

# Oceanographic characteristics of the habitat of benthic fish and invertebrates in the Beaufort Sea

Elizabeth Logerwell · Kimberly Rand ·  
Thomas J. Weingartner

Received: 4 November 2010 / Revised: 13 April 2011 / Accepted: 18 April 2011 / Published online: 13 May 2011  
© US Government 2011

**Abstract** We relate the spatial variability in the distribution of benthic taxa of the Beaufort Sea to oceanographic characteristics of their habitat with the goal of illustrating potential mechanisms linking climate change to Arctic marine communities. Offshore fish of the Beaufort Sea have not been surveyed since 1977 and no synchronous measures of fish distribution and the oceanographic characteristics of their habitat have been made previously. A survey was conducted during August 2008 in the western Beaufort Sea, Alaska. The distribution and abundance of benthic fish and invertebrates were assessed with standard bottom trawl survey methods. Oceanographic data were collected at each trawl station and at several locations between stations. The dominant benthic taxa, Polar cod (*Boreogadus saida*), eelpouts (*Lycodes* sp.), and snow crab (*Chionoecetes opilio*) were associated with cold ( $<-1.5^{\circ}\text{C}$ ), high salinity ( $>33$ ) water found offshore of the shelf break, derived from the Chukchi Sea. These waters are expected to be high in secondary productivity, such that we hypothesize that the distribution of fish and crab was driven by conditions favorable for successful foraging. Predictions of the impacts of climate change require an understanding of the

mechanisms linking the distribution and abundance of marine organisms to their oceanographic habitat. Our study documents the association of dominant benthic fish and invertebrates of the Beaufort Sea with specific water mass types and is thus a step toward this understanding.

**Keywords** Beaufort Sea · Polar cod · Eelpout · Snow crab · Oceanography

## Introduction

The impact of climate change appears to be particularly dramatic in Arctic ecosystems. Ocean warming, loss of sea ice, and ocean acidification are some of the stressors Arctic marine communities are expected to face in the future (IASC 2005). Most predictions of the effect of climate change on marine populations are based on correlations between climate indices and time series of variables such as recruitment or catch (Beamish and Bouillon 1995; Hollowed and Wooster 1995; Mantua et al. 1997). Explicit mechanisms linking climate variability and fish survival or growth remain largely unknown. By relating spatial variability in the distribution of benthic taxa of the Beaufort Sea to oceanographic characteristics of their habitat, we attempt to illustrate potential mechanisms linking climate change to Arctic marine communities and to formulate hypotheses to guide future research.

Arctic marine communities tend to be dominated by benthic fauna. Grebmeier et al. (2006) hypothesize that zooplankton do not extensively graze the primary production associated with sea ice in relatively cold waters and thus more organic carbon settles to the seafloor where it supports a rich benthic food web (Grebmeier et al. 2006). The high benthic standing stock of Arctic continental shelves

---

E. Logerwell (✉) · K. Rand  
Resource Ecology and Fisheries Management Division,  
Alaska Fisheries Science Center, National Marine  
Fisheries Service, National Oceanic and Atmospheric  
Administration, 7600 Sand Point Way NE, Seattle,  
WA 98115, USA  
e-mail: libby.logerwell@noaa.gov

T. J. Weingartner  
School of Fisheries and Ocean Sciences,  
Institute of Marine Science, University of Alaska Fairbanks,  
Box 757220, Fairbanks, AK 99775, USA

supports key benthic-feeding apex predators such as Pacific walrus (*Odobenus rosmarus*), gray whales (*Eschrichtius robustus*), bearded seals (*Erignathus barbatus*), and spectacled eiders (*Somateria fischeri*); some of these species are locally used for human subsistence (Grebmeier et al. 2006). Thus, understanding the processes impacting benthic fish and invertebrates is important for understanding the dynamics of Arctic ecosystems.

Alaskan Beaufort Sea water properties are known to be controlled by the annual freeze–thaw cycle and inflows from the oceanic and coastal boundaries (Mountain et al. 1976; Weingartner et al. 2005). Cross-shelf differences in water column properties are probably quite large. In summer and fall, these gradients are established by river runoff, ice melt, and shelfbreak processes, while in winter, the shelfbreak processes and the landfast/pack ice boundary likely lead to spatial heterogeneity (Pickart 2004; Wiengartner, unpublished data). How these gradients affect biological production patterns remains unknown.

Compared with other Arctic and North Pacific regions (i.e., the Chukchi Sea and Bering Sea), information on the distribution and abundance of fish taxa in offshore marine waters of the Beaufort Sea (>20 m deep) is scarce. The most recent previous survey of Beaufort Sea offshore marine fish was conducted opportunistically from a US Coast Guard cutter during 1976–1977 (Frost and Lowry 1983). The majority of other previous fish studies have focused on anadromous fish in estuaries, inlets, river deltas, or lagoons (Bond and Erickson 1997; Gallaway et al. 1997; Jarvela and Thorsteinson 1997; Moulton et al. 1997; Underwood et al. 1997). A few studies have examined the occurrence of marine fish in nearshore waters (<20 m deep), in the transition zone between marine and brackish waters (Craig et al. 1982; Craig 1984; Moulton and Tarbox 1987; Jarvela and Thorsteinson 1999). The distribution and abundance of benthic invertebrates in the Beaufort Sea have only been documented in a few previous publications, the most recent was published over 20 years ago (Wacasey 1975; Frost and Lowry 1983; Carey et al. 1984). The physical and biological oceanography of the Beaufort Sea shelf has been investigated more thoroughly and more recently (Matthews 1981; Aagaard 1984; Pickart 2004; Pickart et al. 2005; Weingartner et al. 2005; Ashjian et al. 2006; Okkonen 2008; Ashjian et al. 2009).

In August 2008, researchers from National Oceanic and Atmospheric Administration–National Marine Fisheries Service (NOAA–NMFS) Alaska Fisheries Science Center (AFSC), University of Washington (UW), and University of Alaska Fairbanks (UAF) conducted a survey of offshore marine fish, invertebrates, and physical oceanography of the western Beaufort Sea in the vicinity of Cape Simpson to Cape Halkett (Rand and Logerwell 2010). Detailed results regarding the catch numbers and biomass of all the benthic

fish and invertebrate taxa surveyed are found in Rand and Logerwell (2010). The results of the concurrent hydroacoustic survey of pelagic fish are reported in Parker-Stetter et al. (in press). In this present paper, we focus on the relationship between the most abundant benthic taxa (polar cod, eelpouts, walleye pollock, sculpin, and snow crab) and the oceanographic characteristics of their habitat.

