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Demersal and larval fish assemblages in the Chukchi Sea

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ABSTRACT

A multidisciplinary research cruise was conducted in the Chukchi Sea in summer 2004 during which we investigated assemblages of small demersal fishes and ichthyoplankton and the water masses associated with these assemblages. This study establishes a baseline of 30 demersal fish and 25 ichthyoplankton taxa in US and Russian waters of the Chukchi Sea. Presence/absence of small demersal fish clustered into four assemblages: Coastal Fishes, Western Chukchi Fishes, South Central Chukchi Fishes, and North Central Chukchi Fishes. Habitats occupied by small demersal fishes were characterized by sediment type, bottom salinity, and bottom temperature. Abundance of ichthyoplankton grouped into three assemblages with geographical extent similar to that of the bottom assemblages, except that there was a single assemblage for Central Chukchi Fishes. Water-column temperature and salinity characterized ichthyoplankton habitats. Three water masses, Alaska Coastal Water, Bering Sea Water, and Winter Water, were identified from both bottom and depth-averaged water-column temperature and salinity. A fourth water mass, Resident Chukchi Water, was identified only in the bottom water. The water mass and habitat characteristics with which demersal and larval fish assemblages were associated create a baseline to measure anticipated effects of climate change that are expected to be most severe at high latitudes. Monitoring fish assemblages could be a tool for assessing the effects of climate change. Climate-induced changes in distributions of species would result in a restructuring of fish assemblages in the Chukchi Sea.

1. Introduction

There is significant evidence that the Arctic climate is warming extremely rapidly and the impacts of that warming will cause significant changes throughout the ecosystem (ACIA, 2004). Surface air temperatures were as much as 3 °C warmer in 2000–2005 than previously noted in the northern Bering and Chukchi Seas (Grebmeier et al., 2006), which is the focal area of RUSALCA (Russian American Long-term Census of the Arctic) and the source of this study. With Arctic warming, the northern Bering Sea is shifting from a shallow, ice-dominated system in which bottom-dwelling fishes prevail to one more dominated by pelagic fishes (Grebmeier et al., 2006).

Little is known about the changes occurring in the Chukchi Sea ecosystem. Interannual variability in the current structure of the Chukchi Sea has been documented (Weingartner et al., 1999), but specific long-term changes in hydrography have not been recorded. This lack does not mean such changes do not exist, but rather that there has not been a regular monitoring of this ecosystem. Even less information is available about fishes than about the physical structure in the Chukchi Sea Because of the paucity of information about fishes, the North Pacific Fishery Management Council has adopted a precautionary approach and has made the eastern Chukchi Sea unavailable for commercial fisheries (NPFMC, 2008). This establishes a clear need for baseline information for fishes in the Chukchi Sea.

The Chukchi Sea consists of distinct water masses that are connected to the Bering Sea by northward water transport through Bering Strait (Fig. 1; Weingartner, 1997). The Alaska Coastal Current flows rapidly northward along the east side of the Bering Strait and is recognizable as the mass of warm, dilute Alaska Coastal Water (ACW) along the east side of the Chukchi Sea and north into the Arctic Ocean. Bering Sea Water (BSW), composed of a mixture of Bering Shelf and Anadyr Waters, flows along the central and western Bering Strait to the north. Resident Chukchi Water (RCW) is found offshore in the northern Chukchi Sea and is separated from ACW by a semi-permanent front that extends from surface to bottom at ~70–71°N (Weingartner, 1997). Winter Water (Pickart et al., 2005, 2010) is a subsurface mass of very cold and salty water in western Herald Canyon that remains from the preceding winter (Coachman et al., 1975). Some the hydrographic features observed in the Chukchi Sea are permanent while others are transient; all are expected to have significant biological implications (Weingartner et al., 1999) and to be important determinants of fish and plankton distributions.

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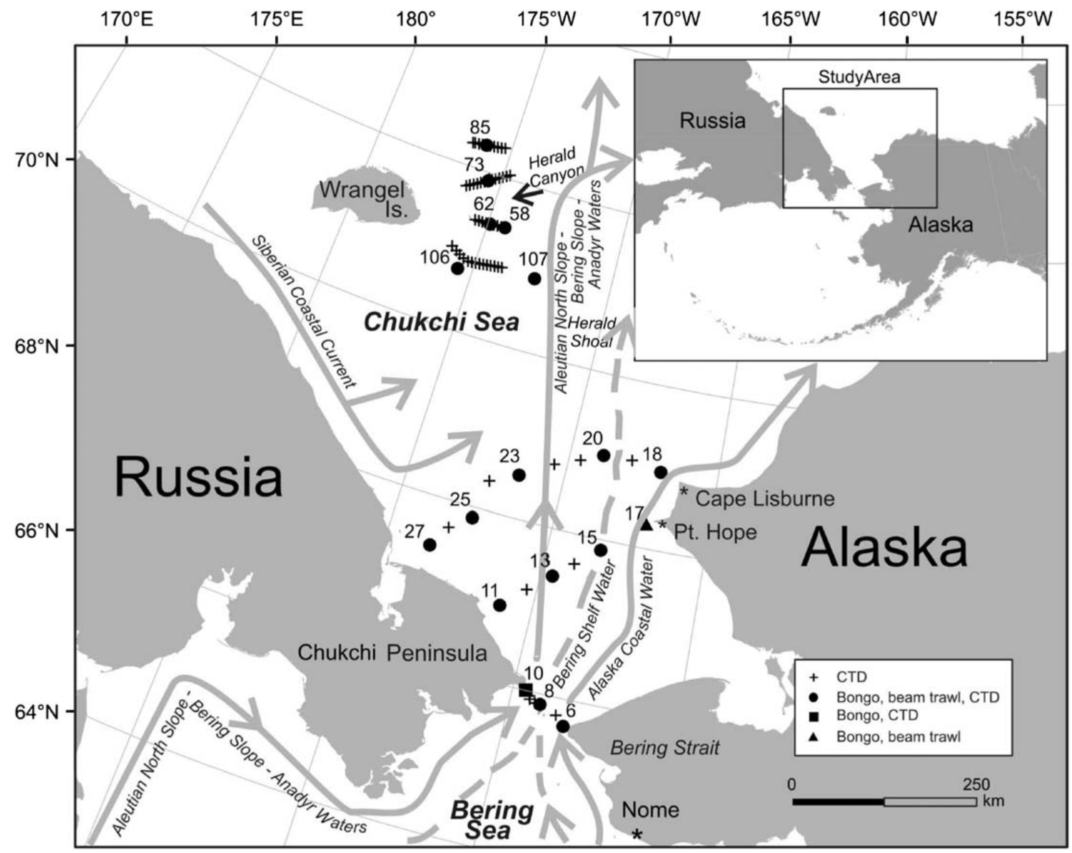

Fig. 1. Stations sampled August 2004. Symbols indicate type of gear deployed. Numbers indicate stations at which fish were collected. Arrows represent generalized flow of currents from the Bering Sea and in the Chukchi Sea (after Coachman et al., 1975, Weingartner et al., 1999, 2005).

