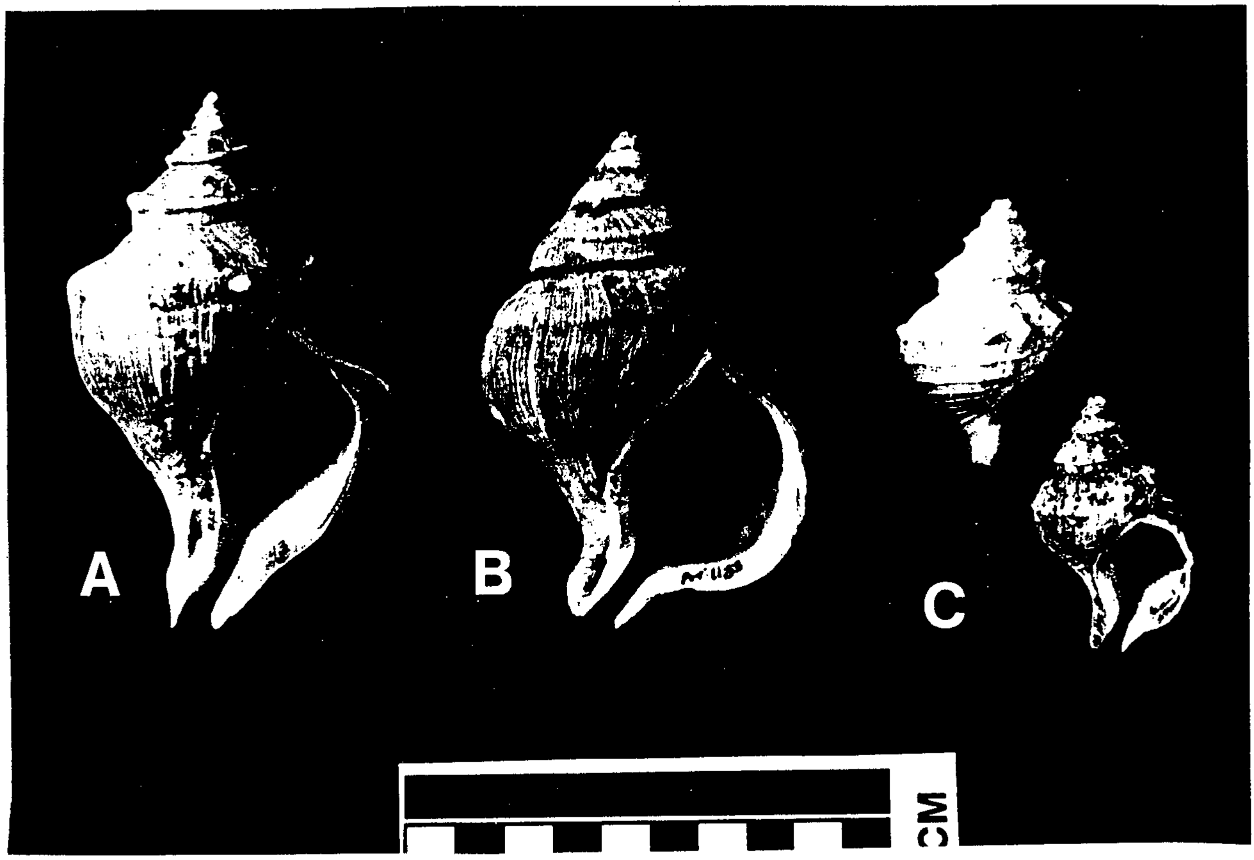

Figure 9a. *Neptunea heros,* 9b. *Neptunea ventricosa,* and 9c. *Neptunea borealis.*

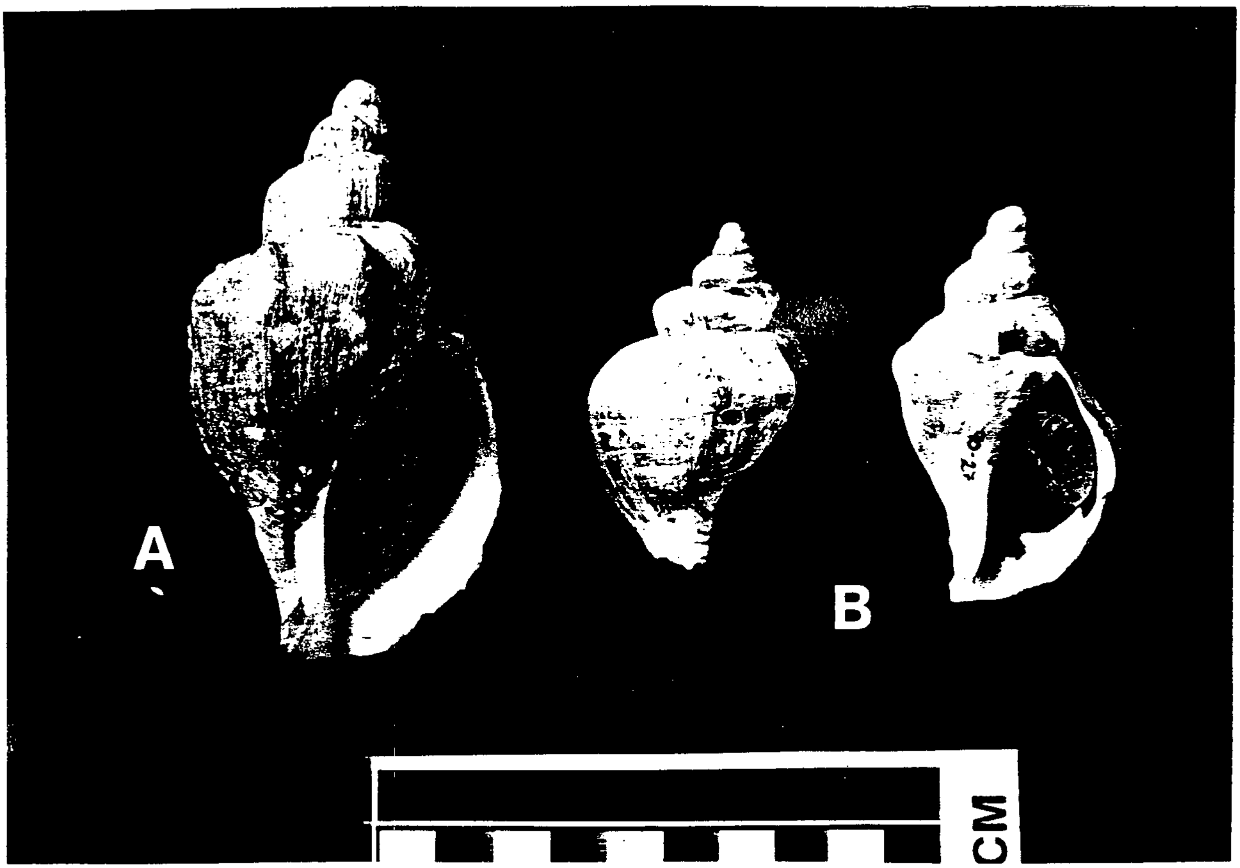

Figure 10a. *Volutopsius stefanssoni,* and 10b. *Volutopsius fragilis.*

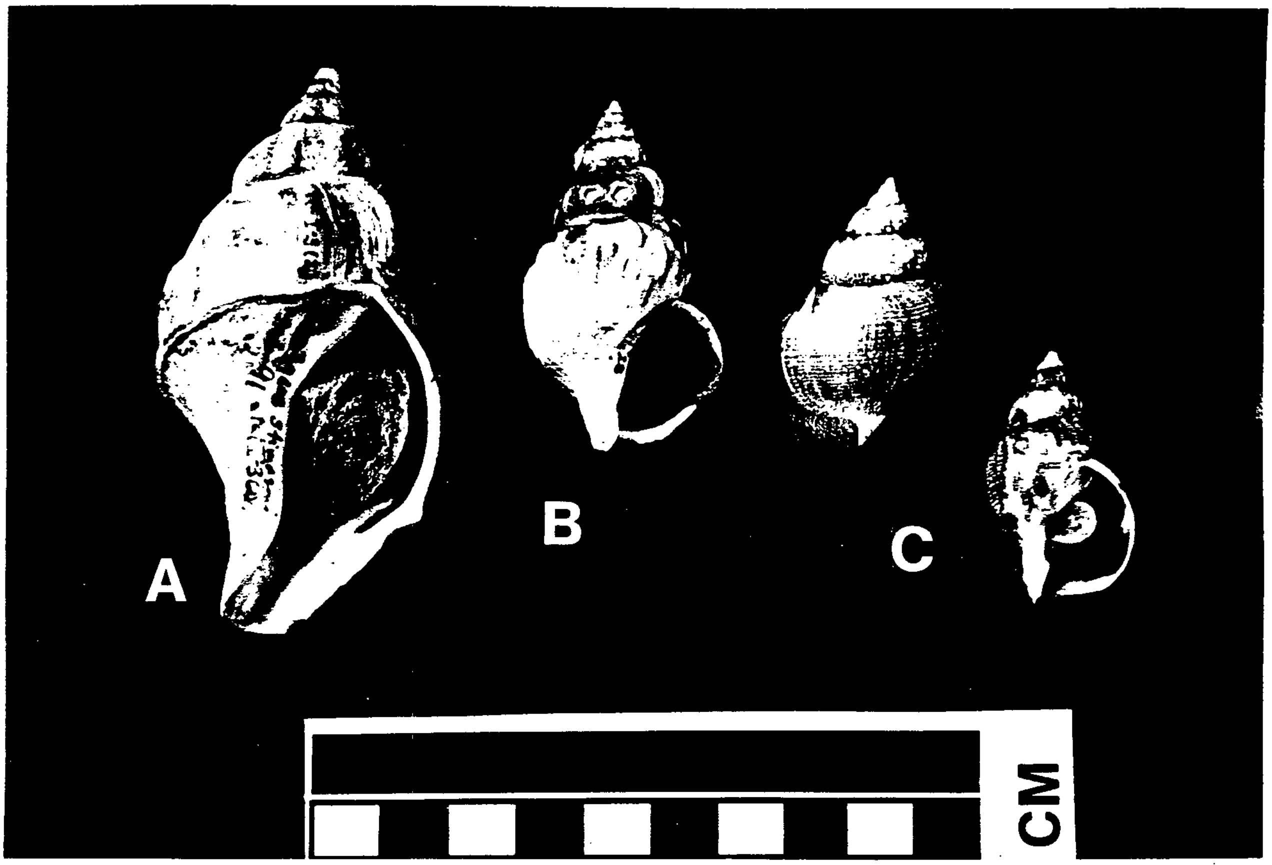

Figure 11a. *Beringius stimpsoni,* 11b. *Buccinum solenum,* and 11c. *Buccinum tenellum.*

The most abundant bivalve was the scallop *Chlamys behringiana* which occurred at 12 stations, with especially high numbers observed (24,000 ind/km^2) at Station 7 off Point Hope (Figure 12). The scallop was also common at Stations 19 and 22 north of Cape Lisburne and Stations 25, 26, 27 and 33 adjacent to Point Franklin. The cardiid bivalves *Serripes groenlandicus* and *Clinocardium ciliatum* were abundant at 22 and 13 stations, respectively.

The chiton *Amicula vestita* was found at 17 stations, with the greatest abundance just north of Cape Lisburne. An octopus, tentatively identified as *Octopus leioderma*, occurred at 12 stations and, although never abundant, was common offshore (Figure 13a). Four relatively common gastropods (*Colus spitzbergensis*, *Beringius beringi*, *Buccinum glaciale*, and *Trichotropis bicarinata*) were present in the nearshore areas (see Figure 13b for example).

Five species (*Beringius stimpsoni*, *C. magna*, *C. behringiana*, *Cyclocardia crassidens*, and *Astarte montagui*) had disjunct distributions, with individuals occurring at stations off Cape Lisburne and at northern stations (see Figures. 13c,d for examples).