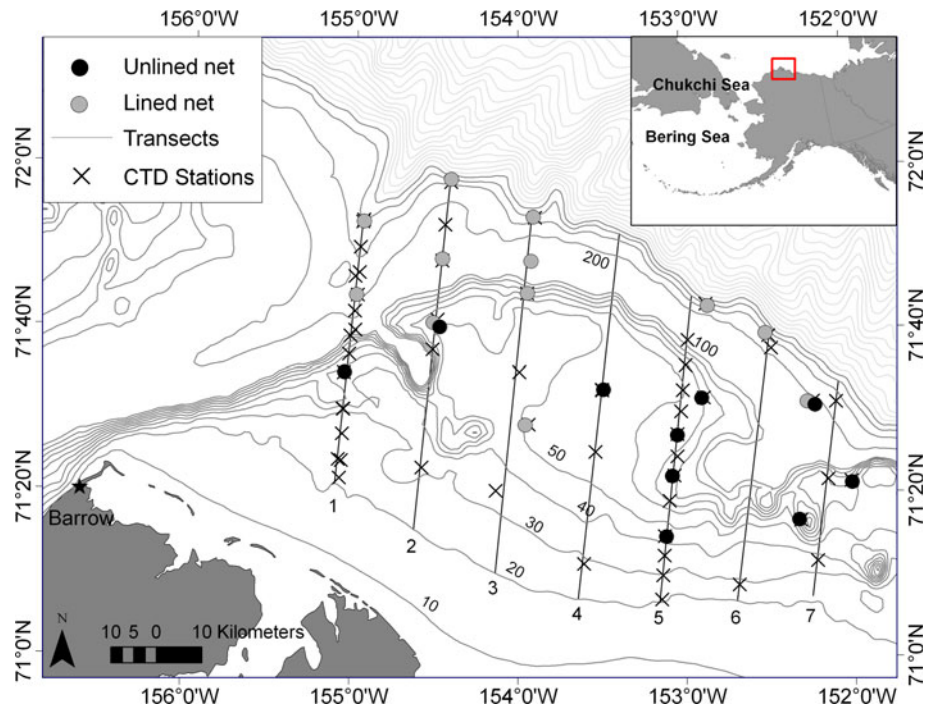
## Materials and methods

### Field methods

The survey was conducted during August 6–22, 2008, and in the area from approximately 155°W to 152°W in the Beaufort Sea, Alaska (Fig. 1). The 155-foot fishing vessel *Ocean Explorer* was chartered for the survey. Benthic fish and invertebrates were surveyed using bottom trawls deployed in concordance with standards set by the AFSC's Resource Assessment and Conservation Engineering (RACE) Division (Stauffer 2004). The net used for the bottom trawls was an 83–112 Eastern otter trawl built to standards detailed in Stauffer (2004), with a 25.3-m (83 ft) headrope and a 34.1-m (112 ft) footrope. In addition, a small-mesh liner was used on several trawls to catch relatively small Arctic fishes. The net was deployed and retrieved as rapidly as possible to minimize the catch of fish in the water column. The original field plan was to conduct the entire survey with the lined 83–112 nets. Unfortunately, all three lined nets were irreparably damaged during the first half of the cruise and trawls during the latter half of the survey were conducted with 83–112 nets with no liner (Fig. 1). A total of 22 bottom trawl tows were conducted. Net height, width, and bottom contact were measured so that area swept by the net and thus catch-per-unit-effort (CPUE) could be calculated. Each trawl catch was sorted to the lowest taxonomic level possible and individual taxa were counted and weighed. See Rand and Logerwell (2010) for details of bottom trawl field methods. An attempt was made to evenly distribute trawl station locations along transect lines from 20 to 500 m bottom depth (Fig. 1). However, due to the presence of sea ice during the first six days of the survey and several areas of untrawlable habitat (e.g., boulders, high relief), bottom trawls were limited to areas that would minimize potential gear loss or damage. In addition, we were not able to deploy bottom trawls in water less than 40 m, also due to untrawlable habitat.

A conductivity-temperature-depth (CTD) instrument was deployed at all bottom trawl locations immediately following the trawl. Additional intensive sampling occurred along Transects 1 and 5 to characterize cross-shelf variability in the western and eastern portions of the study area (Fig. 1). CTDs were deployed at a total of 56 stations.

**Fig. 1** Study area for August 2008 Beaufort Sea marine fish survey. Bottom trawl stations sampled with the unlined and lined net, survey transects, and CTD stations are shown. Depth contours are in meters



The instrument was a calibrated SBE 19*plus* CTD profiler (Seabird Electronics Inc., Bellevue, WA, USA) deployed with a portable winch installed on the vessel for this survey. The CTD was deployed to depths of 1–2 m off bottom at a rate of not more than 30 m/min. In addition, a micro-bathymograph, or MBT (SBE-39 Seabird Electronics Inc., Bellevue, WA, USA), was attached to the headrope of the trawl net. Temperature and depth were recorded at 3-s intervals from the time of net deployment from the vessel to net retrieval and instrument removal.

#### Data analysis

As part of the exploratory data analysis, we mapped the distribution of fish and invertebrate CPUE using ArcMap (version 9.3, 2008, ESRI, Inc.). We also compared the distribution of fish and invertebrates to vertical sections of temperature, salinity, density, and geostrophic flow (calculated from pressure gradients as estimated from horizontal density gradients) along transects with a sufficient density of CTD stations for adequate oceanographic profiles (Transects 1, 2, 3, and 5; Fig. 1). We then examined the relationships between several environmental variables and fish distributions using linear regression. Statistical analyses were carried out in S-PLUS 7.0 2005 (Insightful Corp., Seattle, WA, USA). Due to low sample sizes, we chose a *P* value of 0.10 as our significance threshold for all statistical analyses; this reduces the risk of making a Type II error.

All regressions were done with a single independent variable, and separate analyses were conducted for each gear

type (lined and unlined net). Due to the low sample size and increasing variance with increasing means, CPUE data were log transformed. In cases where there was a zero observation, 0.5 was added to all data points before log transformation. Due to the high number of zero catches for sculpins at lined net stations and eelpouts at unlined net stations, it was not appropriate to do a linear regression. Instead, a generalized linear model (GLM) was formulated assuming a binomial distribution with a logit link and first-order terms only. If the model showed a significant decrease from the null to residual deviance, then that independent variable was considered significant in explaining the variance in the data (Chambers and Hastie 1992). The independent variables were as follows:

1. Longitude
2. Bottom water temperature (°C)
3. Bottom depth (m)
4. Bottom water salinity (unitless, practical salinity scale)
5. Bottom water density (sigma-t)
6. Density difference (sigma-t) (difference between water density at the seafloor bottom and water density 1 m below the surface)

Bottom temperature and bottom depth were obtained from the MBT attached to the survey net because the CTD was not deployed all the way to the bottom. Salinity and density data were obtained from the CTD casts because the MBT does not measure salinity. The difference between bottom and near surface density is an indicator of the amount of water column stratification (a lesser difference indicates

greater vertical mixing). Longitude was included as an environmental variable because the exploratory maps suggested a longitudinal trend in the distribution of some species. For stations sampled with the unlined net, bottom depth was not included in the regression analyses, due to the limited range of depths (i.e., there was only one observation in the 100–500 m depth range, see Fig. 1).

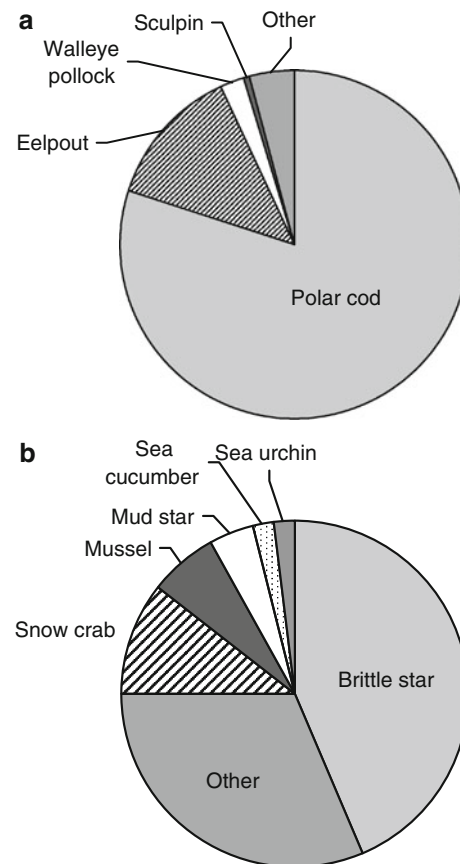
## Results

Fish made up 6% of the bottom trawl catch by weight and a total of 34 taxa were identified (Rand and Logerwell 2010). Polar cod (*Boreogadus saida*), eelpouts (predominantly *Lycodes ravidens* and *Lycodes polaris*), walleye pollock (*Theragra chalcogramma*), and sculpin (predominantly *Myoxocephalus verrucosus*, *Triglops pingeli*, and *T. nybelini*) were the most abundant benthic fish (Fig. 2a), so the analyses below focused on these taxa. Invertebrates made up 94% of the bottom trawl catch by weight and a total of 174 taxa were identified (Rand and Logerwell 2010). Brittle stars (*Ophiura sarsi*), snow crab (*Chionoecetes opilio*), mussels (*Musculus* spp.), mud stars (*Ctenodiscus crispatus*), sea cucumbers (*Psolus fabricii* and *P. phantapus*), and sea urchin (*Strongylocentrotus* sp.) were the most abundant invertebrate taxa (Fig. 2b). Given their potential commercial value (Food and Agriculture Organization 2010), we focused our analyses of the invertebrate catch on snow crab.

## Physical oceanography

Transect 1 extended across the eastern wall of Barrow Canyon and terminated at the mouth of the canyon in about 400 m water depth. Vertical sections of water mass properties along this transect show that seaward of the 30 m isobath the surface waters were separated from cold (<2°C) sub-surface waters by a strong halocline at ~30 m water depth in which salinities increased rapidly from 30 to 32 (Fig. 3). Below 30 m, salinities increased more gradually and reached a maximum of ~33.5 at 140 m. Temperatures at depths below 30 m were colder than 0°C, and temperatures at depths greater than 40 m were all below -1°C. The geostrophic velocity relative to the bottom indicated a strong eastward jet over the eastern side of the canyon, at 10–20 m water depth, with weaker westward flow to either side of the jet. There was a thermohaline front trapped to the bottom between the 30 and 40 m isobaths, in which salinity increased and temperature decreased seaward. Although this front included strong salinity and temperature gradients, the density contrast was primarily associated with the salinity change.