Fish assemblages are composed of fishes with similar temporal or spatial distributions (Cowan et al., 1993) that possess one or more common characteristics. A stable fish assemblage is composed of the same taxa in the same proportions across time, though the geographic distribution of the assemblage might change (Fossheim et al., 2006). In addition to taxa that are abundant, species that are absent or not abundant also contribute in a notable way to the fish assemblage. Demersal fish assemblages are usually governed by temperature (Genner et al., 2004), depth (e.g., Mueter and Norcross, 2002), or a combination of these two factors, perhaps incorporating another variable such as substrate (e.g., Mueter and Norcross, 1999; Barber et al., 1997; Tissot et al., 2007). Ichthyoplankton assemblages are related to bathymetry (Duffy-Anderson et al., 2006), local topography, prevailing current patterns (Doyle et al., 2002), and water masses (Norcross et al., 2003, Quattrini et al., 2005).

This study specifically addresses assemblages of small demersal and larval fishes in the Chukchi Sea. Our focus is to detect water mass and habitat characteristics with which fish assemblages are associated. The findings documented here will provide a much-needed baseline of the distribution of small demersal and larval fishes in the Chukchi Sea and establish a means for future comparison in light of a changing climate.

2. Methods

2.1. Field collections and laboratory analyses

We collected physical oceanographic data, small demersal fishes, and ichthyoplankton 10–22 August 2004 aboard the R/V *Professor Khromov*. The cruise was an interdisciplinary investigation of the regional physical, biological, and chemical oceanography conducted by the RUSALCA Program in the Bering Strait and Chukchi Sea. Three transects were sampled in the southern Chukchi Sea between the Chukchi Peninsula of eastern Russia and Alaska at the Bering Strait, Point Hope, and Cape Lisburne (Fig. 1). Four transects were occupied across Herald Canyon in the northern Chukchi Sea to the east of Wrangel Island. Bottom depth and standard GPS positions were recorded. A SeaBird model SBE911+CTD profiler collected salinity, temperature, depth, turbidity, fluorescence, and oxygen data at 68 stations (Pickart, 2006; Pickart et al., 2010). No CTD data were collected at station 17. Small demersal fishes were collected at 17 stations using a beam trawl (Fig. 1). Ichthyoplankton was collected using a bongo net at the 17 bottom trawl stations plus station 10, which was not suitable for bottom trawling due to the presence of boulders. At 14 bottom trawl stations, a Van Veen grab was used to collect substrate; grain size was later analyzed and classified by type of sediment (J. Grebmeier, Univ. Maryland, pers. comm.). The presence of mud, sand, gravel, shell or rock in trawl contents was used to classify the substrate of the three bottom trawl stations at which no grab was taken.

Small fishes were collected from the sea floor with a plumb staff beam trawl with a 7 mm net mesh and 4 mm codend liner (Gunderson and Ellis, 1986). We modified the net by seizing a lead-filled line to the footrope for better bottom contact and using a 3.05 m beam to hold the net open; the effective fishing swath was 2.26 m, i.e. 74% of beam length. Fishing scope was approximately 3.5:1, and vessel speed was approximately 1.5 knots. At some sites the net was damaged or the catch was so large that it filled the net beyond the codend. Because these difficulties prevented us from calculating an accurate CPUE for every collection, bottom trawl analyses were conducted on presence/absence rather than

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abundance of fish species. Up to 50 individuals of each taxon present in the bottom trawl samples were measured for total length to the nearest mm. Identification of fish species was performed at sea; scientific and common names of fishes followed Mecklenburg et al. (2007). A subsample of specimens was returned to laboratories for further examination and verification. Demersal fishes in poor condition or with problematic taxonomy were categorized to the genus level, i.e. *Liparis* spp., *Gymnelus* spp., as detailed by Mecklenburg et al. (2007). Demersal fishes were not differentiated between juvenile and adult.

A 60-cm diameter bongo frame with two 500-μm mesh nets and flowmeter was towed obliquely to collect ichthyoplankton from the water column. Fishing depth was recorded by fixing a VEMCO Minilog Temperature Depth Recorder to the bongo frame. Samples were preserved in 5% formalin buffered with sodium borate.

Plankton samples were sorted and fish eggs, larvae, and juveniles were removed and identified to the lowest taxonomic level possible at the Plankton Sorting and Identification Center in Szczecin, Poland. Taxonomic identifications were verified at the Alaska Fisheries Science Center (AFSC) in Seattle, WA. Some larval fishes could only be categorized into genera groups (e.g., *Icelus* spp., *Liparis* spp.) or families (e.g., Osmeridae) due to limitations associated with identification or because the specimens were damaged. Planktonic cods >25 mm were categorized as juveniles because at this size *Theragra chalcogramma* begins transformation (Brown et al., 2001). Up to 50 larval and juvenile individuals of each taxon present in the ichthyoplankton samples were measured for standard length to the nearest 0.1 mm.

2.2. Analytical methods

Water masses were identified using a standard oceanographic technique, i.e. potential density plots (Ocean Data View v.2.3.3, Schlitzer, 2007) and an unconventional technique that is familiar to biologists and ecologists, i.e. dendrograms. Cluster analysis (PRIMER software v. 6) was used to delineate water masses from CTD records of temperature and salinity. Temperature and salinity data were normalized and Euclidean distances between stations were measured (Clarke and Gorley, 2006). Dendrograms were produced via group-averaged linkages. The deepest temperature and salinity from CTD collections at the 68 stations were used to delineate water masses. Standardized temperature and salinity were averaged over the plankton-sampling depth for each of the 17 stations where ichthyoplankton were collected. Because each ichthyoplankton collection was sampled to a unique depth, stations not sampled for ichthyoplankton could not be included in this analysis. The objective of multiple analyses was to demonstrate a method of identifying water masses that is readily accessible to non-oceanographers. We assigned water masses based on the dendrograms.