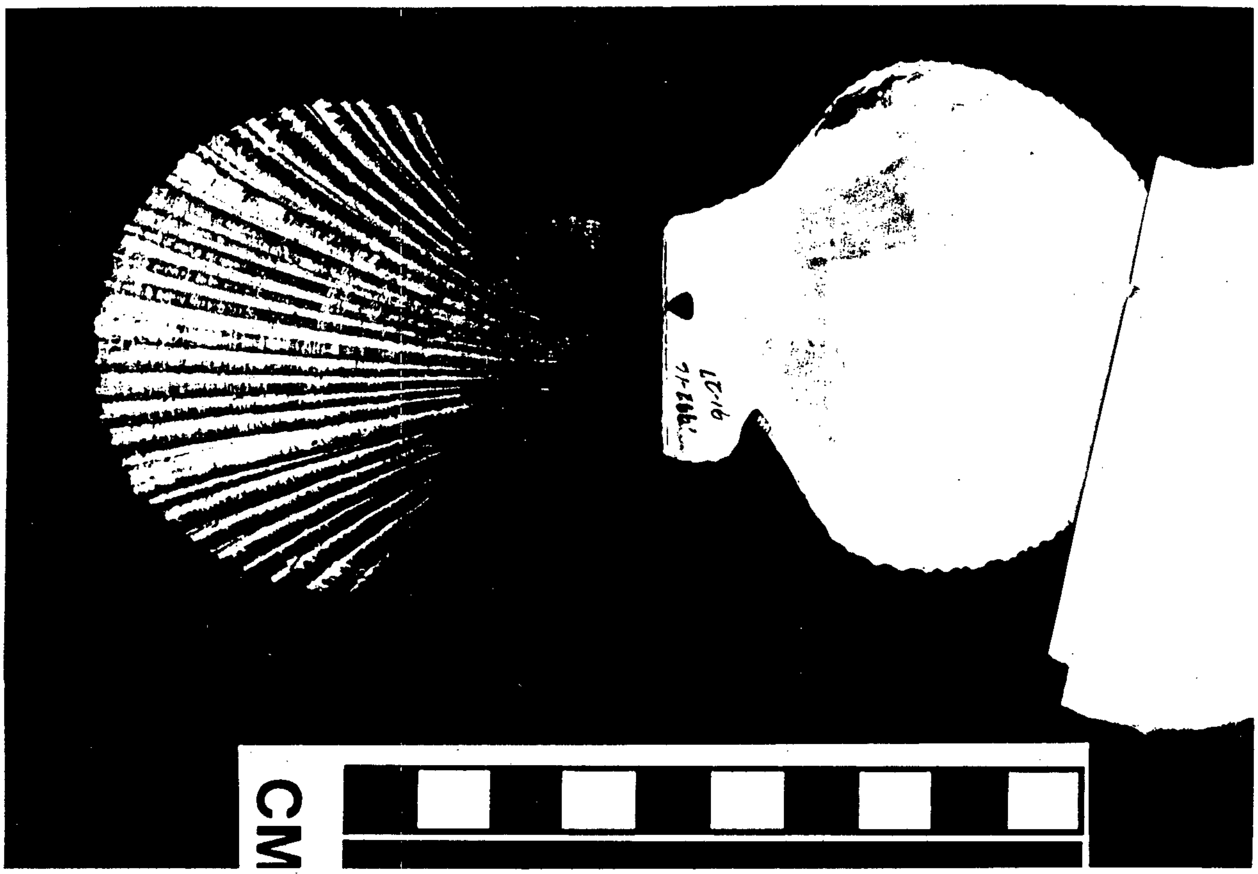

Figure 12. *Chlamys behringiana.*

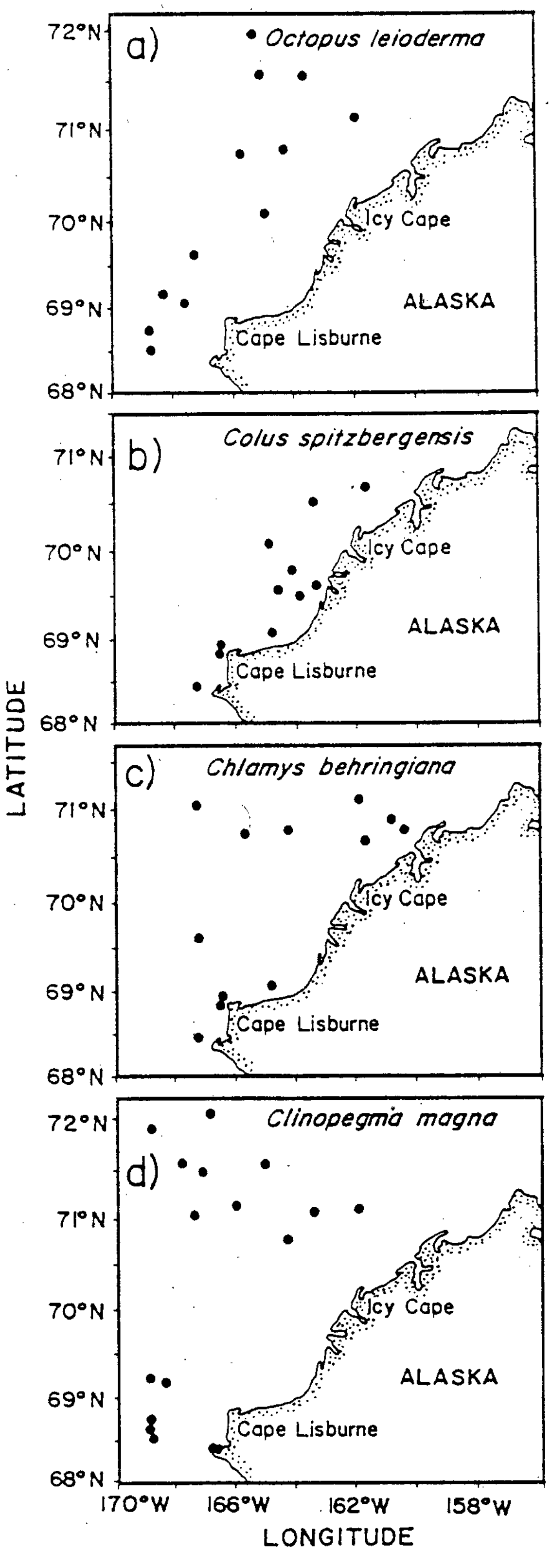

Figure 13a. Distribution of *Octopus leioderma,* 13b. Distribution of the gastropod *Colus spitzbergensis,* 13c. Distribution of the scallop *Chlamys behringiana,* and 13d. Distribution of the gastropod *Clinopegma magna.*

From the recurrence of stations in the cluster analysis of abundance data (Figure 14) five station groups were identified, with three stations not classified (Figures 14 and 15). Dominant fauna characterizing each of the station groups are found in Table 4.

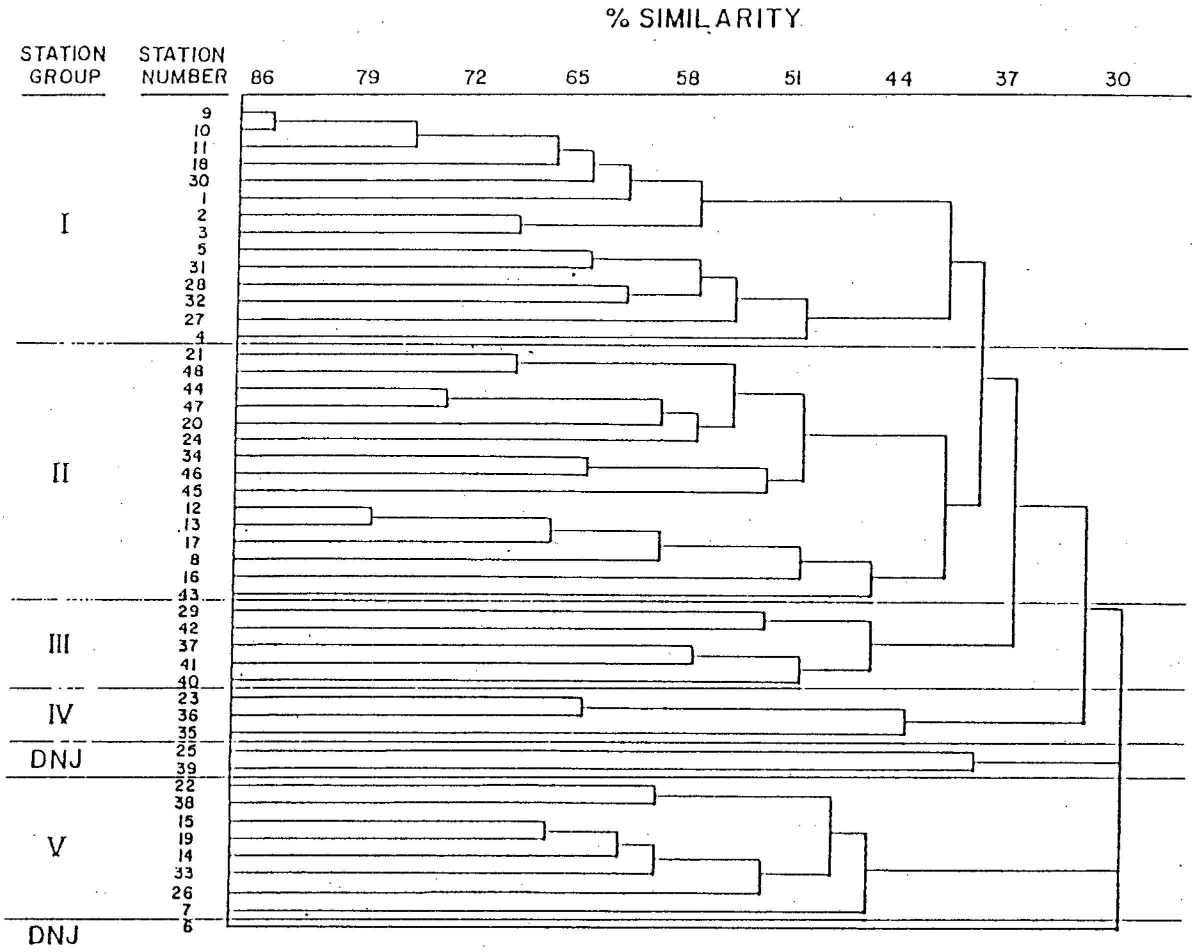

Figure 14. Dendogram showing grouping of stations based on a cluster analysis of epifaunal molluscan abundance data. DNJ = did not join any group.

Table 4.—Epifaunal molluscan abundance dominants within five station groups. Taxa occurred at 50% or more of stations within a station group. DNJ = Did not join a Group.

Station Group	**Stations in Group**	**Taxa**	**Abundance (ind/km^2)**	**% Occurrence in Group[1]**
I	2 3 4 5 9	*Neptunea heros*	1021	100
	11 18 27	*Buccinum polare*	390	100
	30 31 32	*Neptunea borealis*	236	100
		Buccinum scalariforme	128	100
		Volutopsius fragilis	126	50
		Natica aleutica	97	86
		Polinces pallidus	87	86
		Clinopegma magna	81	93
		Onchidiopsis sp.	76	100
II	8 12 13 16 17 20	*Neptunea heros*	4256	100
	21 24 34 43 44 45	*Neptunea ventricosa*	668	60
	46 47 48	*Buccinum scalariforme*	506	93
		Neptunea borealis	436	100
		Buccinum angulosum	147	93
		Onchidiopsis sp.	72	67
		Beringius beringi	54	73
		Volutopsius fragilis	33	60
		Serripes groenlandicus	31	67
III	29 37 40 42 41	*Neptunea heros*	442	100
		Neptunea borealis	72	100
		Buccinum scalariforme	71	100
		Buccinum polare	51	80
		Neptunea ventricosa	37	60
		Plicifusu kroyeri	17	60
IV	23 35 36	*Neptunea heros*	752	100
		Buccinum tenellum	98	100
		Buccinum polare	91	67
		Buccinum angulosum	85	67
		Natica clausa	57	67
		Neptunea borealis	56	100
		Polinices pallidus	28	67
		Neptunea ventricosa	28	100
		Bulbus fragilis	3	67
		Buccinum sp.	6	67
V	7 14 15 19 22 *26*	*Chlamys behringiana*	3971	100

Table 4. continued

Station Group	**Stations in Group**	**Taxa**	**Abundance (ind/km^2)**	**% Occurrence in Group[1]**
V cont.	33 38	*Neptunea heros*	2363	100
		Neptunea ventricosa	1814	100
		Buccinum angulosum	1471	88
		Trichotropis bicarinata	1457	63
		Amicula vestita	1168	100
		Margarites costalis	821	50
		Onchidiopsis sp.	794	100
		Plicifusus kroyeri	748	100
		Buccinum scalariforme	477	75
		Cyclocardia cassidens	419	88
		Volutopsius deformis	391	62
		Beringius stimpsoni	431	50
		Volutopsius stefansoni	341	62
		Buccinum polare	293	50
		Beringius beringi	258	88
		Boreotrophon clathratus	204	63
		Colus spitzbergensis	167	63
		Neptunea borealis	136	50
		Buccinum glaciale	127	75
		Serripes groenlandicus	61	63
		Clinocardium ciliatum	57	75
		Crepidula grandis	35	62
		Musculus discors	32	50
DNJ	25	*Neptunea heros*	3177	
		Neptunea ventricosa	498	
		Volutopsius deformis	453	
		Buccinum plectrum	199	
		Buccinum glaciale	199	
		Chalmys behringiana	199	
		Beringius beringi	54	
		Beringius stimpsoni	54	
		Buccinum polare	54	
DNJ	39	*Chlamys behringiana*	160	
		Neptunea heros	114	
		Buccinum angulosum	46	
		Plicifusus kroyeri	23	
		Neptunea ventricosa	23	
		Buccinum polare	23	
		Clinopegma magna	23	
DNJ	6	*Neptunea ventricosa*	410	

Table 4. continued

Station Group	Stations in Group	Taxa	Abundance (ind/km^2)	% Occurrence in Group[1]
DNJ cont.		*Clinocardium californiense*	155	
		Neptunea heros	114	
		Musculus discors	68	
		Serripes groenlandicus	46	
		Beringius beringi	33	
		Clinopegma magna	22	

[1] The value for each taxon in the column of % Occurrence in Group is based on the number of stations at which the particular taxon occurs.