Although the stations along Transects 2 and 3 had coarser horizontal station spacing, the water property distri-



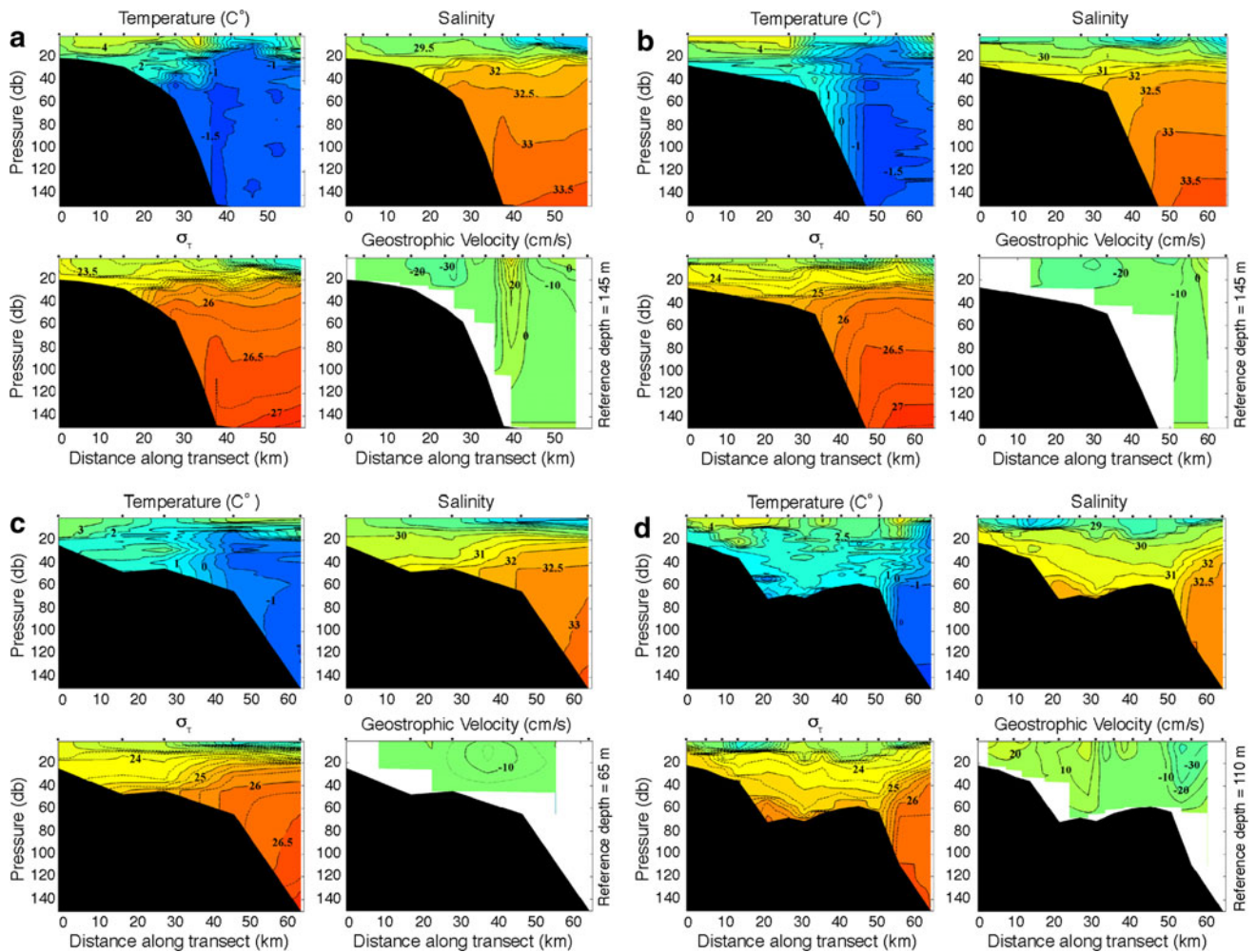
**Fig. 2** Relative catch (by weight) of benthic fish (a) and invertebrates (b)

butions along both had several features in common with those along Transect 1 (Fig. 3). In particular, cold, salty water occupied the outermost stations below 50-m depth along both transects. Bottom-trapped thermohaline fronts spanning the 30.5–32 isohalines was also evident on both transects but these were more diffuse than the subsurface front on Transect 1.

Most of the stations used in constructing Transect 5 were occupied following an August 13–15 upwelling wind event and the effects of this event were readily apparent. For example, note the upward bowing of the isohalines and isotherms beginning within 30 km of the 20 m isobath which had brought cold (2°C), salty (31) water inshore and to within 10 m of the surface at the innermost station (Fig. 3). The salinities of the water masses comprising the shelf-break front along Transect 5 were identical to those along the front in Transect 1. The temperatures within the shelf-break front along Transect 1 were, however, colder than those along Transect 5 (-1°C vs. 2°C) suggesting that these water masses had different mixing histories as they flowed along the shelfbreak.

The spatial distribution of water masses can be summarized in separate potential temperature-salinity ( $\theta$ -S) plots





**Fig. 3** Vertical sections of temperature, salinity, sigma-t (density), and velocity (positive = eastward flow, negative = westward flow) for Transects 1 (a), 2 (b), 3 (c), and 5 (d)

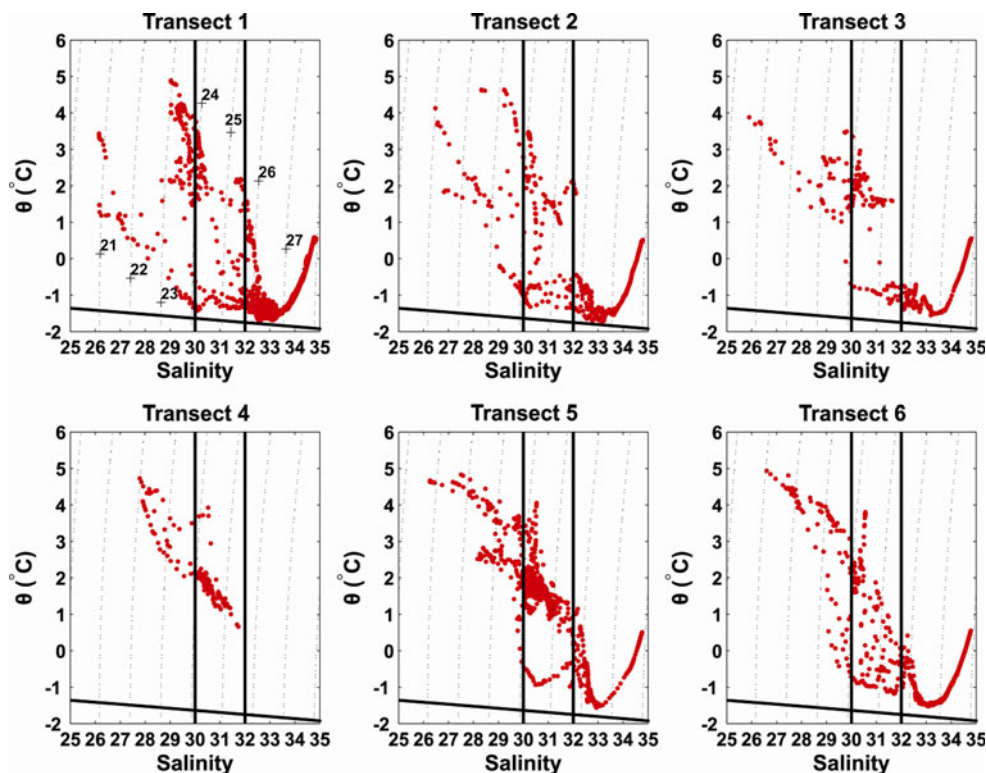
composited for each transect (Fig. 4). Potential temperature is the temperature that a parcel of water would acquire if brought to a standard reference pressure, 1,000 millibars. These show that the coldest water (near the freezing point and with salinities of between 30 and 33.1) was found along Transects 1 and 2. Some of this water flowed eastward along the slope and apparently warmed since the temperatures in this salinity range had increased slightly as evident in the  $\theta$ -S panels for Transects 3, 5, and 6. The heat must have been introduced through vertical mixing, either with warmer and fresher water at shallower depths or with saltier and warmer water from deeper depths. These figures also show that water types in the 30–32 salinity range span a broad temperature range. The coldest waters in this salinity range occur over and seaward of the shelf break, while the warmer waters are inshore of the shelfbreak. Nevertheless, these water types have similar densities so that they can mix laterally along isopycnal (constant density) surfaces.

#### Fish and crab distribution

The highest CPUE for polar cod was found where water depths ranged from 100 to 500 m in the western portion of the study area (Fig. 5a). Similar to polar cod, the highest CPUE of eelpouts occurred in 100–500 m depths and in the western portion of the study area (Fig. 5b). Walleye pollock were caught for the first time in the offshore marine waters of the Beaufort Sea (Rand and Logerwell 2010) and also were relatively abundant offshore of the 100 m isobath and to the west (Fig. 5c). Sculpins (Cottidae) showed a different distribution from polar cod, eelpouts, and walleye pollock. CPUE of sculpins was generally higher inshore of the 100 m depth contour (Fig. 5d). With the exception of one station, catches of sculpin were zero offshore of 100 m.