Cluster analyses (PRIMER software, v. 5.2.9) based on Bray–Curtis similarity coefficients were used to identify assemblages of presence/absence of small demersal fishes and abundance (# fish larvae per 10 m^2 sea surface) of ichthyoplankton (4th root transformation; Clarke and Warwick, 2001). Only species that occurred at more than one station were included in analyses. The resulting dendrograms established station and species groupings separately for demersal fishes and for ichthyoplankton. Two-way joining analyses regrouped the station and species clusters to produce one matrix that illustrated demersal fish assemblages and a second matrix of ichthyoplankton species assemblages and clearly characterized species and spatial relationships.

Differences in species composition among water masses were estimated using Analysis of Similarity (ANOSIM, PRIMER software, v. 5.2.9). ANOSIM is a nonparametric multivariate permutation test, based on Bray–Curtis similarity coefficients, analogous to the parametric univariate ANOVA and reported as a Global R statistic with associated *p*-value. When the ANOSIM indicated significant differences ($p<0.05$) in species composition among water masses, Similarity Percentages (SIMPER, PRIMER software, v. 5.2.9) determined which species accounted for most differences in the ANOSIM results. Average dissimilarities, associated *p*-value ($p<0.05$), and cumulative percentage by individual species explained differences in species compositions between water masses.

Species composition was correlated to physical variables using BIO-ENV, which calculates a rank correlation (Spearman coefficient r_s) of Bray–Curtis similarity between stations based on biotic data and the Euclidean distance between environmental variables (PRIMER software, v. 5.2.9). The nonparametric Spearman's ρ was used for non-normal abundance data and because the parametric Pearson's r has high sensitivity to outlying data. For both bottom and water-column data sets, all possible combinations of recorded physical variables were used to determine the best subset of correlated variables. Analysis of small demersal fish data used seven physical variables (bottom temperature, bottom salinity, bottom dissolved oxygen, bottom fluorescence, bottom turbidity, mean tow depth, and sediment classification). The first five variables were values from the greatest depth of the CTD cast at each station. Mean tow depth was calculated from bottom depths recorded while the net was fishing. Sediment classifications were split into three categories, i.e. mud, sand, and gravel/shell. Analysis of ichthyoplankton data used values for five physical variables (temperature, salinity, dissolved oxygen, fluorescence, and turbidity), each of which was averaged over the unique depth range fished.

Table 1
Physical attributes from which water masses in the Chukchi Sea were assigned.

	Alaska Coastal Water	Bering Sea Water	Winter Water	Resident Chukchi Water
Bottom water mass ($p<0.002$)				
Deepest CTD depth (m)	44–51	37–76	33–96	34–55
Temperature (°C)	3.7–10.5	0.9–3.7	−1.78 to −0.3	−1.7 to −1.5
Salinity	30.6–31.9	32.3–33.2	32.8–33.7	31.6–32.5
Density	$23.4<\sigma<25.3$	$25.5<\sigma<26.6$	$26.3<\sigma<27.2$	$25.3<\sigma<26.3$
Number of CTD stations	4	26	32	6
Number of demersal trawl stations	3	9	5	0
Icthyoplankton station water mass ($p<0.15$)				
Maximum fishing depth (m)	22–37	29–55	22–81	–
Temperature (°C)	8.1–11.8	2.0–4.5	−1.4 to 0.3	–
Salinity	29.5–31.2	31.9–33.1	31.1–32.2	–
Density	$22.3<\sigma<24.3$	$25.4<\sigma<26.4$	$24.9<\sigma<25.9$	–
Number of CTD stations	4	8	5	0
Number of plankton tow stations	5	8	5	0

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Table 2
Count of fishes caught by beam trawl within each bottom water mass and station.

Bottom water mass	ACW			BSW									WW					Number caught	Total length range (mm)
Station	6	17	18	8	11	13	15	20	23	25	58	107	27	62	73	85	106		
Mean tow depth (m)	50	39	46	48	43	51	59	54	56	49	61	40	34	78	72	101	72		
Substrate	Sh[t]	GSM[tg]	M	GM[t]	SM	MS	M	M	M	M	M[t]	SM	GR	MGR	M	MSR[tg]	M		
Gadidae (cods)[abc]																			
Boreogadus saida[bc]	–	–	–	–	–	2	–	–	–	9	2	8	–	11	3	2	1	38	47–191
Eleginus gracilis[c]	11	58	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	69	47–270
Theragra chalcogramma[b]	–	1	4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	132–168
Hexagrammidae (greenlings)																			
Hexagrammos stelleri	4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4	77–86
Cottidae (sculpins)[bc]																			
Artediellus scaber	–	59	–	–	–	–	–	–	–	–	–	3	64	–	–	–	–	126	27–83
Enophrys diceraus	5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5	102–136
Gymnocanthus tricuspis[bc]	9	9	5	2	26	22	5	8	4	70	1	58	175	4	35	7	3	443	29–168
Icelus spatula	1	–	–	1	–	–	–	–	–	–	1	–	–	–	2	–	–	5	37–79
Myoxocephalus scorpius	27	43	3	12	1	12	–	–	1	8	2	6	69	6	–	–	–	190	31–403
M. polyacanthocephalus	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	30–135
Triglops pingelii	2	1	2	–	–	–	–	–	–	–	–	–	2	–	–	–	–	7	36–110
Hemitripteridae (sailfin sculpins)																			
Nautichthys pribilovius	7	10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	17	43–82
Agonidae (poachers)[b]																			
Pallasina barbata	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	125
Podothecus veternus	1	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	107–127
Ulcina olrikii[b]	–	–	2	–	–	2	1	3	1	–	1	3	2	–	4	–	–	19	39–76
Liparidae (snailfishes)[b]																			
Liparis spp.[b]	–	–	–	–	–	4	–	–	–	–	–	–	–	–	–	–	–	4	22–93
Liparis fabricii[b]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	1	94
Liparis gibbus[b]	1	–	–	1	–	–	–	1	–	–	–	–	–	–	–	–	–	3	20–139
Liparis tunicatus[b]	–	–	–	–	–	–	–	–	–	1	–	1	1	–	–	–	1	4	31–72
Zoarcidae (eelpouts)																			
Gymnelus spp.	4	4	–	–	–	–	–	–	–	–	–	–	3	–	1	–	–	12	73–154
Lycodes mucosus	1	–	–	1	–	–	–	–	1	–	–	–	1	–	–	–	–	4	67–202
L. palearis	–	–	6	–	–	–	–	1	–	1	–	–	–	–	–	–	–	8	41–205
L. polaris	–	–	–	–	–	–	–	–	–	–	2	5	–	–	1	–	–	8	37–230
L. raridens	–	–	–	–	–	–	–	–	–	–	–	3	–	–	–	–	–	3	114–128
Stichaeidae (pricklebacks)[b]																			
Anisarchus medius	–	–	13	–	–	13	1	12	8	8	26	18	–	–	3	–	–	102	55–152
Lumpenus fabricii[b]	31	18	14	–	2	10	1	1	–	4	–	–	6	–	–	–	1	88	51–218
Stichaeus punctatus[b]	5	57	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	63	34–133
Pholidae (gunnels)																			
Pholis fasciata	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	159
Pleuronectidae (flatfishes)[ab]																			
Hippoglossoides robustus[ab]	–	–	13	–	–	17	4	7	11	11	9	1	–	–	–	–	1	74	49–229
Limanda aspera[b]	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	176
Total caught	113	261	64	18	29	82	12	33	26	112	44	106	323	21	50	9	7	1310	20–403