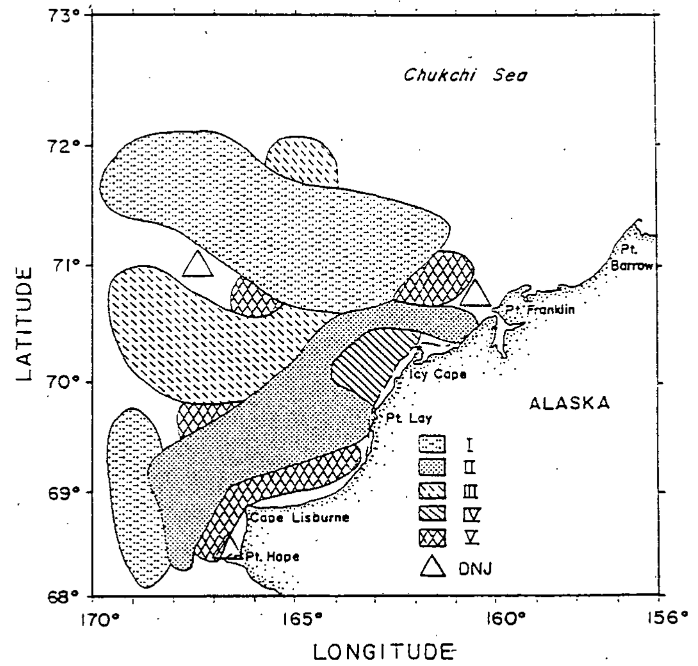

Figure 15. Epifaunal molluscan assemblages in the northeastern Chukchi Sea based on cluster analysis.

Number of taxa at station groups varied from 16 in Group IV to 65 at Group V (Table 5). Abundance ranged from 765 in Group III to 18,993 ind/km^2 in Group V (Table 5). Biomass ranged from 24 to 292 kg/km^2 at Groups IV and V, respectively. As observed for offshore infaunal station groups, the northern epifaunal offshore Group I had a larger number of taxa, and higher abundance and biomass than southern offshore epifaunal Group III. Also, as noted for the infauna, there is a distinctive epifaunal assemblage (inshore Group IV) in the sandy area between Icy Cape and Point Lay. The number of taxa, abundance, and biomass here was relatively low. Distinctive species in Group IV were *Buccinum tenellum*, *B. polare*, *B. angulosum*, and *Natica clausa*. The most diverse group, Group V, has a disjunct distribution (Figure 15). The group was dominated by large numbers of *C. behringiana*. Group II wasdistinguished by its relatively large number of taxa, and high abundance and biomass values.

Table 5.—Number of taxa, abundance, and biomass of epifaunal station groups.

Station Group	Number of Taxa	Abundance (ind/km^2)	Wet Weight Biomass (kg/km^2)
I	63	2770	54
II	52	6884	188
III	20	765	33
IV	16	1245	24
V	65	18993	292

Table 6 shows the results of the multiple discriminant analysis of the environmental conditions relative to epifaunal station groups identified by multivariate analysis. Discriminant Functions (DF) 1 and 2 contribute 88.8% of the total separation among the groups ($P \leq 0.001$), and only these two functions are considered further in the interpretations. Sixty-one percent of the stations and station groups were correctly classified. After the final step in the discriminant analysis, F statistics between most pairs of station groups showed significant differences ($P \leq 0.001$). Station and station group positions along these two functional axes are plotted in Figure 16 (also see station group locations in Figure 15). The low negative value along DF 1 is due to higher bottom-water temperature. The low negative value along DF 2 is due to the high percent gravel. The centroid of northern offshore Station Group I is well separated from most of the other groups along the axis of DF 1. Also, the centroid of offshore Group III is separated from inshore Groups II, IV, and V on DF 1. The centroids of inshore Group V and inshore Group IV are separated from the other groups along the axis of DF 2. The separation of offshore Groups I and III from the other stations is a result of lower bottom water temperature; both groups share similar sediment characteristics. The separation of Group V from the other groups is due to the high percentage of gravel present at stations of this group, and Group IV differs from the other groups by the low percent of gravel present (see Figures 15 and 16).

DISCUSSION

Our results show higher abundance and biomass values for infaunal mollusks adjacent to and north and northwest of the bottom front separating Bering Shelf (BSW) and Resident Chukchi Water (RCW) from Alaska Coastal Water (ACW). A north-south infaunal biomass difference in the northeastern Chukchi Sea was also noted for total infauna by Feder *et al.* (1990a) where higher biomass for the northern region was explained by lower bottom-water temperatures and higher bottom salinities in the northern region. In contrast, epifaunal mollusks have their greatest abundance and biomass within stations adjacent to the coast. Of particular interest is the observed enhancement of infauna at northern stations relative to those farther south. Oceanographic mechanisms which could lead to the observed enhancement of the infaunal benthos to the north include: (1) advection into the area by BSW with its high nutrient and POC load, (2) a flux of ungrazed phytoplankters to the bottom, (3) the recurring presence of polynyas along the coastal region north of Point Franklin (Stringer and Groves, 1991), (4) enhanced primary productivity associated with the summer-fall position of the marginal ice zone (which is typically observed in this region at this time: Grantz *et al.* 1982), and (5) enhanced primary production due to upwelling and slope/shelf exchange of nutrient-rich water found at depth along the continental slope to the north of the study area.

Table 6.—Results of the discriminant analysis of environmental factors among the five epifaunal station groups. Sediment data used are dry weight values from Naidu (1987) and oceanographic data from Feder *et al.* (1990a). *Significance at $P \leq 0.001$.

Discriminant Function	**1**	**2**	**3**
Percent Separation	58.31	30.45	11.25
Cumulative Percent Separation	59.31	88.76	100.00
Test of significance			
Chi-squared value	58.55*	27.71*	8.55
Degrees of freedom	12	6	2

Variables and Standardized Discriminant Function Coefficients			
Depth	0.43	-0.60	0.78
Bottom Temperature	-0.99	0.27	0.69
Percent Gravel	0.54	-0.86	-0.69

The northward flow of BSW along the east flank of Herald Shoal (Weingartner, Chapter 2), with its contained nutrients and POC, spreads north and eastward along the bottom, mixes with RCW, and forms a bottom-intersecting front with ACW. The annual water-column primary production north of this front is estimated to be from 50-100 gC/m^2 (Parrish, 1987). Much of the initial pulse of this water-column primary productivity probably remains ungrazed as observed for the northeastern Bering Sea (Grebmeier *et al.* 1988). The sinking of ungrazed phytoplankton, as well as POC within the BSW/RCW, would enrich the benthic environment north of the front. Additional nutrient enrichment along the front might also contribute to increases in benthic organisms at stations adjacent to that front. Fronts are characterized by high primary productivity, and it is here that high values for benthic abundance and biomass are often found (Creutzberg, 1986). An increase in benthic organisms along the frontal system in the northeastern Bering and southeastern Chukchi Seas was also noted by Grebmeier *et al.* (1988, 1989) and Feder *et al.* (1990b).

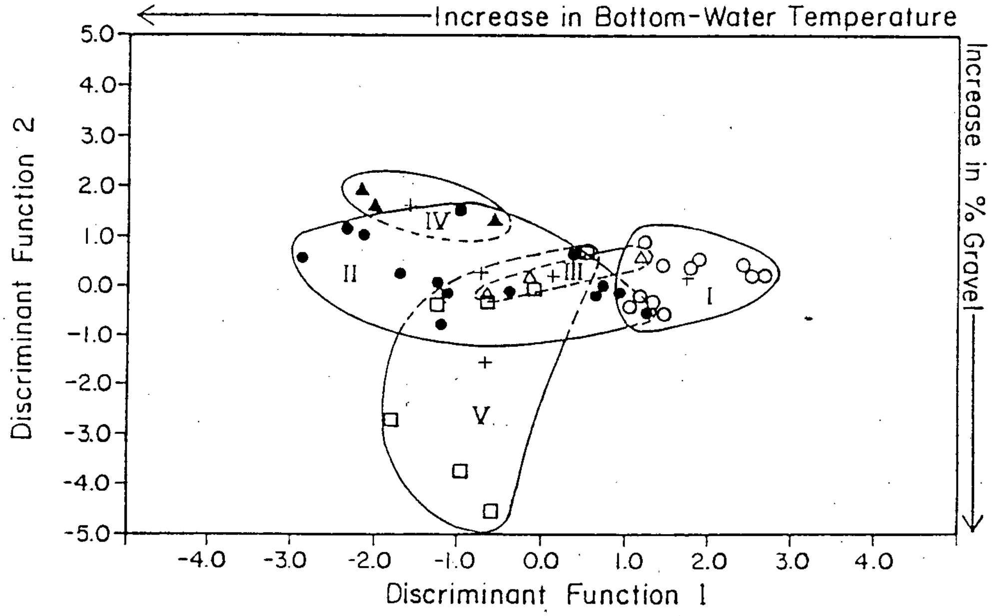

Figure 16. Station and station group plot from stepwise multiple discriminant analysis of molluscan epifauna utilizing environmental variables. + = centroids of the station groups. Sediment values used in the anlysis based on dry weights.

Open-water regions within polynyas are considered important in sustaining primary and secondary productivity in polar regions and are regularly associated with large numbers of sea birds and marine mammals (Dunbar, 1981; Stirling *et al.* 1981; Massom, 1988; Smith *et al.* 1990; Grebmeier and Barry, 1991; Deming *et al.* 1993). The ice-water boundary at marginal ice zones is the site of the earliest spring water-column phytoplankton blooms in polar regions (Alexander and Niebauer; 1981, Johannessen *et al.* 1982; Niebauer and Alexander, 1985). It is hypothesized that polynyas influence water-column productivity due to ice-edge dynamics at the marginal ice zone, but few studies have investigated pelagic-benthic coupling processes in polynyas (Grebmeier and Barry, 1991). Concentrations of plant-derived pigments and meiomacrofauna were higher in sediments under the Northeast Water (NEW) polynya off the northeast coast of Greenland than under ice-covered regions (Deming *et al.* 1993). Also, Piepenberg (1988) describes an enhanced epifaunal abundance in the area of the NEW compared to benthos underneath the ice pack. Increased infaunal abundance and biomass north of Icy Cape, observed in our study and by Feder *et al.* (1990a), may reflect, in part, a flux to the bottom of locally produced POC within polynyas that supplements advected carbon sources. Additionally, the recurring presence of early summer feeding walrus at the ice edge off Point Franklin (Fay, 1982), adjacent to a northern polynya in the northeastern Chukchi Sea, indicates that flux of carbon to the bottom in this area is an annual event that enhances food resources for these animals.

Upwelling of nutrient-rich water along the shelf break might also stimulate primary production on the outer shelf. This upwelling is seasonally modulated and occurs most frequently from October through January when sea ice covers the region (Aagaard and Roach, 1990). Hence, upwelling could enhance water-column production insofar as it preconditions shelf waters prior to the seasonal sea-ice retreat.

The higher molluscan abundance and biomass values in the northeastern Chukchi Sea compared to the Beaufort Sea can be related, in part, to the higher primary productivity in the former region (Parrish, 1987). As mentioned above, much of the primary productivity in the northeastern Chukchi Sea probably remains ungrazed and fluxes to the bottom. However, only 1-10% of water-column production in the Beaufort Sea is estimated to reach the bottom (Carey and Ruff, 1977; Carey, 1987). Thus, carbon limitation has an important influence on benthic abundance and biomass in the Beaufort Sea.

Ice-scouring of the sea floor disrupts and modifies the sea bed over much of the ice-stressed continental shelf of the Alaskan arctic, and influences faunal abundance and biomass (Barnes and Reimnitz, 1985; Carey and Ruff, 1977; Carey, 1991; Grebmeier and Barry, 1991). Comparison of benthic infaunal biomass in the northeastern Chukchi and adjacent Beaufort Sea shelves indicates regional differences (Carey *et al.* 1974; Feder *et al.* 1990a; Grebmeier and Barry, 1991). In the Beaufort Sea, ice gouging contributes to the lowered benthic abundance and biomass in the inner shelf (Feder and Schamel, 1976; Carey and Ruff, 1977; Carey *et al.* 1984; Braun, 1985), and is also responsible for much of the mid-shelf faunal patchiness (Carey and Ruff, 1977). In contrast, benthic abundance and biomass are higher on the northeastern Chukchi inner and midshelf areas. In fact, in the vicinity of Point Franklin, there are high molluscan abundance and biomass values inshore (Figures 4 and 8). Decreased annual ice cover occurs in the northeastern Chukchi Sea as compared the Beaufort Sea (Grantz *et al.* 1982). Further, polynyas along the coastal shelf areas of the northeastern Chukchi Sea (Stringer and Groves, 1991) periodically exclude ice in winter. Ice gouging is markedly reduced here during this period. Consequently, the effects of sea ice on benthos of the Chukchi shelf are less intensive and pervasive than on the Beaufort shelf (Grantz *et al.* 1982).