Snow crab (*Chionoecetes opilio*) were one of the most abundant benthic invertebrate species caught, second only to brittle stars, *Ophiura sarsi* (Rand and Logerwell 2010). Similar to the benthic fish species described above, snow crab were most abundant where water depths ranged from

**Fig. 4** Potential temperature ( $\theta$ , the temperature that a parcel of water would acquire if brought to a standard reference pressure) versus salinity (S) plots for each CTD transect. The black vertical bars delineate the region between 30 and 32 in salinity. The sloped horizontal line is the freezing point curve



100 to 500 m and in the western portion of the survey area (Fig. 5e). In addition, commercially legal-sized crab (>0.22 kg individual weight; Rand and Logerwell 2010) were found only at the deepest stations, greater than 300 m depth (Fig. 5f).

#### Fish and crab distribution relative to water mass properties

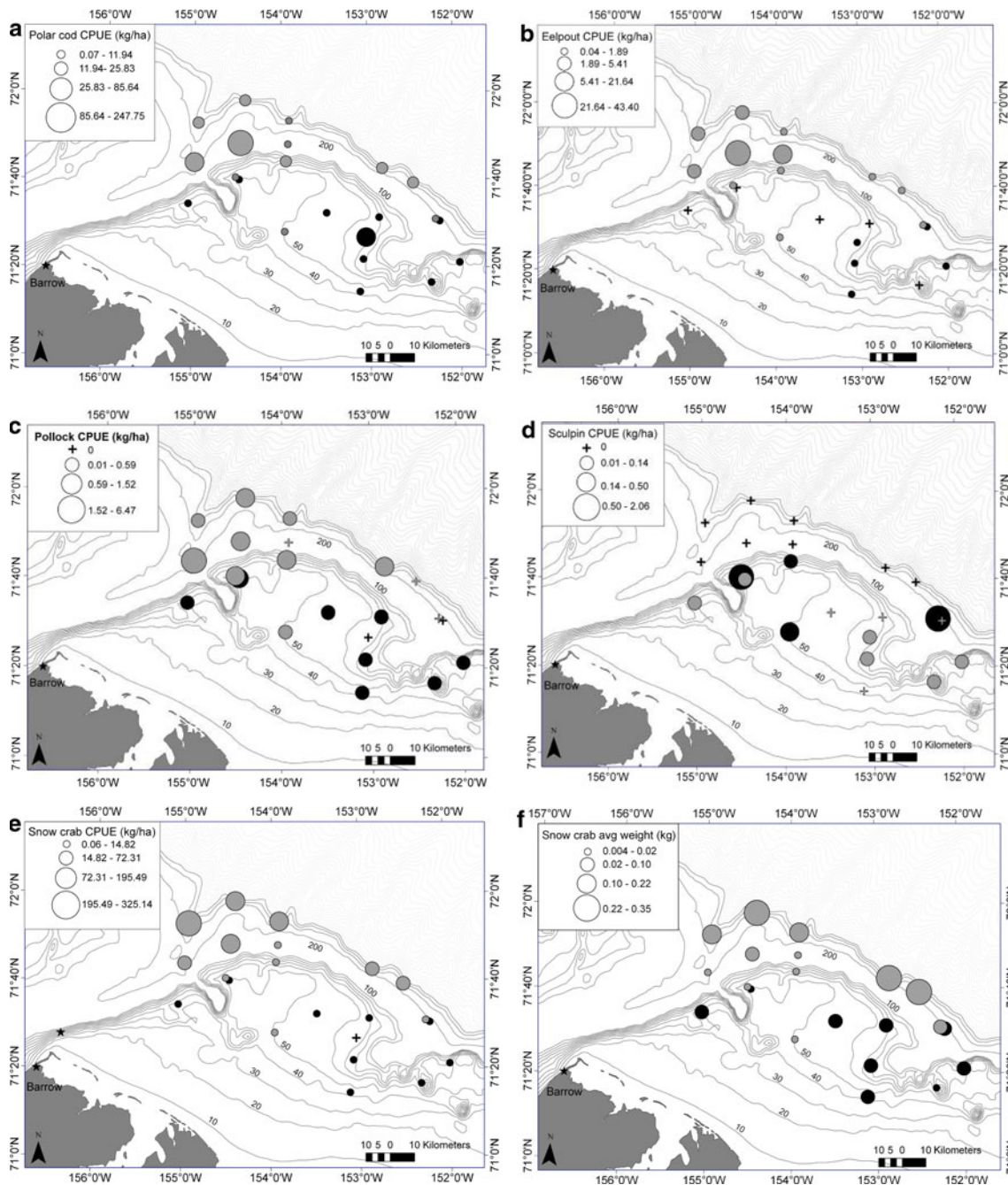
Polar cod along Transects 1 and 2 were relatively abundant in water offshore of the bottom-trapped thermohaline front where bottom temperature dropped to less than  $-1.5^{\circ}\text{C}$  and bottom salinity increased to greater than 33 (Fig. 6). There is some indication that polar cod were more abundant in relatively cold and high salinity water along Transect 3. However, compared with Transects 1 and 2, the abundance of polar cod along Transects 3 and 5 was lower overall and the very cold ( $<-1.5^{\circ}\text{C}$ ) and high salinity (>33) waters observed toward the west were only observed at the outermost stations, if at all. Eelpouts showed similar associations with water mass properties as polar cod (Fig. 6). Eelpout density along Transects 1 and 2 was highest offshore of the bottom-trapped thermohaline front in cold ( $<-1.5^{\circ}\text{C}$ ), high salinity (>33) water. The pattern continued toward the east, with eelpout density being relatively high in cold, high salinity water at the offshore ends of Transects 3 and 5. The greatest density of walleye pollock was observed along Transect 1, particularly in cold high salinity water offshore of the bottom-trapped front (Fig. 6). Walleye pollock densi-

ties were lower overall along the transects to the east, but there appeared to be an increase in walleye pollock density with decreasing temperature and increasing salinity, particularly along Transects 3 and 5. Sculpins showed a very different distribution than the other fish taxa. Sculpin density was relatively high inshore of the bottom-trapped thermohaline front along Transects 1 and 2 (Fig. 6). The association between sculpins and relatively warm, low salinity water was consistent along all four transects. Similar to polar cod and eelpouts, snow crab showed a strong association with cold, high salinity bottom water along all four transects examined (Fig. 6).

#### Linear models

Correlations between environmental variables were examined in order to determine which independent variables were correlated with each other. At the stations sampled with the lined net, bottom depth was correlated with all of the salinity and density variables (Table 1). Predictably, salinity, and density were highly correlated. At the stations sampled with the unlined net, longitude was significantly correlated with density difference (Table 2). Similar to the results for the lined net stations, salinity, and density variables were correlated.

There was a significant correlation between polar cod lined net CPUE and bottom temperature, and the correlation was negative (Table 3). There were no significant relationships



**Fig. 5** Distribution of fish and snow crab. Light gray symbols are stations sampled with the lined net. Solid black symbols are stations sampled with the unlined net: **a** polar cod, **b** eelpouts, **c** walleye pollock,

**d** sculpins, **e** snow crab, **f** snow crab individual weight. Depth contours are in meters

between polar cod unlined net CPUE and any of the environmental variables (Table 4).