ACW = Alaska Coastal Water; BSW = Bering Sea Water; WW = Winter Water. Total caught is the number of individuals, and length range is the minimum and maximum size of each taxon. Substrates are abbreviated as Sh = shell hash, R = cobble/rock, G = gravel, S = sand, and M = mud, with the predominant fraction first. Substrates were classified from grab contents except where the beam trawl was deployed without the grab or where the trawl retained a substrate fraction not observed in the grab contents, as indicated by superscript t or tg, respectively. Taxa also caught by bongo net within the water column as eggs, larvae, or juveniles are indicated by superscript a, b, or c, respectively.

3. Results

3.1. Description of study area

Station depths were shallow over the Chukchi Sea shelf and variable in Herald Canyon. Station depths across the Bering Strait were 45–51 m, and the depth range on the Point Hope transect was similar, 40–55 m. Stations across the Cape Lisburne transect ranged in depth from 34 to 55 m. Across the four Herald Canyon transects the sampled depth range was much broader, 34–101 m, depending on station location at edge or middle of canyon. The deepest CTD data in Herald Canyon (33–96 m, Table 1) were similar to those of bottom trawl collections (40–101 m, Table 2). Sediments were predominantly mud, though it was often mixed with sand or embedded with gravel, rocks or shell (Table 2). There was no apparent pattern in the distribution of sediment related to depth.

3.2. Water mass designations

Standard potential density plots (Fig. 2) and cluster analyses (Fig. 3) from 68 CTD stations differentiated four bottom water masses (Table 1) in the Chukchi Sea: Alaska Coastal Water (ACW), Bering Sea Water (BSW), Winter Water (WW), and Resident Chukchi Water (RCW). Though no CTD data were collected from station 17 on the Point Hope transect, we included this station in ACW because no other water mass was expected to be entrained at the coast in that location, and because stations to its north and south were grouped under the ACW designation. A plan view of bottom water mass designations (Fig. 4) offered approximate realistic geographic distributions of the water masses. Station 27

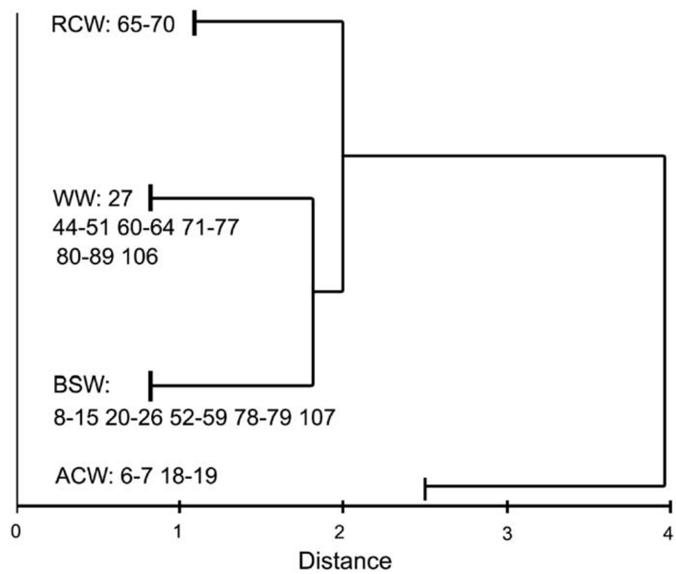

Fig. 3. Cluster analysis of all CTD stations based on temperature and salinity at maximum CTD depth. ACW = Alaska Coastal Water, BSW = Bering Sea Water, WW = Winter Water, RCW = Resident Chukchi Water. To simplify presentation, detailed clusters within water masses are not shown.