The large numbers of molluscan epifauna, observed in this study adjacent to the coast north of Icy Cape, probably represent a response to the abundant infaunal food there. Additionally, increased abundance and biomass of infaunal and epifaunal mollusks at stations adjacent to and northeast of Cape Lisburne appear related to POC originating in Kotzebue Sound (Feder *et al.* 1990 a,b) and the gyre northeast of the Cape (Coachman *et al.* 1975; Johnson, 1989;) which presumably concentrates this POC.

The abundance and biomass of bivalves, the dominant component of the molluscan infauna, appear related to specific physical properties of sediments, bottom salinity, and regional availability of POC. This relationship is reflected by the relatively discrete station groups (composed mainly of bivalves) determined by cluster analysis and the station group affinities shown by discriminant analysis. The dominance of the protobranch bivalve *Nucula tenuis* at infaunal Station Groups I, II, III, and IV is attributed to the presence of muddy sediments where this species typically occurs (Levinton, 1977; Feder and Jewett, 1987; Feder *et al.* 1990a). However, there are subtle differences in the sediment nature at stations comprising these groups, as illustrated by differences in proportions of coarse grains (gravel+sand) and water (Figure 17). These sediment differences are reflected by dissimilarities in abundance of dominant species between groups. The relatively higher water content in mud at stations in northern offshore Group I results in a fluidized sediment, which facilitates access to its contained POC for the common deposit-feeding bivalves *N. tenuis* and *Macoma calcarea* present there. Close association of POC with muddy sediments is shown by numerous investigators (e.g., see Weston, 1988, for references). Sediments at stations of northern offshore infaunal Group I generally have a relatively high organic carbon and nitrogen content (Feder *et al.* 1990a). The importance of muddy, fluidized, and POC-enriched sediments as an environment for deposit-feeding organisms is further demonstrated by the variety of surface and subsurface deposit-feeding infaunal species present offshore (Feder *et al.* 1990a). Carey *et al.* (1984) observed an increase in the abundance and diversity of protobranch and other deposit-feeding bivalves in muddy sediments of shallow nearshore areas of the southwestern Beaufort Sea. Similarly, Mann (1977) found protobranchs and *Macoma* spp. in greater abundance in soft sediments. The high bottom salinity at northern offshore Groups I and III and northern inshore infaunal Group V, which separates them from inshore Groups IV and VI, indicates the presence of BSW/ RCW with its relatively high POC content in the northern portion of the study area.

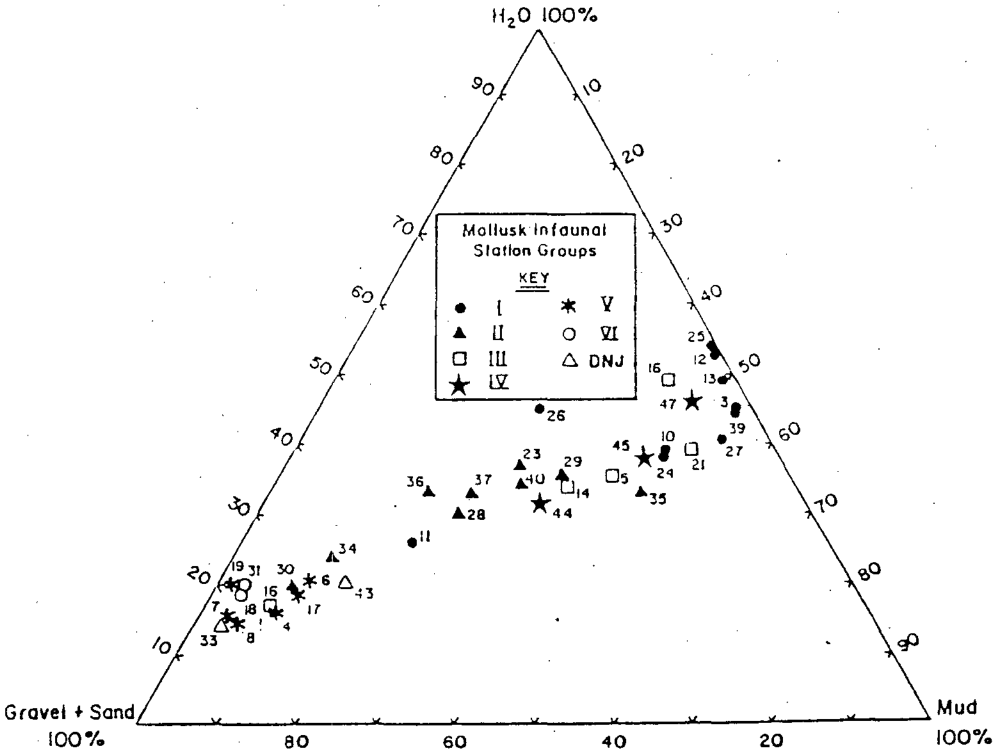

Figure 17. Ternary diagram relating infaunal molluscan stations and station groups to percent water, gravel+sand, and mud (see Figures 3a, 5, and 6).

The broad distribution of large, epifaunal gastropods, primarily the abundant *Neptunea* spp., in the study area can probably be attributed to their mobility and opportunistic feeding behavior (Golikov, 1963; Feder, 1967; Pearce and Thorson, 1967; Taylor, 1978; MacIntosh and Somerton, 1981). The mobility of molluscan epifauna is reflected by the considerable overlap of station groups in the cluster and discriminant analyses. The relatively low abundance levels of most species of epifaunal gastropods offshore may be related to lack of suitable substrate for egg-laying activities in the muddy sediments there. However, Golikov (1963) and Pearce and Thorson (1967) indicate that the large gastropod *Neptunea* mainly attaches its egg cases to shells of other *Neptunea* spp. and consequently, we do not believe that substrate type explains the distribution of this genus. In our study area, *Neptunea* spp. was common on the muddy offshore substrate.

The surface-deposit feeding clam *Thyasira gouldi* and the suspension-feeding scallop *Chlamys behringiana* occurred in large numbers off Point Hope, and to a lesser extent, the deposit-feeding clams *Nucula tenuis* and *Nuculana radiata* were important here (infaunal Group

IV and epifaunal Group V). High levels of suspended and deposited organic carbon, which furnish food for these species, were reported for this area (Feder *et al*, 1990b). South of our study area, along the coast from Kivalina to Point Hope, relatively high densities of suspension-feeding organisms (e.g., barnacles and tunicates) occur. Their presence indicates the availability of a stable source of carbon in the water column, derived from Kotzebue Sound, which ultimately contributes POC to the benthos off Point Hope (Feder *et al.* 1990b; Naidu *et al.* 1993). This POC is concentrated north of Cape Lisburne by a gyre where it sustains another large population of scallops. The scallop, as well as ampeliscid amphipods, were common northwest of Point Franklin in an area where high levels of POC occur (Feder *et al.* 1990a). 1990; Grebmeier and Barry, 1991; Deming *et al.* 1993). The ice-water boundary at marginal ice region (Moore and Ljunglad, 1984; Moore and Clarke, 1986; Phillips and Colgan, 1987; Feder *et al.* 1990a).

Inshore infaunal Group V is located in a sandy-gravelly environment dominated by suspension-feeding bivalves. The relatively intense longshore currents entrain suspended sediments and associated POC as a food source for the mollusks here (Feder *et al.* 1990a). A general increase in the proportion of suspension-feeding bivalves with coarser sediments is reported by Mann (1977) in the eastern Chukchi Sea and Carey *et al.* (1984) in the nearshore areas of the southwestern Beaufort Sea. High abundance values of molluscan epifauna, mainly *Neptunea* spp., occurred in the same general inshore area (Figure 8a), presumably attracted by the abundant infaunal food available here (Feder *et al.* 1990a).

Stations of inshore infaunal Group VI and epifaunal Group IV are occupied by low numbers of a few molluscan species. This region sustains a large, resident population of suspension-feeding sand dollars, *Echinarachnius parma* Lamarck (Feder *et al.* 1990a), which presumably excludes other infauna via their sediment reworking activities (Brenchley, 1981; Smith, 1981; Highsmith, 1982; Highsmith and Coyle, 1991). Reduced numbers of epifaunal gastropods here probably reflect the low abundance of prey species (Feder *et al.*1990a).

Mollusks, particularly when small, represent a food resource for bottom-feeding predators in the study area. Documented and potential crustacean predators on mollusks in the northeastern Chukchi Sea include pandalid and crangonid shrimps, and pagurid and majid crabs. The pandalid shrimp *Pandalus goniurus* Stimpson and the crangonid shrimps *Sclerocrangon boreas* (Phipps) and *Argis lar* (Owen), were common to abundant at some stations in the study area (Feder *et al.* 1990a; Foster, unpublished); these and related species feed on small mollusks in the Gulf of Alaska (Rice, 1980; Rice *et al.* 1980; Feder and Jewett, 1981; Feder *et al.* 1981; Feder and Jewett, 1986). Forty-one percent of the majid crab *Chionoecetes opilio* (Fabricius) examined in the southeastern Chukchi Sea were feeding on small bivalve mollusks (Feder and Jewett, 1978) and 61% of those examined in the northeastern Chukchi Sea were utilizing small bivalves (Feder *et al.* 1990a). This crab also fed on small gastropods to a lesser extent in these areas. Other large, predatory crustaceans in the study area were hermit crabs (Paguridae) and the majid crab *Hyas coarctatus* Brandt (Feder *et al.* 1990a; Foster, unpublished). In the Gulf of Alaska some species of hermit crabs and *H. lyratus* Dana feed on small mollusks (Feder *et al.* 1981).

The distribution of predatory naticid gastropods, *Natica clausa* and *Polinices pallidus*, in the northern portion of the study area overlaps that of the most dense populations of the thin-shelled bivalves *N. tenuis* and *M. calcarea*, on which they probably prey. Evidence that naticids consume infaunal bivalves, and especially *M. calcarea*, comes from observing their characteristic boreholes in shells in the study area (personal observation) and from fossil and subfossil assemblages in the Canadian Arctic (Aitken and Risk, 1988). Neptunid snails, abundant in the study area (Table 4), also utilize bivalves as one component of their diet (Pearce and Thorson, 1967; MacIntosh and Somerton, 1981), as do the Muricidae, represented in the study area by *Boreotrophon* spp.

Ophiuroids and asteroids also prey on gastropods and bivalves in the study area. A common ophiuroid in the study area, *Ophiura sarsi* Lütken, fed heavily on small mollusks, with 92% of those examined utilizing bivalves and 50% feeding on gastropods (Feder *et al.* 1990a). It is suggested by Feder (1981), based on the related *O. ophiura* Linnaeus (=*O. texturata* Lamarck), that where ophiuroids are common they can cause rapid disappearance of bivalve spat after settlement, which subsequently results in low densities of adult clams (also see Thorson, 1966). Large sea stars are abundant in the southeastern (Feder and Jewett, 1978) and northeastern Chukchi seas (Feder *et al.* 1990a; Foster, unpublished). At least nine sea-star taxa [*Asterias amurensis* Lütken, *Crossaster borealis* Fisher, *C. papposus* (Linnaeus), *Evasterias echinosoma* Fisher, *Lethasterias nanimensis* (Verrill), *Leptasterias polaris acervata* (Stimpson), *Leptasterias* spp., *Orthasterias koehleri* (de Loriol), and *Pteraster obscurus* (Perrier)] were identified from epifaunal samples collected in the northeastern Chukchi Sea in 1986 (Feder *et al.* 1990a) and 1991 (Foster, unpublished). Feeding observations on *L. polaris acervata* from the southeastern Chukchi Sea revealed that 75% of the prey types were mollusks, with gastropods more frequently taken than bivalves by two to one (Feder and Jewett, 1978). Since *L. polaris acervata* is one of the most abundant sea stars in the northeastern Chukchi Sea (Feder *et al.* 1990a; Foster, unpublished), it is probable that mollusks are important prey here as well. Other sea stars documented as predators on mollusks in the southeastern Chukchi Sea and elsewhere in Alaskan waters are *A. amurensis*, *Leptasterias* sp., *E. echinosoma* and *L. nanimensis* (Feder and Jewett, 1978, Feder and Jewett, 1981; Jewett and Feder, 1981).

Mollusks are a minor component of the diet of fishes in the study area (Coyle *et al.*, Chapter 8). Gastropods and bivalves were present, but never important, in the diet of the staghorn sculpin *Gymnocanthus tricuspis* Reinhardt. The arctic flounder *Hippoglossoides robustus* Gill and Townsend utilized bivalve mollusks for food in only a small percentage of fish examined. Mollusks are also a minor portion of the diet of the related flathead sole *H. elassodon* Jordan and Gilbert in the southeastern Bering Sea (Mineva, 1964; Mito, 1974).

Two marine mammals, the walrus *Odobenus rosmarus divergens* Illiger and the bearded seal *Erignathus barbatus* Fabricius, are the most important predators on mollusks in the study area. Bivalves are an important component of the diet of walrus (Fay, 1982). *Macoma calcarea* and other small bivalves were common in our northern offshore infaunal Group I and at stations within the same general region studied by Stoker (1981), an area where walrus feed on these mollusks (Fay, 1982; Fay, pers. comm. in Feder *et. al.*, 1990a). Neptunid and buccinid snails are occasionally reported as prey for walrus (Fay, 1982). Limited data from the northwestern and northeastern Chukchi Sea suggest that mainly smaller molluscan species are consumed by walrus (Krylov, 1971; Feder *et al.* 1990a). The bearded seal feeds on the cockle *Serripes groenlandicus*, the clam *Mactromeris (=Spisula) polynyma* Stimpson and the gastropods *Buccinum* spp. and *Polinices* spp. in the Bering Sea (Lowry *et al.* 1979; Lowry *et al.* 1980a). Snails are of minor importance (one percent of invertebrate prey volume) as food for the bearded seal in the northeastern Chukchi Sea, but the clams *S. groenlandicus* and *M. polynyma* (this species was not taken in our study) can be important dietary components for this mammal in the area (Lowry *et. al.*, 1980a).