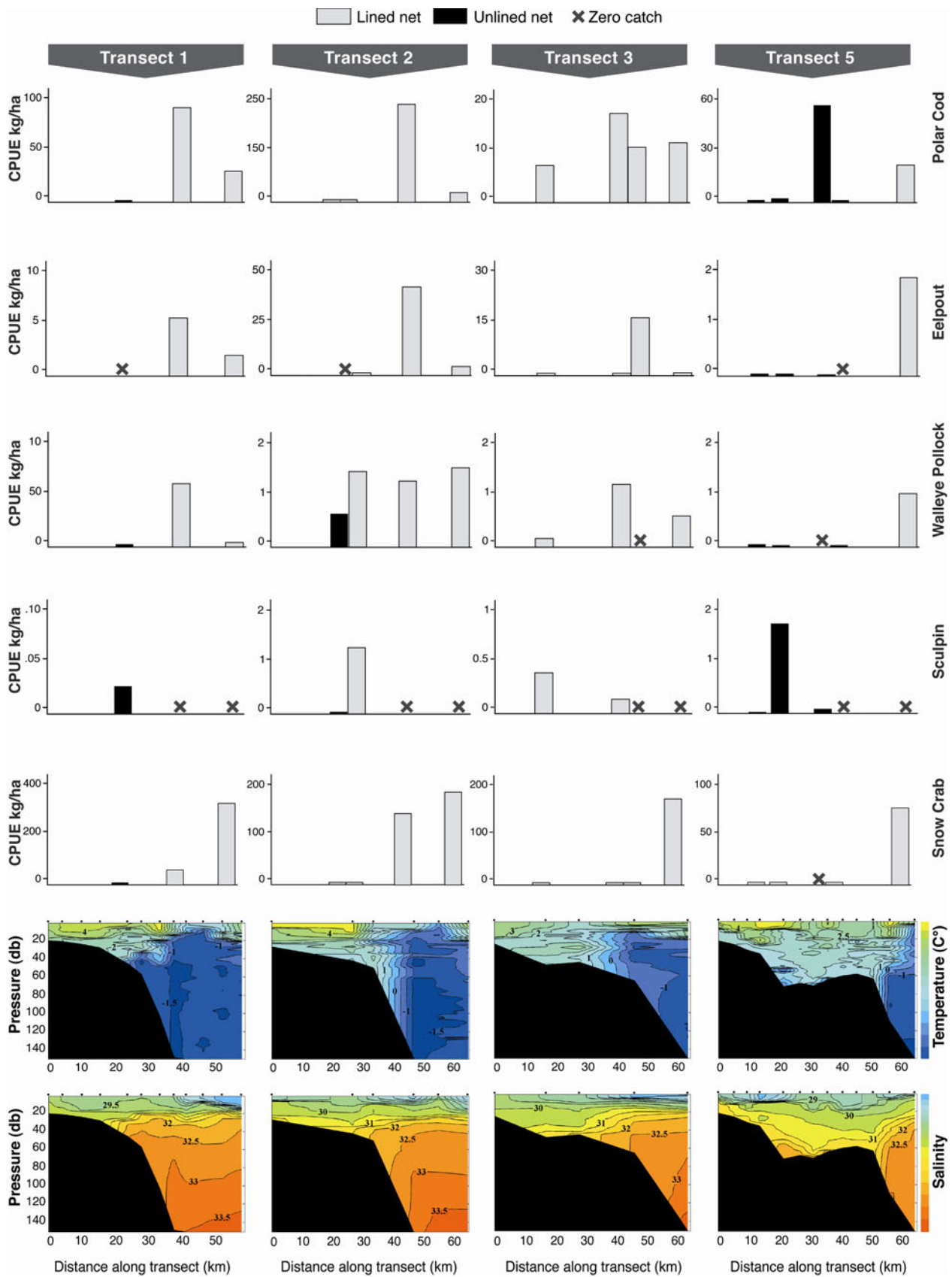
There was a significant negative relationship between eelpout lined net CPUE and bottom temperature (Table 3). The unlined net GLM showed that none of the independent variables alone were significantly related to the presence/absence of eelpouts.

There was a significant negative relationship between walleye pollock lined net CPUE and longitude, with CPUE

decreasing from west to east (Table 3). There was also a significant negative relationship between walleye pollock unlined net CPUE and longitude (Table 4).

The lined net GLM for sculpins showed that bottom depth and density difference (correlated environmental variables) were significantly related to sculpin presence/absence at the  $P < 0.05$  level (Table 5). There were no significant relationships between sculpin unlined net CPUE and any of the environmental variables (Table 3).





**Fig. 6** Along transect polar cod, eelpout, walleye pollock, sculpin, and snow crab catch-per-unit-effort (CPUE) over vertical sections of temperature and salinity for Transects 1, 2, 3, and 5



**Table 1** Correlation matrix of all the environmental variables at the stations sampled with the lined net

	Density difference (sigma-t)	Bottom density (sigma-t)	Bottom salinity	Bottom depth (m)	Bottom temperature (°C)	Longitude (decimal degrees)
Longitude (decimal degrees)						
$R^2$	0.02	0.05	0.05	<0.01	<0.01	
$P$ value	0.63	0.50	0.50	0.98	0.97	
Bottom temperature (°C)						
$R^2$	0.09	0.01	<0.01	<0.01		
$P$ value	0.37	0.76	0.86	0.82		
Bottom depth (m)						
$R^2$	<b>0.67</b>	<b>0.73</b>	<b>0.74</b>			
$P$ value	<b>&lt;0.01</b>	<b>&lt;0.01</b>	<b>&lt;0.01</b>			
Bottom salinity (psu)						
$R^2$	<b>0.67</b>	<b>1.0</b>				
$P$ value	<b>&lt;0.01</b>	<b>&lt;0.01</b>				
Bottom density (sigma-t)						
$R^2$						
$P$ value						
Density difference (sigma-t)						
$R^2$						
$P$ value						

Values in bold indicate significant relationships ( $P < 0.10$ ). The variable name,  $R^2$ , and  $P$  values are shown. Correlations between density difference and bottom density are not reported because the variables are derived from the same data

There were significant relationships between snow crab lined net CPUE and bottom depth and the suite of correlated salinity and density variables (Table 3). There were significant positive relationships between crab unlined net CPUE and bottom salinity and bottom density (Table 4).

In summary, high CPUEs of polar cod, eelpout, and snow crab were statistically associated with colder bottom temperatures and increasing bottom depth. High snow crab CPUE was also associated with increased bottom salinity and westerly longitude, as evidenced from the catches with the unlined net only. Walleye pollock CPUE was correlated with longitude, being more abundant toward the west. GLM showed that sculpin distribution was positively influenced by shallow bottom depths and lesser density differences.

## Discussion

Our 2008 survey was the only offshore marine fish survey of the US Beaufort Sea since 1977 and the first Beaufort Sea survey to use benthic trawl gear and methods standard for NOAA-NMFS AFSC demersal surveys. Our study thus provides the first quantitative estimates of demersal fish and benthic invertebrate density in this area, and contributes to a baseline for future monitoring (Rand and Logerwell 2010). The concurrent hydroacoustic study provides quantitative estimates of pelagic fish distribution (Parker-Stetter

et al., in press). These studies are also the first to illustrate relationships between the distribution and the abundance of offshore benthic and pelagic taxa of the Beaufort Sea and oceanographic habitat characteristics. The occurrence of cold, high salinity water from the Chukchi Sea appears to be a factor in driving the distribution of benthic fish and snow crab in our study area.

The cold, high salinity water observed off the shelf break, particularly toward the western portion of the study area, was most likely formed on the Chukchi Sea shelf in the previous winter during the formation of sea ice (Weingartner et al. 2005). Winds were generally southwesterly during the survey, which favored outflow of this Chukchi Sea water northeast through Barrow Canyon and into our study area in the Beaufort Sea. The occurrence of Pacific Ocean-derived waters (modified on the Bering and Chukchi shelves) that exit the Chukchi shelf through Barrow Canyon and into the Beaufort Sea has been documented previously (Mountain et al. 1976; Aagaard and Roach 1990; Weingartner et al. 1998; Pickart et al. 2005; Weingartner et al. 2005; Woodgate et al. 2005). Some of this outflow continues eastward (in the surface layer in summer) and/or as a subsurface current along the Beaufort shelfbreak and slope and contributes to the upper halocline of the Canada Basin (Mountain et al. 1976; Aagaard 1984; Pickart 2004; Pickart et al. 2005) and some appears to spread westward and/or offshore in the polar mixed layer

**Table 2** Correlation matrix of all the environmental variables at the stations sampled with the unlined net

	Density difference (sigma-t)	Salinity difference (psu)	Bottom density (sigma-t)	Bottom salinity	Temperature difference (°C)	Bottom temperature (°C)	Longitude (decimal degrees)
Longitude (decimal degrees)							
$R^2$	<b>0.46</b>	<b>0.49</b>	0.19	0.18	0.04	0.02	
$P$ value	<b>0.03</b>	<b>0.03</b>	0.21	0.21	0.56	0.69	
Bottom temperature (°C)							
$R^2$	0.04	0.03	0.2	0.17	<b>0.36</b>		
$P$ value	0.56	0.61	0.2	0.23	<b>0.07</b>		
Temperature difference (°C)							
$R^2$	<b>0.32</b>	0.28	0.26	0.23			
$P$ value	<b>0.09</b>	0.12	0.13	0.16			
Bottom salinity (psu)							
$R^2$	<b>0.67</b>		<b>1.0</b>				
$P$ value	<b>&lt;0.01</b>		<b>&lt;0.01</b>				
Bottom density (sigma-t)							
$R^2$		<b>0.67</b>					
$P$ value		<b>&lt;0.01</b>					
Salinity difference (psu)							
$R^2$	<b>1.0</b>						
$P$ value	<b>&lt;0.01</b>						
Density difference (sigma-t)							
$R^2$							
$P$ value							