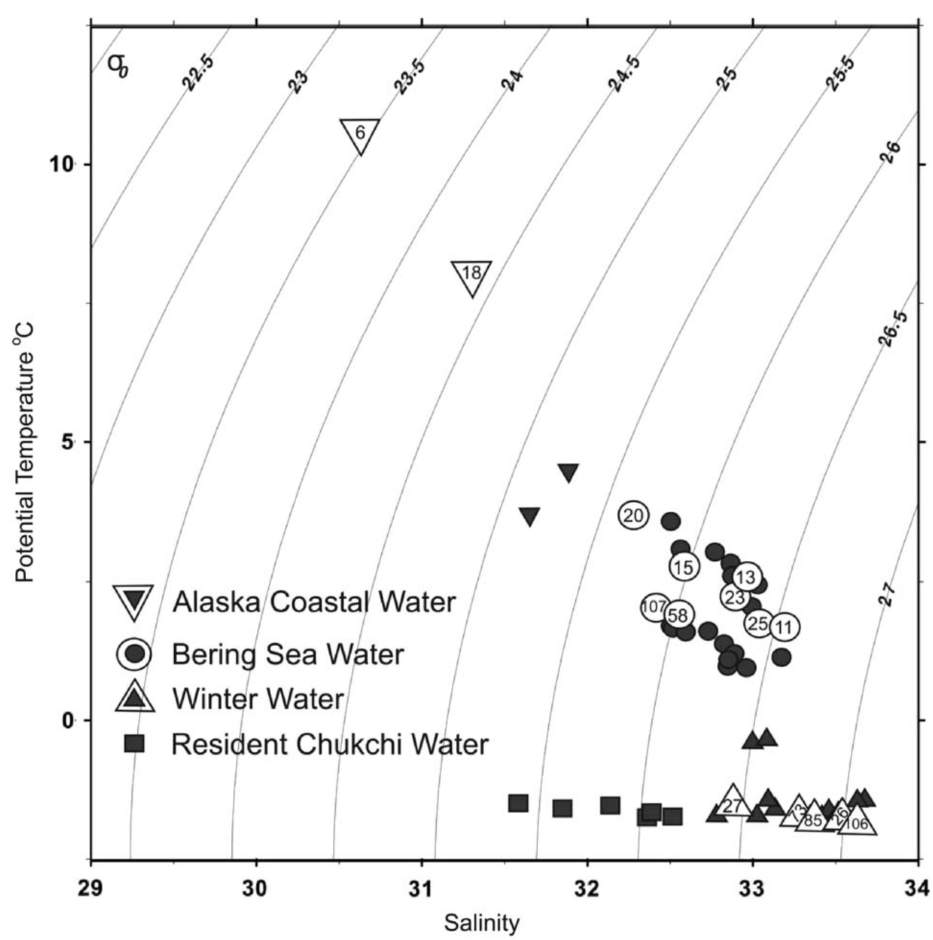

Fig. 2. Potential density for maximum depth at all CTD stations. Symbols correspond to the water masses designated by cluster analysis. Fishing sites are identified by number within hollow symbols; solid symbols are non-fishing sites. There was no CTD at station 17.

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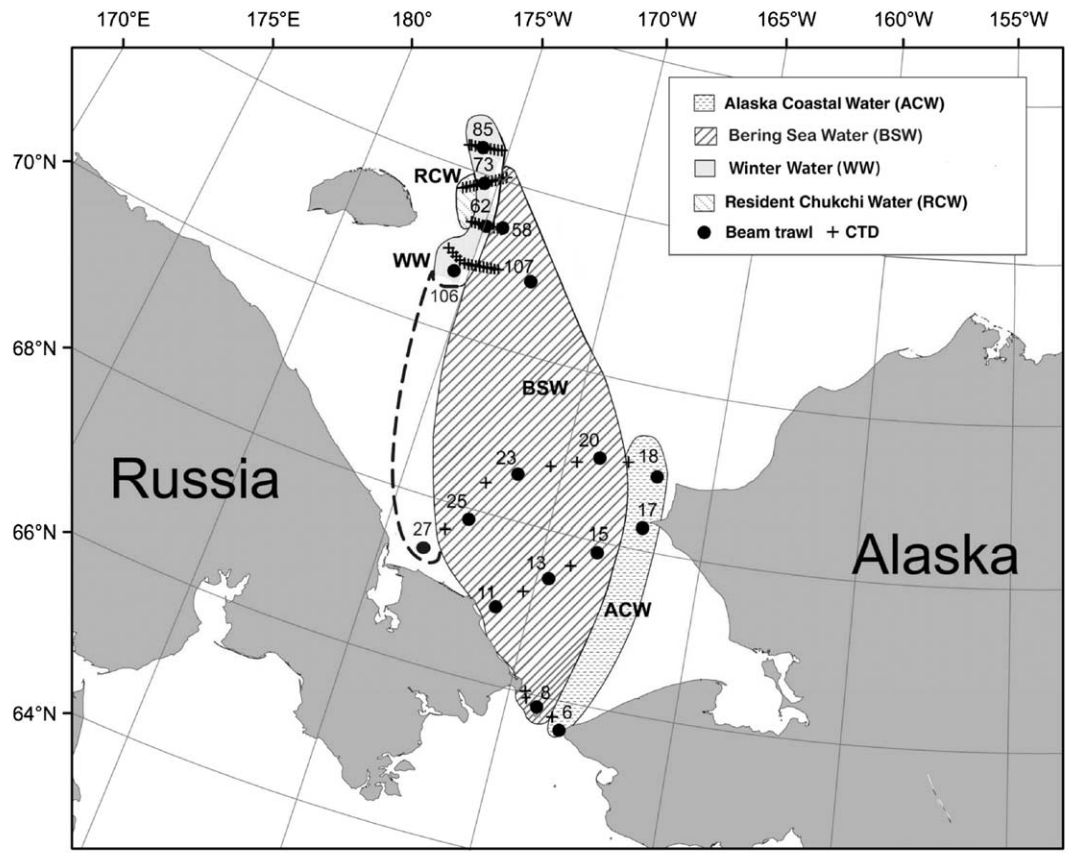

Fig. 4. Bottom water masses designated for all CTD stations. Station #27 clustered with Winter Water. A large geographic distance, containing no data, separates Stations #27 and #106. The dashed line connecting the stations indicates interpolated water mass connections based on cluster analysis and confirmed by potential density plots.

grouped with WW (Fig. 2 and Fig. 3), yet its southern location off the coast of the Chukchi Peninsula made that association questionable.

To correspond to ichthyoplankton tows, standard potential density plots (Fig. 5) and cluster analysis (Fig. 6) were produced over plankton fishing depths that ranged from 22 to 55 m, except station 85 that was fished to 81 m. These tows approached within 3–36 m of the sea floor. Averaging temperature and salinity data over these varying sample depths, excluding CTD casts from stations not sampled for ichthyoplankton, and physical oceanographic conclusions from this cruise (Pickart et al., 2010) led to the designation of three water masses for the ichthyoplankton stations: ACW, BSW, and WW (Figs. 5 and 6, Table 1). As with the bottom water mass designations, we included station 17 in ACW in the plan view (Fig. 7). The plan view of the depth-averaged data is very similar to that of the bottom water data, except that stations 20 and 107 were assigned to a different water mass, i.e. ACW instead of BSW. Once again station 27 clustered in WW. Station 107, at the southeastern end of the Herald Canyon transects, grouped in ACW with the coastal stations.