In summary, the northeastern Chukchi Sea has an abundant and diverse molluscan fauna. Distribution, abundance and biomass can be related to several environmental factors.

Dissimilarities in abundance of particular infaunal molluscan species are primarily related to specific sediment parameters but also to bottom salinity. Epifaunal species are more abundant inshore where sandy-gravelly substrate prevails, although the large gastropods *Neptunea* spp. are common throughout the study area. Increase in biomass for infaunal mollusks north of 71°N latitude appears to be influenced by the presence of a bottom front adjacent to Point Franklin. Further, advection of POC-enriched water from the southeast Chukchi Sea to north of the front appears to support, in part, an enhanced infaunal molluscan fauna there. Although mollusks are not the dominant food utilized by invertebrate, fish, and walrus predators in the study area, they can occur in the diet of most of these organisms. However, it seems that small molluscan species and juvenile stages of large mollusks are mainly consumed by these predators. Clams, but rarely gastropods, serve as prey for the bearded seal. Mollusks, in general, are long lived in arctic seas (Thorson, 1936, 1957; Ockelmann, 1958; Golikov, 1963; Dunbar, 1968; Chia, 1970). Consequently, larger species, as adults, particularly gastropods, represent a carbon sink that mainly contribute carbon to the system via gamete production and death [see discussions in Isaacs (1976) and Feder and Jewett (1981)].

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APPENDIX I. CHAPTER 10

List of molluscan taxa. Infaunal taxa are those reported in Feder *et al.* (1990a). Taxa designated "sp." were generally too small to be determined to species. Epifaunal mollusks were identified in the field by Rae Baxter. Name changes are based, in part, on specimens collected in the same area in 1991 by N. Foster. Other suggested name changes are by N. Foster.

T=species collected by otter trawl, primarily epifauna, except *Mya* spp.

G=species collected by grab, primarily infauna.

These designations may not always be consistent with the life habits of the animals, as the grab may pick up small epifauna, and, on soft sediments, the otter trawl may dig in and collect larger infaunal species.

Gastropoda

T		*Lepeta caeca* (Müller, 1776)
T		*Margarites argentatus* (Gould, 1841)
T	G	*Margarites costalis* (Gould, 1841)
T		*Margarites giganteus* (Leche, 1878)
T		*Margarites vorticifer* (Dall, 1873)
T	G	*Solariella obscura* (Couthouy, 1838)
T	G	*Solariella varicosa* (Mighels and C. B. Adams, 1842)
	G	Trochidae, not determined
	G	*Moelleria costulata* (Møller, 1842)
	G	*Alvania* sp.
T	G	*Tachyrhynchus erosus* (Couthouy, 1838)
T	G	*Tachyrhynchus reticulatus* (Mighels and C. B. Adams, 1842)
	G	Boreoscala greenlandica (G. Perry, 1811)
T		*Asterophila japonica* Randall and Heath, 1912 [endoparasitic in sea stars (Hoberg *et al.* 1980); biomass was not calculated]
T	G	*Crepidula grandis* Middendorff, 1849
T		*Trichotropis bicarinata* (Sowerby, 1825)
T	G	*Trichotropis borealis* Broderip and Sowerby, 1829
T		*Trichotropis coronata* Gould, 1860
	G	*Trichotropis kroyeri* Philippi, 1848
	G	*Trichotropis* sp.
T		*Bulbus fragilis* (Leach, 1819)
T		*Natica aleutica* Dall, 1919 [may = *N. clausa*][1]
T	G	*Natica clausa* Broderip and Sowerby, 1829
T	G	*Polinices pallidus* (Broderip and Sowerby, 1829)
T		*Marsenina glabra* (Couthouy, 1832) [id. by N. Foster][2]
T		*Onchidiopsis* spp.
T		*Capulacmaea commoda* (Middendorff, 1851)
T		*Velutina plicatilis* (Müller, 1776)
T		*Velutina undata* (T. Brown, 1839)
T		*Velutina velutina* (Müller, 1776)

T	G	*Boreotrophon clathratus* (Linnaeus, 1758)
T		*Boreotrophon muriciformis* (Dall, 1877)
	G	*Boreotrophon beringi* Dall, 1902
T		*Boreotrophon pacificus* (Dall, 1902) [may = *B. beringi*][3]
	G	*Boreotrophon* sp.
T		*Buccinum angulosum* J. E. Gray, 1839
T		*Buccinum ciliatum* Fabricius, 1780
T		*Buccinum glaciale* Linnaeus, 1761
T		*Buccinum plectrum* Simpson, 1865
T		*Buccinum polare* J. E. Gray, 1839
T	G	*Buccinum scalariforme* Møller, 1842
T		*Buccinum solenum* Dall, 1919
T		*Buccinum tenellum* Dall in Kobelt, 1883
T	G	*Buccinum* spp.
T		*Beringius beringii* (Middendorff, 1848)
T		*Beringius stimpsoni* (Gould, 1860)
T		*Clinopegma magna* (Dall, 1895)
T		*Colus* cf. *C. capponius* (Dall, 1919)
T		*Colus dautzenbergi* Dall, 1916
T		*Colus ombronius* (Dall, 1919)
T		*Colus* cf. *C. roseus* (Dall, 1877)
T	G	*Colus* sp.
T		*Liomesus ooides* (Middendorff, 1848)
	G	*Liomesus* sp.
T		*Neptunea borealis* (Philippi, 1850)
T	G	*Neptunea heros* J. E. Gray, 1850
T		*Neptunea middendorffiana* MacGinitie, 1959
T		*Neptunea ventricosa* (Gmelin, 1791)
	G	*Neptunea* sp.
T		*Plicifusus kroyeri* (Møller, 1842)
	G	*Plicifusus* sp.
T		*Volutopsius callorhinus* (Dall, 1877)
T		*Volutopsius deformis* (Reeve, 1847)
T		*Volutopsius attenuatus* (Dall, 1874)
T		*Volutopsius fragilis* (Dall, 1891)
T		*Volutopsius stefanssoni* Dall, 1919
	G	*Admete couthouyi* (Jay, 1839)
T		*Admete regina* Dall, 1911
	G	*Admete* sp.
T		*Oenopota harpa* (Dall, 1885)
T		*Oenopota murdochianus* (Dall, 1885)
T		*Oenopota simplex* (Middendorff, 1849)
T		*Oenopota turricula* (Montagu, 1803)
	G	*Oenopota* spp.
	G	*Propebela* spp. [= *Oenopota* spp.][4]
	G	*Cylichna alba* (Brown, 1827)

T		*Cylichna attonsa* (Carpenter, 1865) [questionable identification][5]
	G	*Cylichna occulta* (Mighels, 1841)
	G	*Philine* sp.
	G	*Retusa obtusa* (Montagu, 1803)
T		Tochuina tetraquetra Pallas, 1788
T		unidentified nudibranchs [in part, *Calycidoris geuntheri* Abraham, 1876, id. by N. Foster][2]
Bivalvia		
T	G	*Nucula tenuis* (Montagu, 1808) [= *N. bellotti* A. Adams, 1856][6]
T		*Nuculana buccata* (Møller, 1842) [= *N. pernula* Müller, 1779][6]
T		*Nuculana fossa* (Baird, 1863) [questionable identification][5]
	G	*Nuculana minuta* (Fabricius, 1776)
	G	*Nuculana radiata* (Krause 1885) [= *N. pernula*][6]
	G	*Yoldia amygdalea* (Valenciennes, 1846) [= *Y. hyperborea*][6]
T	G	*Yoldia hyperborea* Torell, 1859
T	G	*Yoldia myalis* (Couthouy, 1838)
T	G	*Yoldia scissurata* Dall, 1897 [= *Y. seminuda* Dall, 1871][6]
	G	*Musculus corrugatus* (Stimpson, 1851) [may = *M. glacialis* Leche, 1883 or *M. discors*][6]
T		*Musculus discors* (Linnaeus, 1767)
T		*Musculus niger* (J. E. Gray, 1824)
T		*Chlamys behringiana* (Middendorff, 1849) [id. by N. Foster][2,6]
T		*Pododesmus macroschisma* (Deshayes, 1839)
	G	*Axinopsida serricata* (Carpenter, 1864)
T		*Thyasira equalis* A. E. Verrill and Bush, 1898
	G	*Thyasira gouldii* (Philippi, 1845)
	G	*Diplodonta* sp.
	G	*Montacuta* sp.
	G	*Mysella planata* (Krause, 1885)
	G	*Mysella* sp.
	G	Montacutidae, unidentified
T	G	*Astarte borealis* (Schumaker, 1817)
T	G	*Astarte montagui* Dillwyn, 1817
T		*Cyclocardia crassidens* (Broderip and Sowerby, 1829)
T		*Cyclocardia crebricostata* (Krause, 1885)
	G	*Cyclocardia ovata* (Rjabinina, 1952)
T		*Cyclocardia* cf. *C. ventricosa* (Gould, 1850)
T		*Clinocardium californiense* (Deshayes, 1839)
T	G	*Clinocardium ciliatum* (Fabricius, 1780)
T	G	*Serripes groenlandicus* (Bruguière, 1789) [may include *Yagudinella notabilis* (Sowerby, 1815)][6]
T	G	*Serripes laperousii* (Deshayes, 1839)
T	G	*Macoma calcarea* (Gmelin, 1791)
	G	*Macoma loveni* (A. S. Jensen, 1905)
T		*Macoma middendorffi* Dall, 1884
	G	*Macoma moesta* (Deshayes, 1855)

	G	*Tellina lutea* W. Wood, 1828
T	G	*Liocyma fluctuosa* (Gould, 1841)
	G	*Liocyma viride* Dall, 1871 [may = *L. fluctuosa*][6]
	G	*Psephidia lordi* (Baird, 1863)
T		*Mya pseudoarenaria* Schlesch, 1931
T		*Mya truncata* Linnaeus, 1758
	G	*Mya* sp.
T	G	*Hiatella arctica* (Linnaeus, 1767)
T	G	*Lyonsia arenosa* (Møller, 1842)
T		*Lyonsia bracteata* (Gould, 1850) [questionable identification][5]
	G	*Lyonsia* sp.
T		*Pandora filosa* (Carpenter, 1864)
	G	*Pandora glacialis* Leach, 1819
	G	*Thracia devexa* G. O. Sars, 1878
	G	*Lampeia adamsi* (MacGinitie, 1959)
	G	*Periploma aleuticum* (Krause, 1885)

Polyplacophora

T		*Amicula vestita* (Broderip and Sowerby, 1829)
T	G	*Stenosemus albus* (Linnaeus, 1767)
	G	*Tonicella rubra* (Linnaeus, 1767) [questionable identification][5]

Cephalopoda

T *Octopus leioderma* (S. S. Berry, 1911) [questionable identification] [7]

[1] Baxter (pers. comm. and 1987) separated the northern Pacific *Natica* into three species, based on shell color and morphology and on the shape of egg cases (see Kessler, 1985).

[2] Based on specimens collected in 1991.

[3] The taxonomy of boreal and arctic species of *Boreotrophon* is in need of revision. Baxter (1987) called both B. *pacificus* and B. *beringi* subspecies of B. *truncatus* (Strøm). There is much variation in the shape and proportions of the shells and number of varices, among the species of *Boreotrophon.*

[4] Vaught, 1989.

[5] Specimens were not found among the UA Museum voucher specimens. This species has not been reported in the northeastern Chukchi Sea (Baxter, 1987).

[6] E. V. Coan and P. H. Scott, pers. comm., based on an unpublished manuscript revision of northeastern Pacific bivalves.

[7] *Octopus leioderma* appeared in Baxter's species list. Cephalopod specimens collected in the northeastern Chukchi Sea in 1991 were sent to J. Voight, cephalopod taxonomist at the Field Museum. She placed them in the genus *Benthoctopus*, but could not determine the species

with confidence. (J. Voight pers. comm. 1993).

CHAPTER 11

THE REPRODUCTIVE BIOLOGY AND DISTRIBUTION OF SNOW CRAB FROM THE NORTHEASTERN CHUKCHI SEA[1]

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Abstract.—This study determined size at maturity, fecundity, distribution, and abundance of the snow crab *Chionoecetes opilio* during 1990 and 1991 in the northeastern Chukchi Sea. Snow crab abundance and biomass varied extensively between stations but tended to be greatest in the southern part of the study area and offshore rather than inshore. Biomass estimates varied extensively ranging from 4,000 kg/km^2 to 1.2 kg/km^2. At all latitudes most females with mature shaped abdominal flaps were gravid. The smallest ovigerous *C. opilio* was 34 mm carapace width (CW). The average CW of ovigerous females was 46 mm (±sd = 4) and carried 19,900 (±sd = 6,500) eggs. The equation describing the relationship between CW (Y) and the number of eggs (X) per clutch was: $Y = 0.672\ X^{2.688}$, $r^2 = 0.54$. The vas deferens of males were examined for the presence of spermatophores. All males 35 mm CW and greater had spermatophores vs. only 19% with CW of 25-29 mm. Spermatophore diameters increased from about 44 µm in 25-29 mm CW males to about 64 µm in males 35 - 44 mm CW. Spermatophore diameters for crabs between 45 and 70 mm CW were similar in diameter, generally between 75 and 80 µm.