Values in bold indicate significant relationships ( $P < 0.10$ ). The variable name,  $R^2$ , and  $P$  values are shown. Correlations between bottom density/salinity and density/salinity difference are not reported because the variables are derived from the same data. Bottom depth was not part of this analysis, see “Materials and methods”

**Table 3** Results of linear regression between environmental variables and fish or crab CPUE (kg/ha) from the lined net stations

	Longitude (decimal degrees)	Bottom temperature (°C)	Bottom depth (m)	<i>Bottom salinity</i>	<i>Bottom density (sigma-t)</i>	<i>Density difference (sigma-t)</i>
Polar cod						
$R^2$	0.09	<b>0.40 (–)</b>	0.02	0.06	0.07	0.13
$P$ value	0.33	<b>0.03</b>	0.63	0.45	0.40	0.25
Eelpouts						
$R^2$	0.02	<b>0.42 (–)</b>	0.13	0.12	0.14	0.18
$P$ value	0.68	<b>0.02</b>	0.25	0.27	0.24	0.18
Walleye pollock						
$R^2$	<b>0.41 (–)</b>	<0.01	<0.01	0.02	0.02	0.05
$P$ value	<b>0.02</b>	1.0	0.99	0.64	0.64	0.47
Snow crab						
$R^2$	<0.01	0.12	<b>0.70 (+)</b>	<b>0.73 (+)</b>	<b>0.75 (+)</b>	<b>0.74 (+)</b>
$P$ value	0.99	0.26	<b>&lt;0.01</b>	<b>&lt;0.01</b>	<b>&lt;0.01</b>	<b>&lt;0.01</b>

$R^2$  and  $P$  values for each regression are shown. Significant  $P$  values and the corresponding  $R^2$  are in bold, positive (+) or negative (–) relationship. Variables in italics were correlated

(Shimada et al. 2001). However, some of the canyon outflow rounds Pt. Barrow and continues onto the inner portion of the Beaufort shelf, although the frequency and the extent to which this occurs are unknown.

Polar cod were the most abundant benthic fish caught during this survey, both numerically and by weight (Rand and Logerwell 2010). Polar cod also dominated the pelagic environment as evidenced by the acoustic survey conducted

**Table 4** Results of linear regression between environmental variables and fish and crab CPUE (kg/ha) from the unlined net stations

	Longitude (decimal degrees)	Bottom temperature (°C)	<i>Bottom salinity</i>	<i>Bottom density (sigma-t)</i>	<i>Density difference (sigma-t)</i>
Polar cod					
$R^2$	0.06	0.08	0.01	0.01	<0.01
$P$ value	0.48	0.44	0.79	0.84	0.98
Walleye pollock					
$R^2$	<b>0.37</b> (–)	0.08	0.12	0.14	0.27
$P$ value	<b>0.06</b>	0.43	0.32	0.23	0.13
Sculpin					
$R^2$	<0.01	0.02	0.04	0.04	0.20
$P$ value	0.83	0.74	0.59	0.56	0.19
Snow crab					
$R^2$	0.07	<0.01	<b>0.42</b> (+)	<b>0.40</b> (+)	0.16
$P$ value	0.47	0.79	<b>0.04</b>	<b>0.05</b>	0.26

$R^2$  and  $P$  values for each regression are shown. Significant  $P$  values and the corresponding  $R^2$  are in bold, positive (+) or negative (–) relationship. Variables in italics were correlated. In addition, longitude was correlated with density difference

**Table 5** Results of GLM of environmental variables and sculpins from the lined net stations

	Longitude (decimal degrees)	Bottom temperature (°C)	<i>Bottom depth (m)</i>	<i>Bottom salinity</i>	<i>Bottom density (sigma-t)</i>	<i>Density difference (sigma-t)</i>
Residual deviance (null deviance: 8.789)	8.547	8.013	<b>3.293</b>	<b>5.833</b>	<b>5.807</b>	<b>4.886</b>
F statistic	0.31	0.93	<b>12.97</b>	<b>3.90</b>	<b>3.93</b>	<b>7.22</b>
$P$ value	0.59	0.36	<b>0.005</b>	<b>0.08</b>	<b>0.08</b>	<b>0.02</b>

Numbers in bold are significant. All variables in italics were correlated

concurrently with the bottom trawl survey (Parker-Stetter et al., in press). Polar cod are known to be a major component of the Beaufort Sea fish community and important prey for higher trophic levels such as seabirds (Hobson 1993) and marine mammals (Bradstreet and Cross 1982; Bradstreet et al. 1986; Welch et al. 1992). They are also the dominant consumer of zooplankton (Atkinson and Percy 1992) and are thus an important conduit for secondary production (Welch et al. 1992). One of the earliest documented records of polar cod in the Alaskan Beaufort Sea is from 1951 (Mecklenburg et al. 2006) and they were the most abundant fish during the 1976–1977 opportunistic trawl survey (Frost and Lowry 1983). Previous studies in near-shore, often brackish waters have documented the distribution of polar cod (Craig et al. 1982; Craig 1984; Moulton and Tarbox 1987; Jarvela and Thorsteinson 1999), but our study is the first to map the distribution of polar cod in offshore marine waters.

Polar cod, two of the other most abundant fish taxa (eelpouts and walleye pollock), and one of the most abundant invertebrates (snow crab) were most abundant off the shelf, where water depths exceeded 100 m. The deeper stations were all sampled with the lined net, and Rand and Logerwell (2010) showed that lined net catches were gener-

ally greater than unlined net catches. So, it is possible that the apparent abundance of polar cod, eelpout, walleye pollock, and crab offshore was an artifact of net type. However, fish and crab CPUE were relatively low at three stations sampled with the lined net at depths shallower than 100 m, suggesting that net type alone did not explain the spatial pattern. In addition, separate statistical analyses of lined and unlined catch data support associations of these taxa with water mass properties characteristic of the offshore environment. The results of the concurrent hydroacoustic fish survey similarly showed that polar cod densities were highest where water depths exceeded 100 m (Parker-Stetter et al., in press).

Polar cod, eelpouts, and snow crab appeared to be associated with water from the Chukchi Sea. Comparing their distribution with water column properties across the shelf showed relatively high fish and crab densities in cold (<–1.5°C), high salinity (>33) waters offshore of the thermohaline front that separated these waters from relative warm and low salinity waters inshore. Regression supported the relationship between polar cod and eelpout density and cold temperatures. Regression of snow crab density derived from lined net catches indicated that both bottom depth and bottom temperature were significant predictors of



crab distribution. Analyses of snow crab density from unlined net catches showed that bottom salinity and longitude were significant.

There appears to be a biologically significant relationship between polar cod and waters derived from the Chukchi Sea. The results of both the benthic survey (this paper) and the pelagic survey (Parker-Stetter et al., in press) support this hypothesis. Previous studies in the marine coastal habitat have similarly shown that polar cod prefer waters that are cold ( $-1$  to  $3^{\circ}\text{C}$ ) and of high salinity (27–32; Craig 1984). However, information about polar cod in this habitat is scarce compared with information on their use of near-shore, brackish water habitats. The distribution of polar cod relative to water temperature and water column mixing may reflect foraging habitat selection. The Chukchi Sea outflow of cold, winter-formed waters is rich in dissolved and particulate organic carbon (Pickart et al. 2005; Mathis et al. 2007) and thus may be high in secondary productivity. Differences in nearshore brackish and offshore marine habitats have been shown to be reflected in polar cod diets. In the nearshore habitat, polar cod prey on epibenthic mysids and amphipods (Craig 1984). In offshore marine waters, they prey on copepods and amphipods (Frost and Lowry 1983). Polar cod are also common along sea ice margins, feeding on ice-associated invertebrates (Cobb and Fast 2008). In the Chukchi Sea polar cod densities were greatest in Bering Shelf water compared with Alaska coastal water and Chukchi water perhaps due to a higher abundance of zooplankton (Gillespie et al. 1997). So there is some evidence that polar cod select habitat based on prey abundance.

Similar to polar cod, the apparent preference of eelpouts for offshore Chukchi Sea waters could be driven by the distribution of their prey. Eelpouts in the Bering Sea typically consume benthic invertebrate prey such as shrimp, polychaetes, and mysids (Aydin et al. 2007). Unfortunately, food habits data for eelpouts do not exist for the Beaufort Sea region.

Virtually nothing is known about the food habits of snow crab in the Beaufort Sea. However, previous studies have suggested a metabolic explanation for the distribution of snow crab relative to temperature. Snow crab on the Scotian Shelf are similarly most abundant in relatively cold water (Tremblay 1997), and it has been suggested that this is because at warmer temperatures metabolic costs are greater than consumption (Foyle et al. 1989).