3.3. *Fish assemblages*

The total number of small demersal fishes collected by bottom trawl was 1310, composed of 30 taxa of at least 30 species within 10 families (Table 2). The uncertainty in number of species was due to the specimens of *Gymnelus* spp. that are presently unidentified but include at least two species, and *Liparis* spp. that were damaged and could not be identified further (Mecklenburg et al., 2007). Fishes measured from demersal tows ranged from 20 to 403 mm TL. Nine species constituted 91% of the total catch by number. Catches were dominated by sculpins, in particular *Gymnocanthus tricuspis* (34%), *Myoxocephalus scorpius* (15%), and *Artediellus scaber* (10%). Other species that comprised 3–8% of the total catch were pricklebacks, flatfishes, and cods; in decreasing order of abundance these were *Anisarchus medius*, *Lumpenus fabricii*, *Hippoglossoides robustus*, *Eleginus gracilis*, *Stichaeus punctatus*, and *Boreogadus saida*. Species caught in demersal but not planktonic tows include all eelpouts, greenlings, sailfin sculpins, and gunnels, as well as six other sculpins, two poachers, and one prickleback.

A comparison of species and station clusters with demersal fish presence and absence identified four distinct spatial assemblages (Fig. 8). A coastal fish (CF) assemblage was characterized by a relatively high diversity of sculpins and pricklebacks. *Myoxocephalus polyacanthocephalus*, *Nautichthys pribilovius*, and *Stichaeus punctatus* were unique to the CF group (Fig. 8). The cod *Eleginus gracilis* also was unique to the CF assemblage while another cod species, *Boreogadus saida*, was notably absent. An assemblage identified in the western Chukchi Sea (WCF) lacked 12 species present in the CF assemblage, but also differed in that *Boreogadus saida* was present at all but one station. Central Chukchi fishes were clearly distinct from WCF and were subdivided into southern and northern groups. A south central Chukchi Sea assemblage (SCCF) was distinguished by the presence of *Anisarchus medius*, *Hippoglossoides robustus*, *Ulcina olrikii*, and *Gymnocanthus tricuspis* at every station. Many taxa present in the north central Chukchi fish assemblage (NCCF) were also present in the other three. However, the NCCF group was differentiated from the SCCF by the absence of *Lycodes palearis*, *Podothecus veternus*, and *Theragra chalcogramma*, plus *Lycodes polaris* was unique to this group.

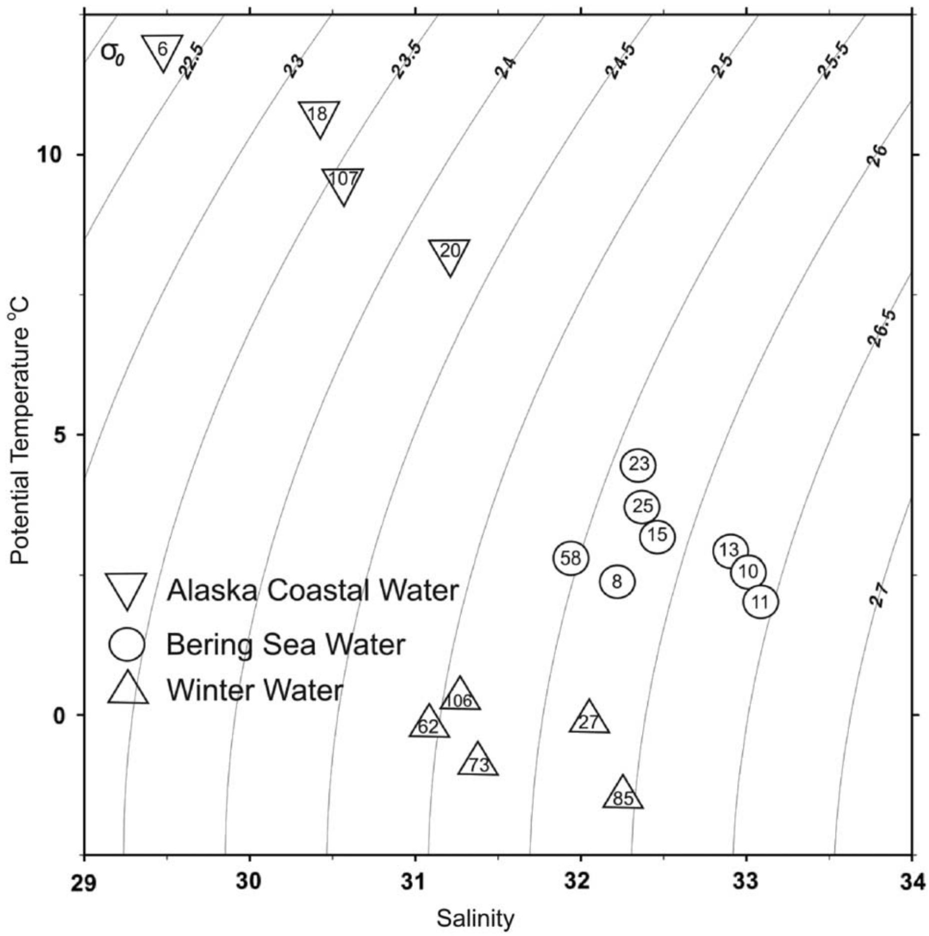

Fig. 5. Potential density averaged over depth of tow at ichthyoplankton stations. Symbols correspond to the water masses designated by cluster analysis. Fishing sites are identified by number within hollow symbols. There was no CTD at station 17.

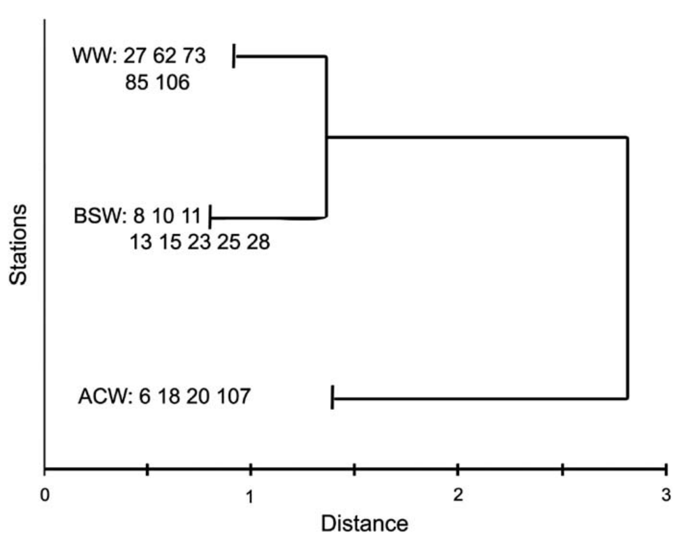

Fig. 6. Cluster analysis of ichthyoplankton stations based on temperature and salinity averaged over depth of plankton tow. ACW = Alaska Coastal Water, BSW = Bering Sea Water, WW = Winter Water. To simplify presentation, detailed clusters within water masses are not shown.