INTRODUCTION

The snow crab, *Chionoecetes opilio* (O. Fabricius), is a circumpolar species for which there are substantial fisheries in the Atlantic and the Pacific. In the northwest Pacific snow crabs occur in the northern Sea of Japan, the Bering and Chukchi Seas from Wrangel Island to Point Barrow, and the Beaufort Sea at the mouth of the Mackenzie River (Slizkin 1989). Most of the existing information on the biology of this species has been developed for Northwest Atlantic Ocean or the Sea of Japan stocks (Bowerman and Melteff 1984).

In the Chukchi Sea snow crab are a dominant benthic species but because they are not harvested their basic biology is poorly described. This preliminary survey provided new

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[1] Submitted for publication in Fish Ecology in Arctic North America.

information on distribution trends, and reproduction, for a seldom sampled population.

METHODS

The sampling sites were dictated by oil lease sales in the area north and east of Pt. Hope (north of approximately 68° 20'N, east of the international boundary (168° 58'W) and limited to the north by sea ice. Prior to sampling, eleven transects and 56 stations were located perpendicular to the coast on a nautical chart. Stations were positioned approximately 30 to 60 nm apart depending on transect length. Nearshore stations were established nearer one another so that within a transect there were at least two stations bounded by the coastal current. In 1990 there were 48 stations occupied and in 1991 eight additional stations were sampled to examined snow crab abundance and biomass (Figure 1). Sea ice or weather precluded actually collecting at some of the predetermined station positions, so samples were taken as close as possible to the desired site.

During 1990 the bottom temperature averaged 3.8°C (± 3.3) and ranged from -1.0 to 12°C and salinity was 29 to 33 psu. Contour maps of bottom temperature and salinity for 1990 occur in Weingartner (this volume). During 1991 the bottom temperature averaged 0.1°C (± 2.0) and ranged from -1.0 to 7°C while salinity was 29 to 33 psu.

A 34 m trawler, *Ocean Hope III*, was used between 16 August and 17 September 1990 and 10 to 23 September 1991 to collect snow crab abundance and distribution data. Otter trawling from this vessel was conducted with the National Marine Fisheries Service's standard 83-112 survey trawl; it was fished hard on the bottom. The trawl had a 34.1 m foot rope set back 7 cm from a tickler chain and a 25.2 m head rope. The mesh of the codend was 90 mm and contained a 32 mm stretched mesh liner. The effective opening of the net was monitored by a Scanmar mensuration unit hung from one wing that indicated the net fished as expected. At most stations there were two 30 minute tows side by side along the same track.

At most stations a gross weight of all snow crabs combined was measured and then all the *C. opilio* counted. Periodically catches had more crabs or other species than could be processed before the next trawl sample. In those cases all the crabs in the catch were put into baskets. Baskets were filled one at a time as the crew cleared the sorting area and no bias such as size selection was apparent. All baskets were then weighed and some were randomly selected to obtain the number and weight of crabs. The average weight of crabs at a station was estimated by dividing the total weight of all individuals in the sample by the number of crabs. Weighing individuals was not feasible aboard ship.

Abundance and biomass (kg) estimates were based trawl opening width, the distance trawled, and the numbers and biomass of the catch. The distance trawled was determined from the ship's location at the beginning and end of each set by a Global Positioning System. To estimate the relative abundance (number/km^2) and biomass (kg/km^2) at each station the data from both tows taken at a station were averaged.

The 73 m *Oshoro Maru* was used in July 1991 to collect snow crab for additional reproductive observations. Its otter trawl net had a 43.3 m head rope, a 48.6 m foot rope with roller gear, and 90 mm stretched mesh with a 32 mm stretched mesh liner. These samples were not used to estimate abundance or biomass. The locations for stations sampled on this cruise occur in Table 1.

To examine crab size vs. latitude the carapace width (CW) of all the females collected at station 21 (n = 25) in July of 1991 and stations 23 (n = 51), and 91-32 (n = 88) in September of 1991 were measured to the nearest mm. The locations of stations 21, 23 and 91-32 are on

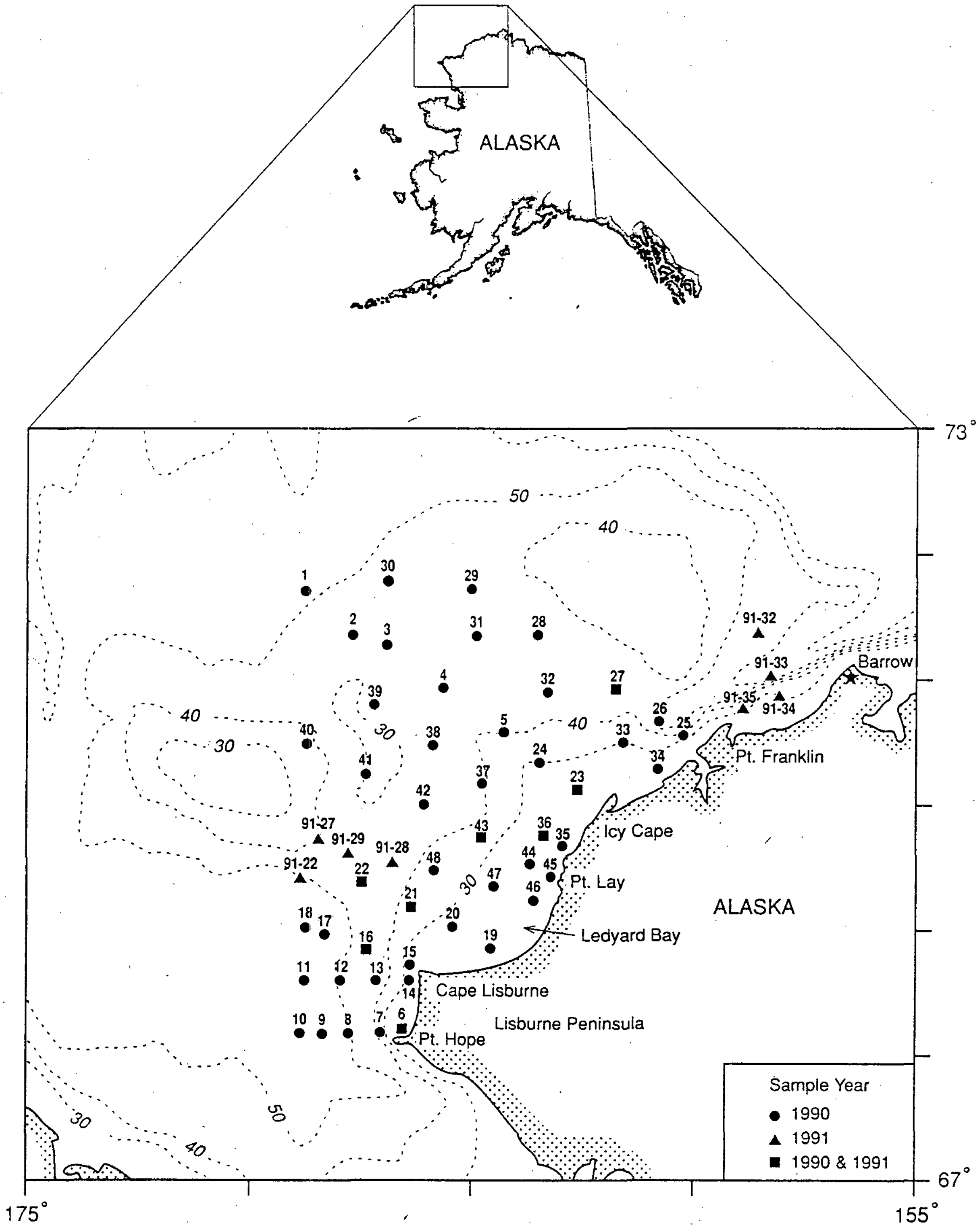

Figure 1. Stations sampled for distribution and abundance of snow crab *Chionecetes opilio* in the northeastern Chukchi Sea during 1990 and 1991. Dashed lines are depth contours in meters.

Figure 1. The CW of all males from stations 91-1 (n = 125) and 91-8 (n = 131) collected in July of 1991 were also measured to the nearest mm. The position of station 91-1 was 69°02'N, 167°38'W, and 91-8 was at 70°31'N, 166°08'W.

Table 1.—Number of northeastern Chukchi Sea female *Chionoecetes opilio* with mature shaped abdominal flaps carrying eggs.

Station	**Location**	**Total Number of Females**	**Number With Mature Shaped Abdominal Flap**	**% Mature With Eggs**
(Lat. N	Long. W)			
69° 02'	167° 38'	100	97	98
69° 03'	166° 43'	12	2	100
69° 23'	166° 28'	22	16	100
60° 32'	165° 59'	8	7	100
69° 38'	167° 41'	50	48	98
69° 40'	168° 31'	50	44	100
69° 54'	168° 42'	35	34	100
70° 00'	165° 03'	4	2	100
70° 13'	167° 04'	27	24	96
70° 21'	162° 53'	41	0	0
70° 31'	166° 08'	50	42	98
70° 33'	162° 20'	4	0	0
70° 58'	163° 39'	2	1	100
71° 37'	159° 02'	88	7	100

To determine if mature female snow crab occurred throughout the sampling area 503 females from 20 to 74 mm CW (Table 2) were collected at 14 sites (Table 2) in July and September of 1991. They were examined for the presence of a mature shaped abdominal flap and eggs.

In the August and September collections eggs were too developed for fecundity estimates but 93 females collected at station 91-1 in July had clutches of bright orange eggs that appeared to be recently extruded. Two females with new eggs had damaged abdominal flaps so the eggs from only 91 clutches were counted. The dry weight of 100 eggs subsampled from each of the 91 clutches was measured. Eggs were dried at 60°C in a convection oven until a constant weight was reached. The remaining eggs on the pleopods of each female were removed and dried as previously stated. Fecundity estimates were determined by dividing the dry weight of the total egg mass by the average dry weight of eggs in the subsample. The number of eggs was related to carapace width with a power curve; $y = ax^b$ $(a > 0)$.

Males (n = 318) used for maturity studies were all captured in September of 1991 at stations 16, 21, 22, 27, 91-29, and 91-32 (Figure 1). Males over 20 mm CW were divided into groups based on five mm increments and had to be taken from several stations to get a minimum of 25 males of the desired sizes (Table 1). In the group with the largest males (70 - 74 mm CW) only 14 individuals were captured. Size at the onset of physiological maturity was determined by histological examination of the vas deferens for spermatophores. The vas deferens were fixed in Bouin's solution followed by embedding, sectioning to 10 to 12 microns thick, and mounted following the techniques of Paul and Paul (1989). Standard Ehrlich's hematoxylin and eosin-y staining sequence (Clarke 1973) was used to enhance morphological identification of spermatophores.

Table 2.—Number of *Chionoecetes opilio* from the northeastern Chukchi Sea examined for the presence of eggs and spermatophores.

Carapace Width (mm)	No. Females	Percent With Eggs	No. Males	Percent With Spermatophores
15 - 19	0	0	1	0
20 - 24	17	0	36	0
25 - 29	27	0	37	19
30 - 34	54	2	49	49
35 - 39	29	52	25	100
40 - 44	156	73	25	100
45 - 49	169	86	26	100
50 - 54	41	93	29	100
55 - 59	9	75	25	100
60 - 64	1	100	25	100
65 - 69	0	---	26	100
70 - 74	0	---	14	100
Total	503		318	

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RESULTS

Snow crabs were present at all stations with the largest abundance and biomass tending to be in the southern part of the study area, but varying extensively between stations (Figures 2A and 2B). Abundance and biomass estimates also varied considerably between trawls at most stations. The highest estimated abundance was at station 1 (mean = 100,000/km^2). The largest biomass (mean = 4,000 kg/km^2) was at station 8 although station 1 biomass was nearly equivalent (mean = 3,100 kg/km^2). Lowest abundance was at station 28 (mean = 190/km^2), whereas the lowest biomass estimates occurred at station 35 (mean = 1.2 kg/km^2). Average crab weight (total weight of catch/number of crabs) was generally greater in the southern area than the northern area and less inshore than offshore (Figure 3). Although individuals from stations south of about 70°N generally had greater average weight, it varied extensively. This trend was also reflected in carapace width. The smallest female crabs occurred at the northern sample sites (Figure 4). At the most northern station they were captured (91-32) the average size of all females (n = 88) was 33 mm CW (±sd = 9, range 20 - 54 mm). At the more southern stations 23 (n = 51) and 21 (n = 22) female CW averaged 35 mm (±sd =5, range 28 - 44 mm) and 45 mm (±sd = 4, range 36 - 50 mm) respectively. Male size at the north (91 - 8) and south (91 - 1) stations follows this same pattern 8 (Figure 4). Gravid females were found at all latitudes sampled and 99% of those with mature shaped abdominal flaps carried eggs (Table 1). Egg bearing females ranged from 34 to 60 mm CW and averaged 46 mm (±sd = 4). Most females over 35 mm CW were carrying eggs (Table 2). Average size of the gravid females from southern station 21 was 45 mm (n = 16, ±sd = 4, range = 36 - 50 mm). At the more northern station 91-32 gravid females had a mean CW of 50 mm (n = 7, ±sd = 4, range 44 - 54 mm). No females below 30 mm CW had mature shaped abdominal flaps or eggs. Of those in the 30 to 34 mm CW size group only 2% had mature shaped abdominal flaps and eggs. In the size groups of females that were larger than 35 mm CW, no less than 52% of them were gravid (Table 2). Of the gravid females examined for fecundity during July, 93 carried recently extruded bright orange eggs while 4 females had eyed eggs that appeared ready to hatch. The average number of eggs carried by the 91 females was 19,900 (±sd = 6,500). The equation Figure 2a (Chapter 11) describing the relationship between CW (Y) and the number of eggs (X) per clutch was: $Y = 0.672\ X^{2.668}$, $r^2 = 0.54$ (Figure 5).