Walleye pollock were not recorded during the 1977 survey of the offshore waters of the Beaufort Sea (Frost and Lowry 1983) and the most recent previous confirmed northerly expansion of the range of walleye pollock was documented during a 2004 survey of the Chukchi Sea (Mecklenburg et al. 2007). During our 2008 Beaufort Sea survey, walleye pollock were most abundant to the west

and were associated with cold, high salinity waters offshore, particularly on the westernmost transect. Regression supported the relationship between walleye pollock density and longitude. The westerly distribution of walleye pollock is consistent with a relatively recent introduction of walleye pollock into the Beaufort Sea from the south and west (Bering and Chukchi Seas). If this hypothesis is true, then future surveys of the Beaufort Sea could show further expansion of the range of walleye pollock to the east. An alternative (and possibly complimentary) explanation for the westerly distribution of pollock is the presence of relatively productive Chukchi Sea water in the west (as described above).

Sculpins had a very different distribution than polar cod, eelpouts, walleye pollock, and crab. They were more likely to be present on the shelf where the water column is less stratified. In fact, virtually no sculpins were caught where bottom depth exceeded 100 m. Sculpins of the Arctic burrow into sand and sand-mud bottoms, feeding on small benthic amphipods and polychaetes (Fedorov 1986). The nearshore distribution of sculpins may be driven by a preference for muddy substrate and small benthic prey.

An additional explanation for the high catches of benthic fish (excluding sculpins) and snow crab offshore of 100 m depth is that the inner shelf may suffer from ice grounding in winter, which could reduce habitat area for benthos. The Beaufort Sea ice cover consists of two components; drifting pack ice over the middle and outer shelf and the virtually immobile landfast ice on the inner shelf. Ice keels can gouge the seafloor (Barnes et al. 1984) and form piles of grounded ice along the seaward edge of the landfast ice (a.k.a. *stamukhi*). Scouring by sea ice has been shown to disturb the composition of benthic communities in both the Arctic and the Antarctic (Gutt 2001). A survey of benthic invertebrates inside and outside ice scour troughs in the Canadian Beaufort Sea showed that species diversity was lower within the troughs and was dominated by scavengers and deposit feeders. The more diverse community outside the troughs was dominated by predators and suspension feeders (Conlan et al. 1998). Ice-scouring can also create depressions in the sediment that are filled with hypoxic, sulfide-rich water (a result of brine release from the ice). These pools can cause mortality of infauna and sessile epifauna and can also act as a lethal trap for motile animals (Kvitek et al. 1998).

Arctic climate is changing at an unprecedented rate. The summer of 2007 saw the largest recession of sea ice since recording began (Stroeve et al. 2007, 2008; Greene et al. 2008; Boé et al. 2009). Several factors have contributed to shifts in observed trends in Arctic ice cover over the last few decades. Both lengthened periods of open water, and an increase in sea surface temperatures have contributed to delays in the Arctic autumn and winter ice growth (Stroeve

et al. 2007). Changes in marine communities are expected to result from ocean warming, such as northerly extensions of fish ranges (IASC 2004; Mueter and Litzow 2008; Spencer 2008; Mueter et al. 2009). Predictions of the impacts of climate change, loss of sea ice, and any associated changes in ocean circulation will require an understanding of the mechanisms linking the distribution and abundance of marine organisms to their oceanographic habitat. Our study documents the association of dominant benthic fish and invertebrates of the Beaufort Sea with specific water mass types and is thus a step toward this understanding.

**Acknowledgments** Funding for this study was provided by the U.S. Department of the Interior's Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), Alaska Region (Interagency Agreement M07PG13152 and AKC-058). We would like to thank the National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center's (AFSC) Resource Assessment and Conservation Engineering Division (RACE) for providing survey gear, support, and expertise. We would like to especially thank Héloïse Chenelot of the University of Alaska Fairbanks for providing species identification on the invertebrates and Erika Acuna (RACE) for providing expertise on fish species identification in the field. James Orr and Duane Stevenson (RACE) provided taxonomic verification and identification of all fish species. Thanks to Sandra Parker-Stetter and Jennifer Nomura who were part of the scientific crew. We would like to thank the captain and crew of the *F/V Ocean Explorer* (Captain Darin Vanderpol and Raphael Guterrez, Tom Giacalone, Joao DoMar, Ben Boyok, and Jessica Heaven) for a productive and safe research cruise. Finally, we thank the reviewers for their time and constructive input. The findings and conclusions in the paper are those of the author(s) and do not necessarily represent the views of the National Marine Fisheries Service, NOAA.

## References

- Aagaard K (1984) The Beaufort undercurrent. In: Barnes PW, Schell DM, Reimnitz E (eds) *The Alaska Beaufort Sea*. Academic Press, Orlando, pp 47–72
- Aagaard K, Roach AT (1990) Arctic ocean-shelf exchange: measurements in Barrow Canyon. *J Geophys Res* 95:18163–18175
- Ashjian CJ, Sherr EB, Campbell RG, Sherr BF, Plourde S, Hill VJ, Cota GF (2006) Mesozooplankton-microbial food web interactions in western arctic shelf and basin regions. *EOS Trans Am Geophys Union* 87 (36 suppl)
- Ashjian CJ, Okkonen SR, Campbell RG (2009) Mooring and broad-scale oceanography. In: Rugh D (ed) *Bowhead whale feeding ecology study (BOWFEST) in the Western Beaufort Sea; 2008 Annual Report*. MMMS-450000120. National Marine Mammal Laboratory, Alaska Fisheries Science Center, NMML, NOAA, 7600 Sand Point Way NE, Seattle, WA, pp 38–48
- Atkinson EG, Percy JE (1992) Diet comparison among demersal marine fish from the Canadian Arctic. *Polar Biol* 11:567–573
- Aydin K, Gaichas S, Ortiz I, Kinzey D, Friday N (2007) A comparison of the Bering Sea, Gulf of Alaska, and Aleutian Islands large marine ecosystems through food web modeling. US Department of Commerce, NOAA Technical Memo, NMFS-AFSC-178, 298 pp
- Barnes PW, Rearic DM, Reimnitz E (1984) *Ice gouging characteristics and processes*. Academic Press, New York
- Beamish RJ, Bouillon DR (1995) Marine fish production trends off the Pacific coast of Canada and the United States. In: Beamish RJ (ed) *Climate change and northern fish populations*. Can Spec Publ Fish Aquat Sci 121:585–591
- Boé J, Hall A, Qu X (2009) September sea-ice cover in the Arctic ocean projected to vanish by 2100. *Nat Geosci* 2:341–343
- Bond WA, Erickson RN (1997) Coastal migration of Arctic ciscoes in the eastern Beaufort Sea. In: *Fish ecology in Arctic North America*. American Fisheries Society, Bethesda, pp 155–164
- Bradstreet MSW, Cross WE (1982) Trophic relationships at high Arctic ice edges. *Arctic* 35:1–12
- Bradstreet MSW, Finley KJ, Sekerak AD, Griffiths WB, Evans CR, Fabijan FF, Stallard HE (1986) Aspects of the biology of polar cod (*Boreogadus saida*) in Arctic marine food chains. *Can Tech Rep Fish Aquat Sci* 1491:193
- Carey AG, Boudrias MA, Kern JC, Ruff RE (1984) Selected ecological studies on continental shelf benthos and sea ice fauna in the southwestern Beaufort Sea. OCSEAP Final Report, U.S. Department of Commerce, vol 23, 164 pp
- Chambers JM, Hastie TJ (1992) *Statistical models in S*. Wadsworth & Brooks/Cole Advanced Books and Software, Pacific Grove, CA
- Cobb D, Fast H (2008) Beaufort Sea large ocean management area: ecosystem overview and assessment report. *Can Tech Rep Fish Aquat Sci* 2780:199
- Conlan KE, Lenihan HS, Kvitek RG, Oliver JS (1998) Ice scour disturbance to benthic communities in the Canadian High Arctic. *Mar Ecol Prog Ser* 166:1–16
- Craig PC (1984) Fish use of coastal waters of the Alaska Beaufort Sea: a review. *T Am Fish Soc* 113:265–282
- Craig PC, Griffiths WB, Haldorson L, McElderry H (1982) Ecological studies of polar cod (*Boreogadus saida*) in Beaufort Sea coastal waters, Alaska. *Can J Fish Aquat Sci* 39:395–406
- Fedorov VV (1986) Cottidae. In: Whitehead PJP, Hureau J-C, Nielsen J, Tortonese E (eds) *Fishes of the northeastern Atlantic and the Mediterranean*. UNESCO, Paris
- Food and Agriculture Organization (2010) Species fact sheets of the United Nations *Chionoecetes opilio*. <http://www.fao.org/fishery/species/2644/en>. Accessed August 24 2010
- Foyle TP, O'Dor RK, Elnor RW (1989) Energetically defining the thermal limits of the snow crab. *J Exp Biol* 145:371–393
- Frost KJ, Lowry LF (1983) Demersal fishes and invertebrates trawled in the northeastern Chukchi and western Beaufort Seas 1976–1977. US Department of Commerce, NOAA Technical Report, NMFS-SSRF-764, 22 pp
- Gallaway BJ, Felchhelm RG, Griffiths WB, Cole JG (1997) Population dynamics of broad whitefish in the Prudhoe Bay region, Alaska. In: Reynolds JB (ed) *Fish ecology in Arctic North America*. American Fisheries Society, Bethesda, pp 194–207
- Gillespie JG, Smith RL, Barbour E, Barber WE (1997) Distribution, abundance, and growth of polar cod in the northeastern Chukchi sea. In: Reynolds JB (ed) *Fish ecology in Arctic North America*, vol 19. American Fisheries Society Symposium, Bethesda, pp 81–89
- Grebmeier JM, Cooper LW, Feder HM, Sirenko BI (2006) Ecosystem dynamics of the Pacific-influenced northern Bering Sea and Chukchi Seas in the Amerasian Arctic. *Prog Oceanogr* 71:331–361
- Greene CH, Pershing AJ, Cronin TM, Ceci N (2008) Arctic climate change and its impacts on the ecology of the North Atlantic. *Ecology* 89:S24–S38
- Gutt J (2001) On the direct impact of ice on marine benthic communities, a review. *Polar Biol* 24:553–564
- Hobson KA (1993) Trophic relationships among high arctic seabirds: Insights from tissue-dependent stable-isotope models. *Mar Ecol Progr Ser* 95:7–18
- Hollowed AB, Wooster WS (1995) Decadal-scale variations in the Eastern SubArctic Pacific: II. Response of northeast Pacific fish