The four demersal fish species assemblages (Fig. 9) were geographically similar to three of the designated water masses in that area, i.e. WW, BSW, and ACW (Fig. 4), except that the fish assemblages had north-south as well as east-west divisions. Species assemblages differed significantly between ACW and BSW ($R = 0.39$; $p = 0.036$) with all species contributing similar amounts towards this observed difference. An even stronger significant difference also was found between species assemblages in ACW and WW ($R = 0.95$; $p = 0.029$); again the contribution to observed differences was very similar among all species. There were no significant differences among demersal fish assemblages associated with other water masses. The most significant factor affecting habitat selection by small demersal fish was sediment type ($r_s = 0.54$), with bottom salinity ($r_s = 0.38$) and bottom temperature having less influence ($r_s = 0.37$).

Larvae and early juvenile fishes were captured in the water column at all 18 stations sampled by plankton net, and pelagic eggs were found at eight stations (Table 3). A total of 111 eggs, representing at least three species from among the families of cod and flatfish, were collected. The total number of larval and early juvenile fishes collected by plankton net was 498, of which 399 were measured. Larvae ranged from 3.0 to 39.0 mm SL and planktonic juveniles ranged from 27.0 to 41.0 mm SL. Twenty-five planktonic taxa (Table 3) were composed of at least 19 separate species within eight families; specimens unidentified at the family or genus taxonomic levels could potentially include two species of smelt and more species of cods, snailfishes, *Lumpenus* spp., *Gymnocanthus* spp., flatfishes, and *Limanda* spp. than were identified. Species caught in the plankton nets but absent from demersal tows included smelts, *Aspidophoroides monopterygius*, *Leptoclinus maculatus*, *Ammodytes hexapterus*, *Limanda proboscidea*, and *Hippoglossus stenolepis*. Ichthyoplankton collections were

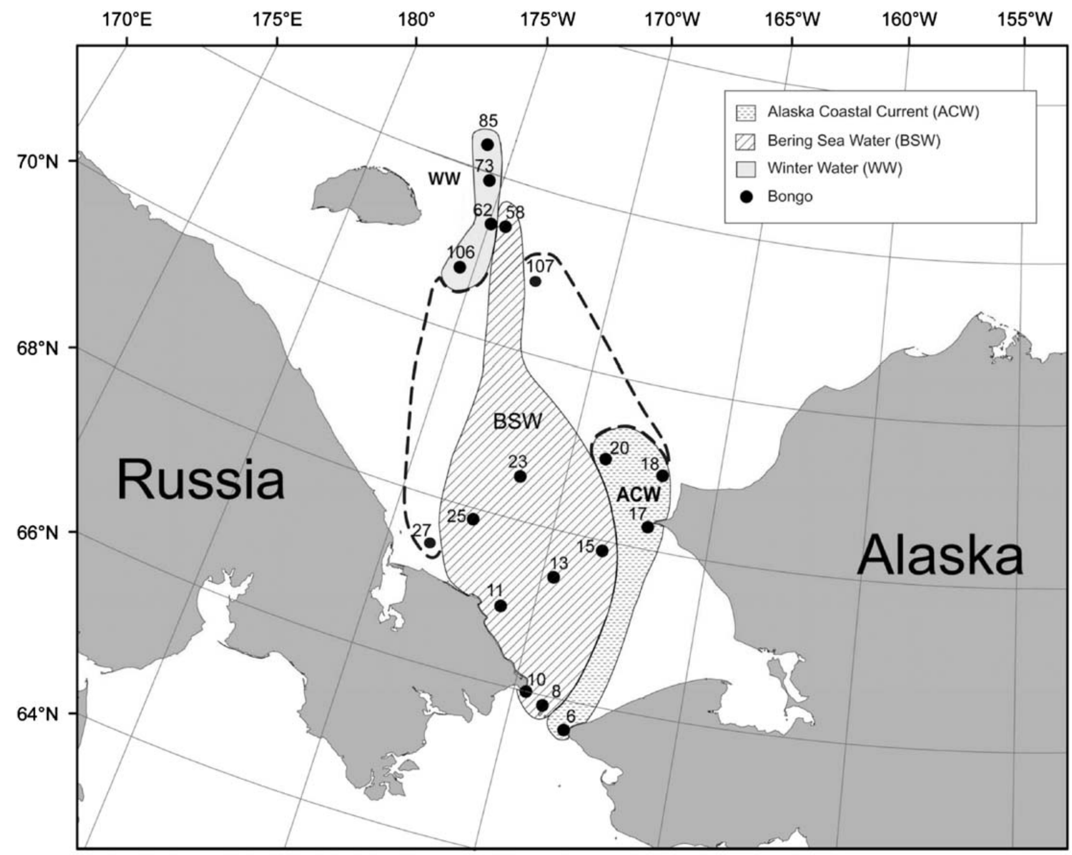

Fig. 7. Depth-averaged water masses designated for ichthyoplankton stations. Large geographic distances, containing no data, separate Stations #27 from #106 in Winter Water and Stations #107 from #18 and #20 in Alaska Coastal Water. The dashed line connecting the stations indicates interpolated water mass connections based on cluster analysis and confirmed by potential density plots.

numerically dominated by *Boreogadus saida* (23%), *Hippoglossoides robustus* (11%), and *Limanda aspera* (9%).

Multiple life stages were caught of several species. *Hippoglossoides robustus* was the only species for which egg, larval, and demersal stages were captured. Eleven additional species caught in demersal tows also were caught in planktonic tows, 10 as larvae and three as juveniles (Table 2). *Liparis gibbus* was the only species having overlapping size of demersal (20–139 mm TL) and planktonic individuals (8.0–27.5 mm SL; Table 3).