Presence of spermatophores in the vas deferens suggests males begin to mature between 25 to 29 mm CW (Figure 6). No males smaller than 25 mm CW contained spermatophores whereas only 19% from those in the 25 to 29 mm CW range did. All males 35 mm CW and larger contained spermatophores (Table 1). Spermatophore diameters increased from about 44 µm in 25 - 29 mm CW size group to 64 µm in males over 35 mm CW. In males between 45 and 70 mm CW spermatophore diameters were 9 similar, between 75 and 80 µm (Figure 6).

DISCUSSION

Although snow crabs are widely distributed through the northwest Atlantic (Elner 1982), Bering Sea (Otto 1982; Slizkin 1989) and Chukchi Sea (this study) little is known about the factors which influence their distribution and abundance. These factors must include larval recruitment dynamics, benthic habitat requirements, thermal tolerance, water depth preferences, predation, competition and cannibalism, but the relative importance of these factors is unknown.

Prey preference for specific sediment types or depths may explain some of the distribution pattern observed for snow crab. In the northwestern Gulf of St. Lawrence, where

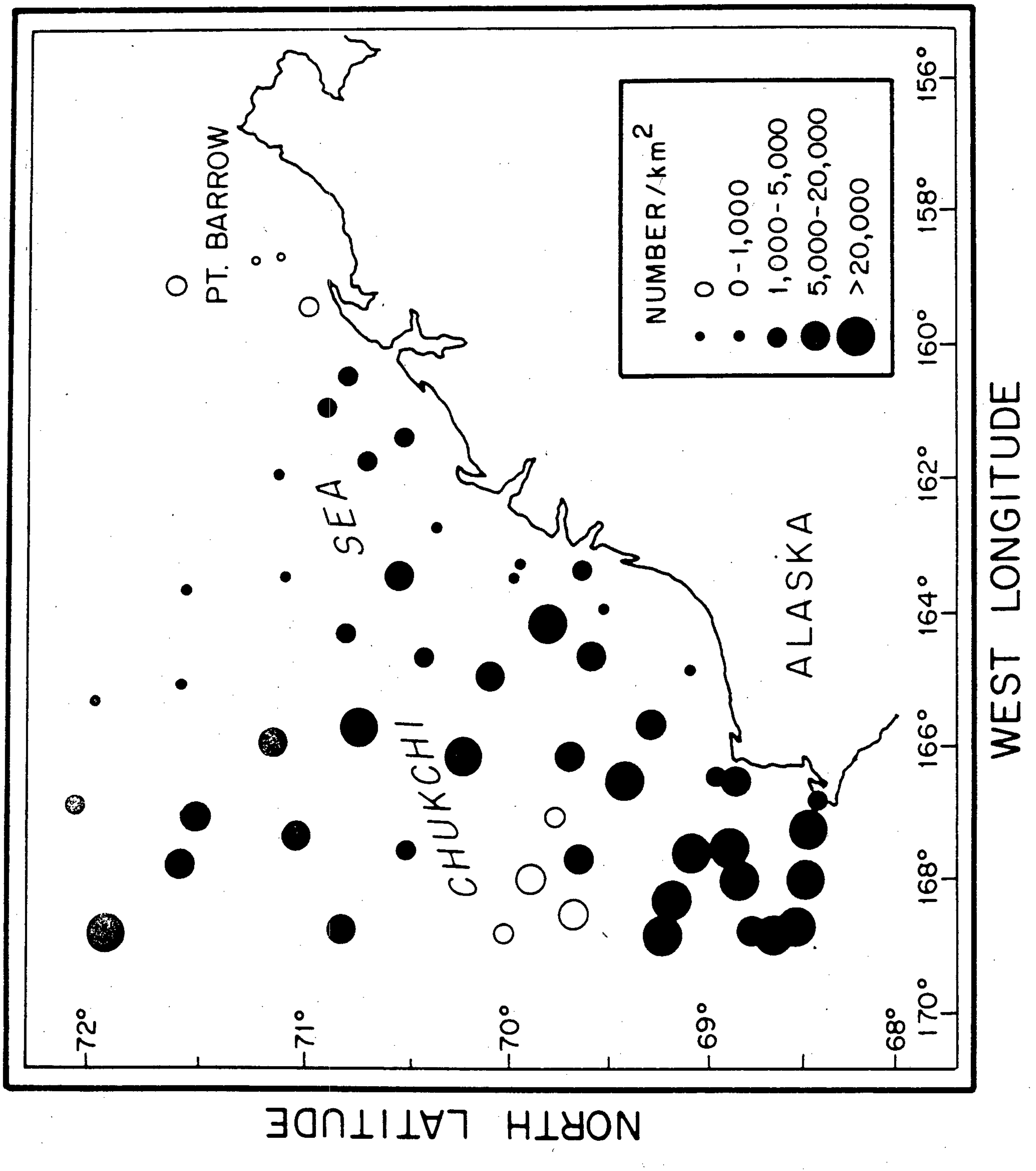

Figure 2a. Abundance of the snow crab *Chionoecetes opilio* captured by otter trawl at stations occupied in the northeastern Chukchi Sea during 1990 (filled O) and 1991 (open O).

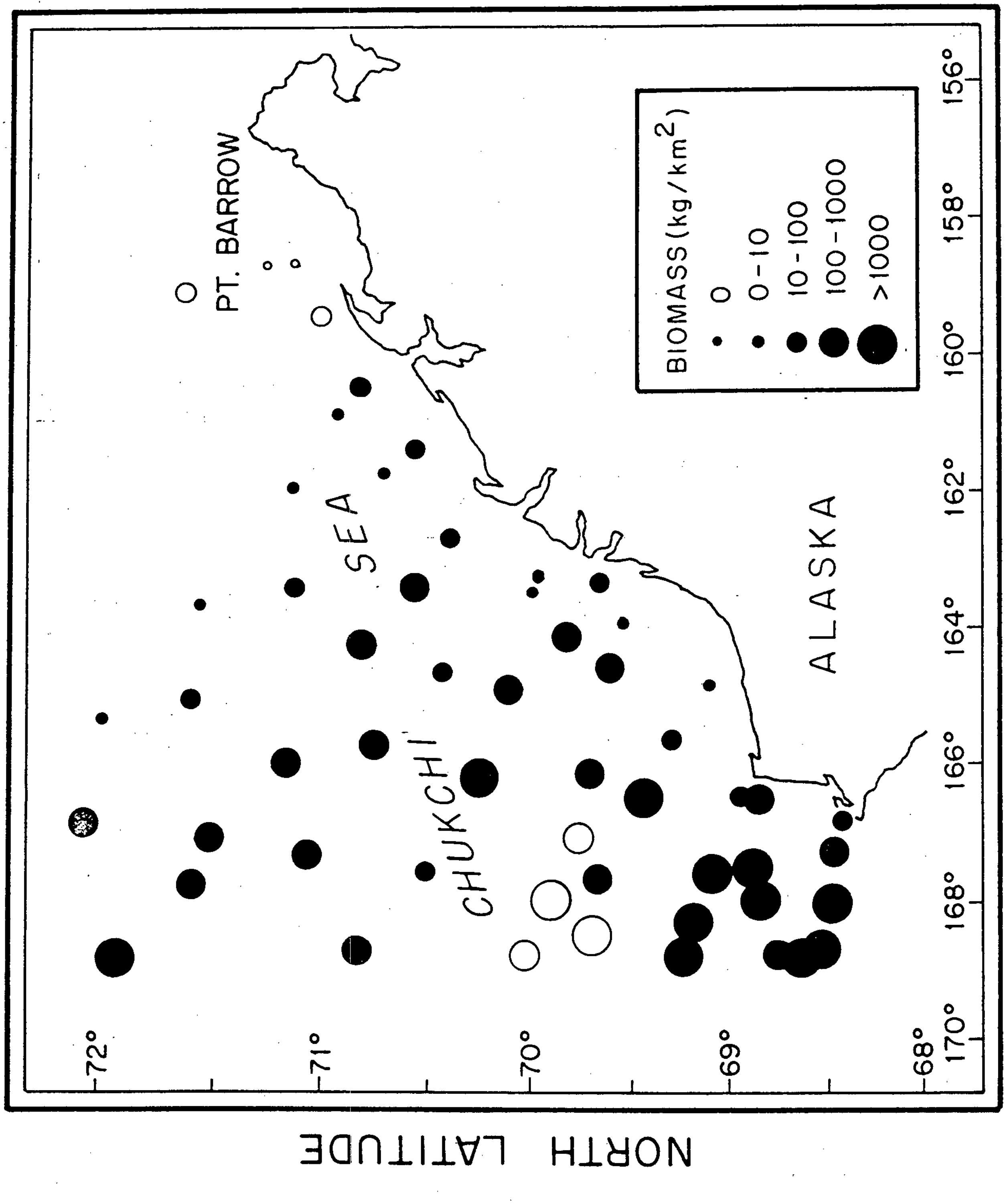

Figure 2b. Biomass of the snow crab *Chionoecetes opilio* captured by otter trawl at stations occupied in the northeastern Chukchi Sea during 1990 (filled O) and 1991 (open O).

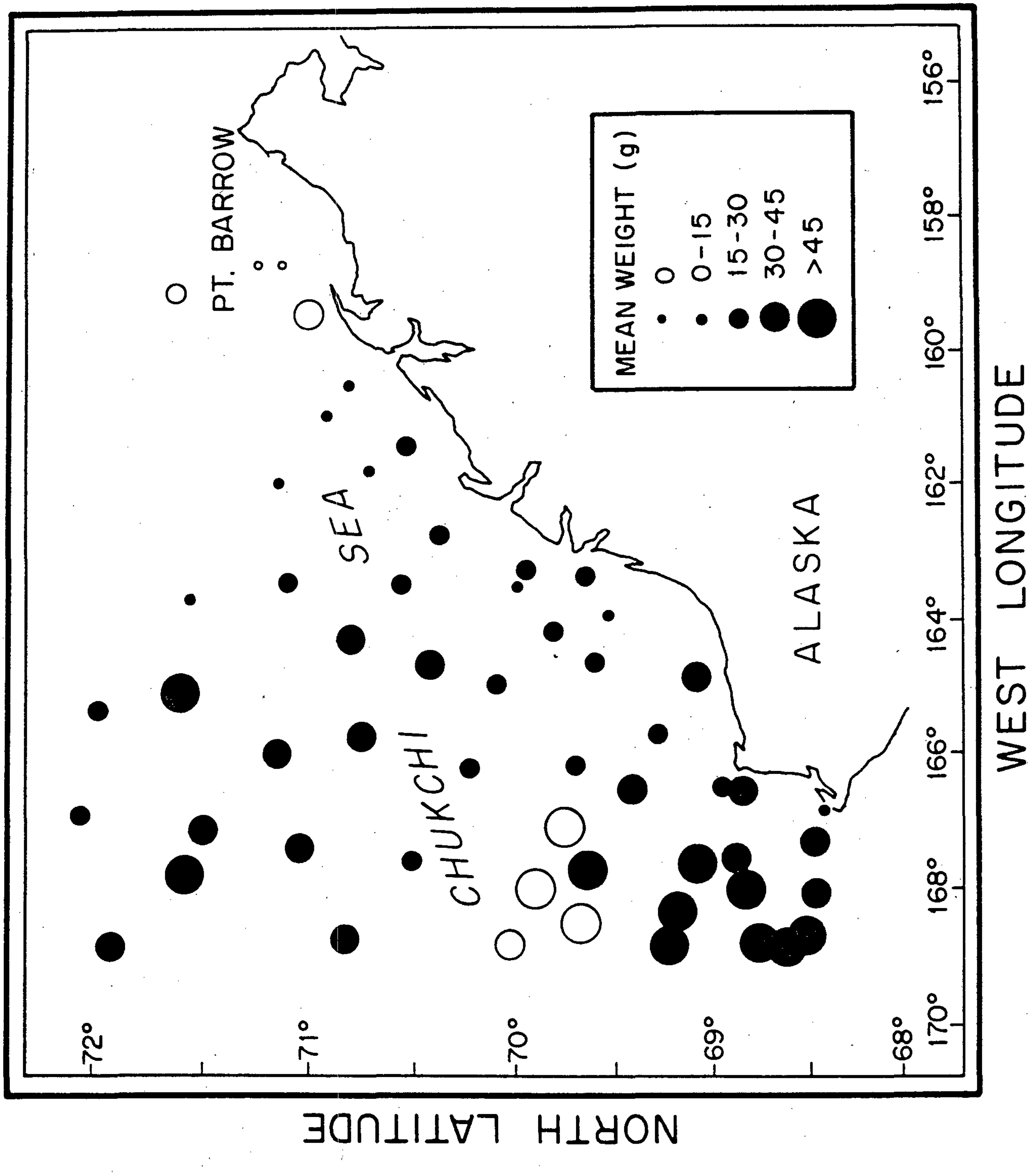

Figure 3. Mean weight of snow crab *Chionoecetes opilio* captured by otter trawl at stations occupied in the northeastern Chukchi Sea during 1990 (filled O) and 1991 (open O).