- stocks. In: Beamish RJ (ed) Climate change and northern fish populations, *Can J Fish Aquat Sci* 121:373–385
- IASC (2004) Impacts of a warming Arctic: Arctic climate impact assessment. Cambridge University Press, Cambridge, 146 pp
- IASC (2005) Arctic climate impact assessment. Cambridge University Press, Cambridge, UK, 1020 pp
- Jarvela LE, Thorsteinson LK (1997) Movements and temperature occupancy of sonically tracked Dolly Varden and Arctic ciscoes in Camden Bay, Alaska. In: Reynolds JB (ed) Fish ecology in Arctic North America. American Fisheries Society, Bethesda, pp 165–174
- Jarvela LE, Thorsteinson LK (1999) The epipelagic fish community of Beaufort Sea coastal waters, Alaska. *Arctic* 52:80–94
- Kvitek RG, Conlan KE, Iampietro PJ (1998) Black pools of death: hypoxic, brine-filled ice gouge depressions become lethal traps for benthic organisms in a shallow Arctic embayment. *Mar Ecol Prog Ser* 162:1–10
- Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull Am Meteorol Soc* 78:1069–1079
- Mathis JT, Pickart RS, Hansell DA, Kadko D, Bates NR (2007) Eddy transport of organic carbon and nutrients from the Chukchi shelf: Impact on the upper halocline of the western Arctic ocean. *J Geophys Res* 112:C05011. doi:05010.01029/02006JC003899
- Matthews JB (1981) Observations of surface and bottom currents in the Beaufort Sea near Prudhoe Bay, Alaska. *J Geophys Res* 86 (C7):6653–6660
- Mecklenburg CA, Mecklenburg TA, Sheiko BA, Chernova NV (2006) Arctic marine fish museum specimens. Database submitted to ArcOD Institute of Marine Science, University of Alaska Fairbanks. <http://ak.aaos.org/rest/metadata/ArcOD/2007F1>
- Mecklenburg CW, Stein DL, Sheiko BA, Chernova NV, Mecklenburg TA, Holladay BA (2007) Russian-American long term census of the Arctic: Benthic fishes trawled in the Chukchi Sea and Bering Strait, August 2004. *Northwest Nat* 88:168–187
- Moulton LL, Tarbox KE (1987) Analysis of Polar cod movements in the Beaufort Sea nearshore region, 1978–79. *Arctic* 40:43–49
- Moulton LL, Philo LE, George JC (1997) Some reproductive characteristics of least ciscoes and humpback whitefish in Dease Inlet, Alaska. In: Reynolds JB (ed) Fish ecology in Arctic North America. American Fisheries Society, Bethesda, pp 119–126
- Mountain DG, Coachman LK, Aagaard K (1976) On the flow through Barrow Canyon. *J Phys Oceanogr* 6:461–470
- Mueter FJ, Litzow MA (2008) Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecol Appl* 18:309–320
- Mueter FJ, Broms C, Drinkwater KF, Friedland KD, Hare JA, Hunt GLJ, Melle W, Taylor M (2009) Ecosystem response to recent oceanographic variability in high-latitude northern hemisphere ecosystems. *Prog Oceanogr* 81:93–110
- Okkonen SR (2008) Exchange between Elson Lagoon and the nearshore Beaufort Sea and its role in the aggregation of zooplankton. US Minerals Management Service, Outer Continental Shelf Study, vol 1008-010
- Parker-Stetter SL, Horne JK, Weingartner TJ (in press) Distribution of Polar cod and age-0 fish in the US Beaufort Sea. *Polar Biol*
- Pickart RS (2004) Shelfbreak circulation in the Alaskan Beaufort Sea: mean structure and variability. *J Geophys Res* 109:1–14
- Pickart RS, Weingartner T, Pratt LJ, Zimmermann S, Torres DJ (2005) Flow of winter-transformed Pacific water into the western Arctic. *Deep-Sea Res Pt II* 52:3175–3198
- Rand K, Logerwell EA (2010) The first survey of the abundance of benthic fish and invertebrates in the offshore marine waters of the Beaufort Sea since the late 1970 s. *Polar Biol*. doi:10.1007/s00300-010-0900-2
- Shimada K, Carmack EC, Hatakeyama K, Takizawa T (2001) Varieties of shallow temperature maximum waters in the western Canadian Basin of the Arctic Ocean. *Geophys Res Lett* 28:3441–3444
- Spencer PD (2008) Density-independent and density-dependent factors affecting temporal changes in spatial distribution of Eastern Bering Sea flatfish. *Fish Oceanogr* 17:396–410
- Stauffer G (2004) NOAA protocols for groundfish bottom trawl surveys of the nation's fishery resources. US Department of Commerce, NOAA technical report, NMFS-F/SPO-65, 205 pp
- Stroeve J, Holland MM, Meier W, Scambos T, Serreze M (2007) Arctic sea ice decline: faster than forecast. *Geophys Res Lett* 43(L09501). doi:10.1029/2007GL029703
- Stroeve J, Serreze M, Drobot S, Gearheard S, Holland M, Maslanik JA, Meier W, Scambos T (2008) Arctic sea ice extent plummets in 2007. *EOS T Am Geophys Union* 89:13–14
- Tremblay MJ (1997) Snow crab (*Chionoecetes opilio*) distribution limits and abundance trends on the Scotian Shelf. *J NW Atlantic Fish Sci* 21:7–22
- Underwood TJ, Palmer DE, Thorpe LA, Osborne BM (1997) Weight-length relationships and condition of dolly varden in coastal waters of the Arctic National Wildlife Refuge, Alaska. In: Reynolds JB (ed) Fish ecology in Arctic North America. American Fisheries Society, Bethesda, pp 295–309
- Wacasey JW (1975) Biological productivity of the southern Beaufort Sea: Zoobenthic Studies. Beaufort Sea Technical Report #12b. Department of the Environment, Victoria, 39 pp
- Weingartner T, Cavalieri DJ, Aagaard K, Sasaki Y (1998) Circulation, dense water formation, and outflow on the northeast Chukchi shelf. *J Geophys Res* 103:7647–7661
- Weingartner T, Okkonen SR, Danielson SL (2005) Circulation and water property variations in the nearshore Alaskan Beaufort Sea, Final Report. US Minerals Management Service, Outer Continental Shelf Study, vol 2005-028
- Welch HE, Bergmann MA, Siferd TD, Martin KA, Curtis MF, Crawford RE, Conover RJ, Hop H (1992) Energy flow through the marine ecosystem of the Lancaster Sound region, Arctic Canada. *Arctic* 45:343–357
- Woodgate RA, Aagaard K, Weingartner T (2005) A year in the physical oceanography of the Chukchi Sea: moored measurements from autumn 1990–91. *Deep Sea Res II* 52:3116–3149