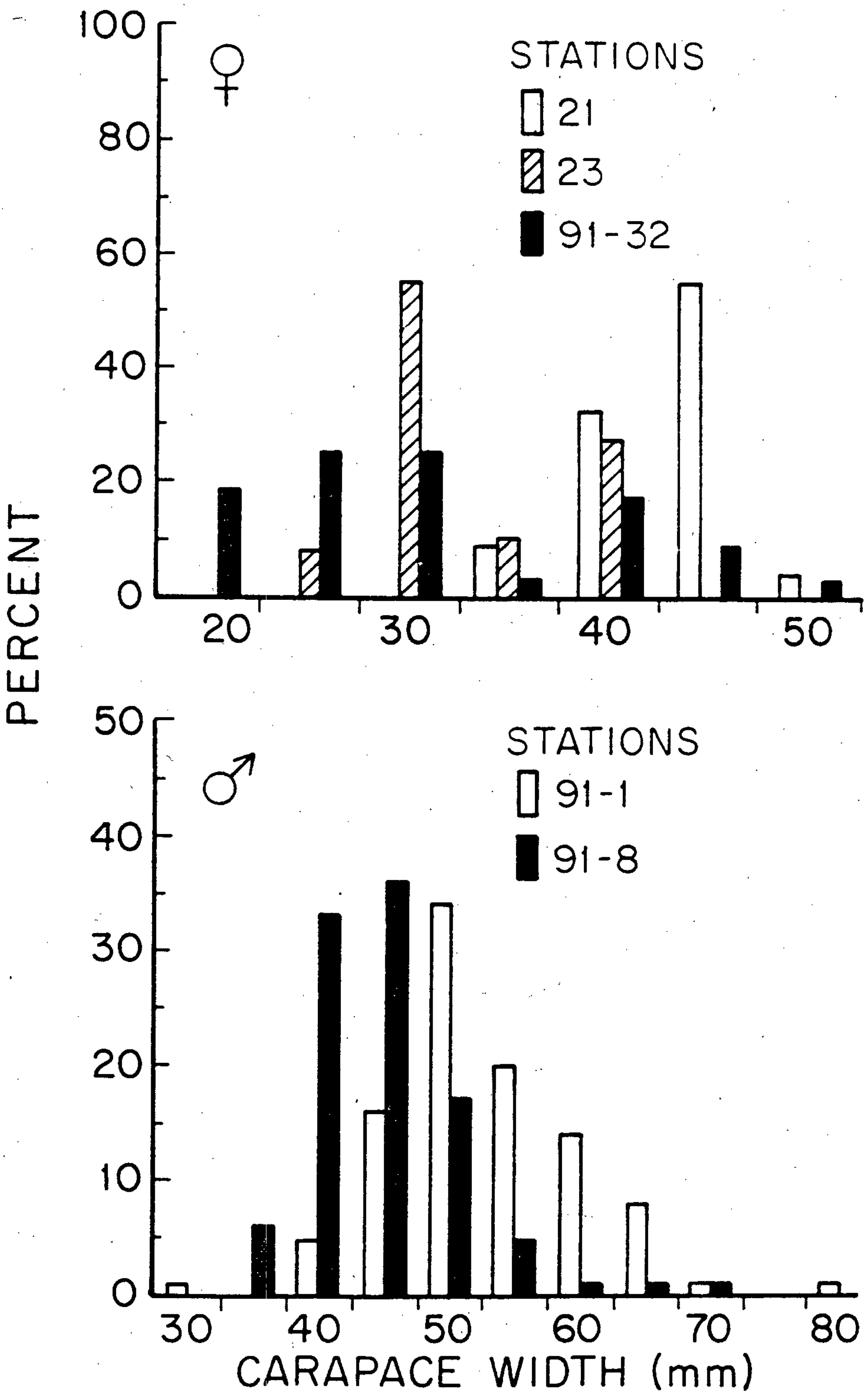

Figure 4. Carapace widths of Chukchi Sea female snow crab *Chionoecetes opilio* (upper) from stations 21 (69°26' 166°31'), 23 (70°22' 162°43'), and 91-32 (71°37' 159°02'), and males (lower) from stations 91-1 (69°02' 167°38'), and 91-8 (70°31' 166°08').

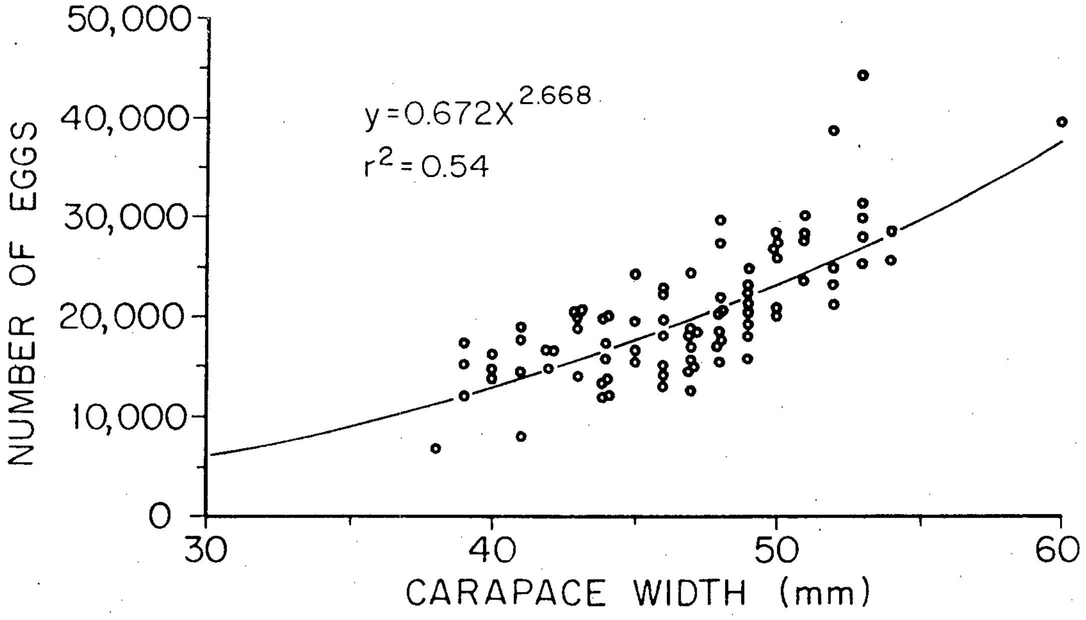

Figure 5. Number of eggs in clutches of various sized snow crab *Chionoecetes opilio* captured by otter trawl in the northeastern Chukchi Sea during July 1991.

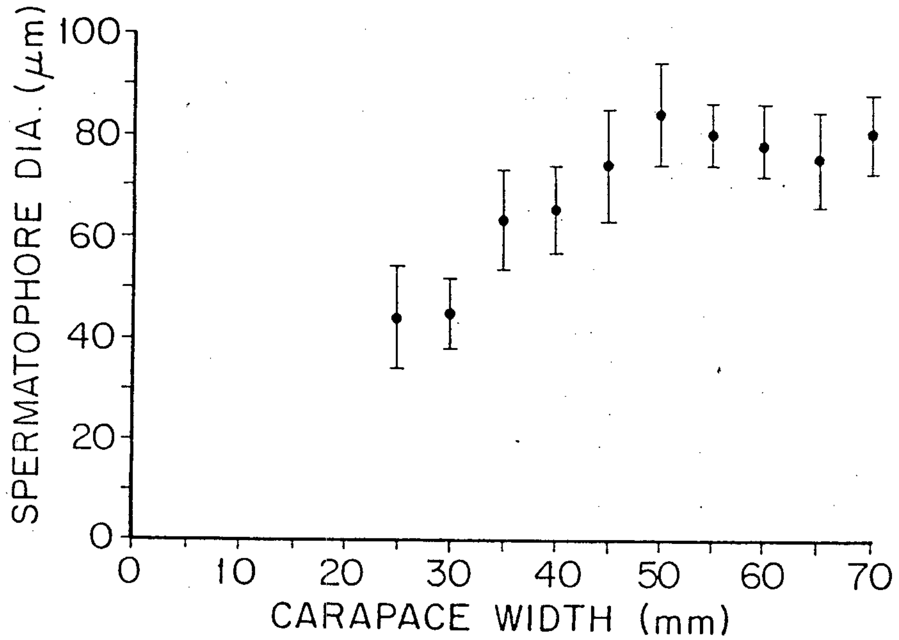

Figure 6. Diameter of spermatophores in relation to size of male snow crab *Chionoecetes opilio* captured by otter trawl in the northeastern Chukchi Sea during September 1991. Vertical bar represents ± one standard deviation.

depths exceeded 135 m, Desrosiers *et al.* (1982) found increases in snow crab size with increasing depth. The Chukchi Sea stations sampled (Figure 1), with one exception (91-33), had depths with a range of only 14 to 52 m and snow crab were found at every station. In the northeast Chukchi Sea the benthic sediments (Sharma 1979) form a general pattern of long narrow gravel belts along the shore and in a few isolated patches in offshore regions. Sand predominates in near-shore areas, and silts and clays predominate offshore. Within this broad pattern, however, there is a mosaic of sediment types (Naidu 1988). This suggests that during sampling we trawled across several bottom types each with its own prey community. Sampling smaller areas will have to be done to better identify sediment habitats preferred by snow crab.

Chukchi Sea snow crab tend to be smaller than Bering Sea or North Atlantic individuals. Chukchi Sea females averaged 46 mm (this study) to 50 mm CW (Jewett 1981) vs. 63 to 72 mm CW in the Bering Sea (Somerton 1981). In commercial fisheries the legal size limit for males ranges from 78 mm CW in Japan (Sinoda 1982) to > 94 mm CW in Atlantic Canada (Elner 1982). Chukchi Sea males seldom reach 78 mm CW.

Fecundity estimates for snow crab from this study are similar to other estimates (Jewett 1981). Fecundity of snow crabs is positively correlated to increasing body size (Haynes *et al.* 1976; Paul and Fuji 1989). In the southeast Bering Sea a 55 mm CW female would have about 24,500 eggs (Haynes *et al.* 1976) vs. 29,000 (Figure 6) for Chukchi Sea specimens 55 mm CW. In Atlantic Canada multiparous females typically carry 52,000 to 80,000 eggs, depending on geographic region (Davidson *et al.* 1985). There they reach maturity around 50 mm CW (Watson, 1970) and a 55 mm female would carry about 26,600 eggs (Haynes *et al.* 1976).

In 1976 Jewett (1981) found only 3.3% of mature Chukchi Sea females were ovigerous vs. 99% in this study. He collected during September to October, with a benthic trawl so the sampling period and collection gear were similar. He reported that 93% (n = 63) of mature females without external eggs had developing orange ova, so it is possible that they had not yet ovulated. In 1991 snow crab had extruded eggs prior to 25 July. These contrasting observations suggests that the dates that snow crab ovulate varies interannually.

Based on claw morphometrics Somerton (1981) estimated that 50% of male snow crab in the Bering Sea that reached 65 mm CW were mature. In the Chukchi Sea males > 65 mm are rare and all > 35 mm have sperm. However, Hartnoll (1965) emphasized that spermatophore presence in small males is only circumstantial evidence of maturity. Laboratory studies, and *in situ* observations, are needed to identify the size at which male Chukchi Sea snow crab mate with primiparous and multiparous mates.

Recently there has been considerable speculation on the reproductive habits of snow crab, especially the importance of male carapace and claw size (Conan and Commeau 1986). Comparison of size at maturity of female snow crab from the Chukchi Sea, Bering Sea, and the North Atlantic suggests that this species has a considerable capacity to modify size at maturity in response to environmental factors. A comprehensive comparison of snow crab mating behavior from several geographical areas, including the Chukchi Sea where there is no fishery, could improve our understanding of the reproductive biology of this valuable circumpolar species.

ACKNOWLEDGMENTS

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