Three assemblages were produced from cluster analysis of ichthyoplankton abundance (Fig. 10). The geographical extent of the ichthyoplankton assemblages was similar to that of the demersal fish assemblages (CF, WCF), except that South Central and North Central Chukchi assemblages were combined for ichthyoplankton into a single group, Central Chukchi Fishes (CCF) (Fig. 11). A coastal larval fish (CF) assemblage was typified by relatively high abundance of *Limanda aspera* and absence of *Boreogadus saida* (Fig. 10). The Central Chukchi Sea (CCF) larval fish assemblage had relatively low abundances of several taxa including the flatfishes *Hippoglossoides robustus*, *L. aspera*, and *Hippoglossus stenolepis*. The diverse Western Chukchi Sea (WCF) ichthyoplankton assemblage was characterized by high abundances of *B. saida* and *Liparis gibbus*. Several taxa including *Ammodytes hexapterus*, *L. gibbus*, *Lumpenus fabricii*, *Stichaeus punctatus*, and *Gymnocanthus tricuspis* were unique to the WCF ichthyoplankton assemblage.

Notable differences in ichthyoplankton species composition were detected among water masses. The geographic distribution of the larval fish assemblages (Fig. 11) was similar to the distribution of depth-averaged water masses (Fig. 7). Species composition was significantly different between ACW and BSW ($R = 0.49$; $p = 0.008$). *Limanda aspera*, *Liparis gibbus*, *Boreogadus saida*, and *Liparis* spp. accounted for over 58% of the observed difference. A significant difference was also found between species assemblages in ACW and WW ($R = 0.71$; $p = 0.029$). Three species, *B. saida*, *Limanda aspera*, and *Liparis gibbus*, accounted for over 55% of the observed difference between ACW and WW. No significant difference between ichthyoplankton assemblages was detected between BSW and WW. Average water-column temperature was the most significant physical variable that contributed to observed differences in ichthyoplankton species composition ($r_s = 0.42$), and salinity contributed an additional small amount ($r_s = 0.26$).

4. Discussion

The Arctic is a complex ecosystem and the role of fish in this ecosystem is largely unexplored. This study establishes a baseline of demersal fish and ichthyoplankton in US and Russian waters of the Chukchi Sea. This baseline will provide a comparison to measure anticipated effects of climate change that are expected to be most severe at high latitudes (ACIA, 2004). This baseline will also be critical prior to development of this ecosystem by oil, gas and commercial fisheries.

Demersal and planktonic stages of fishes, habitats and water masses are documented here for the Chukchi Sea in the summer. On the Chukchi Sea shelf, benthic and pelagic productivity are tightly coupled (Grebmeier et al., 1988). However, high productivity may not be reflected in fish biomass but instead the short

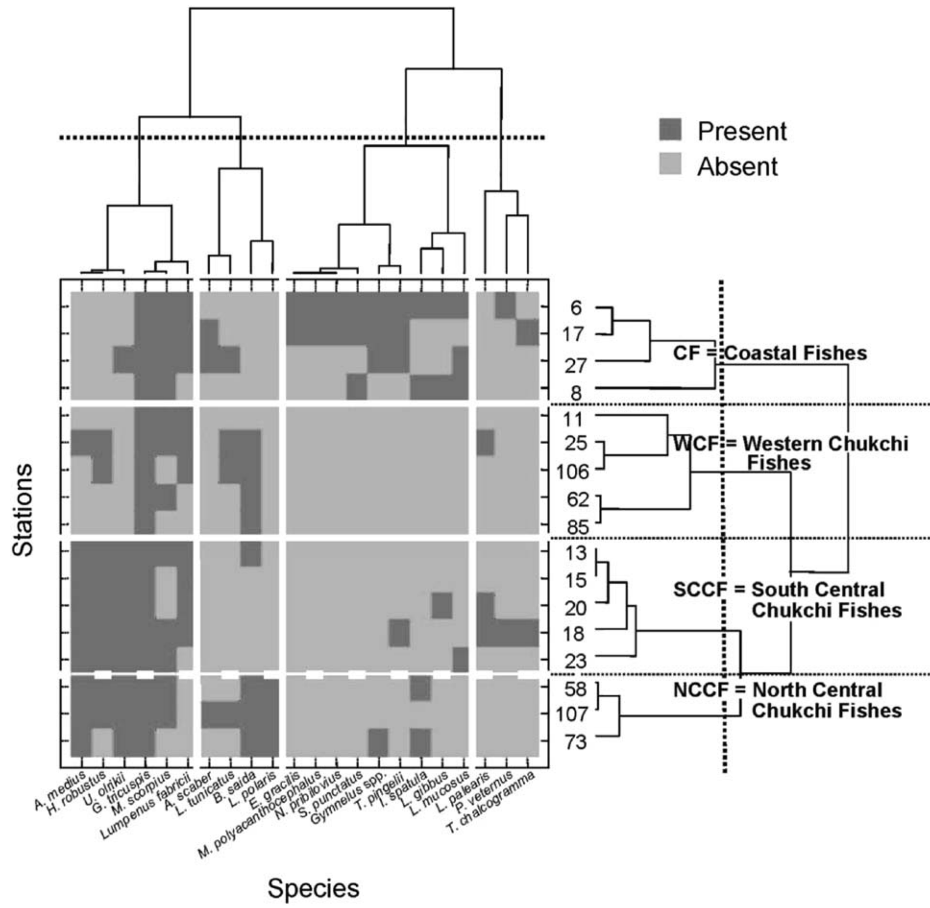

Fig. 8. Two-way joining of species/station clusters showing presence/absence of demersal fishes. Heavy white lines indicate groupings, dashed white line indicates subgroups. Site groups have geographic designations.

food web to benthic biomass from pelagic productivity may be so tightly coupled that it bypasses fish (Dunton et al., 1989). Thus it is necessary that assemblages of both life stages are established for Chukchi Sea fishes. As productivity is affected by oceanographic properties acting upon it, it is important that we determined water mass and habitat characteristics with which demersal and larval fish assemblages are associated.

There are interannual differences in winter temperature and salinity on the Chukchi shelf, thus water masses do not have the same characteristics every year (Weingartner et al., 2005). As a result, water masses do not always have the same temperature and salinity characteristics, nor do they necessarily occupy the same three-dimensional space through time. Multiple water masses can be layered in the water column (Pickart et al., 2010). The four bottom water and three depth-integrated water masses we observed in the Chukchi Sea in summer 2004 were similar to other interpretations of the region's physical oceanography (Weingartner, 1997; Weingartner et al., 2005; Pickart et al., 2005, 2010).

At station 107 east of Herald Canyon on Herald Shoal, the upper layer was grouped with ACW, but the bottom water was classified as BSW. In the water column as well as the bottom, the warm, fresh ACW is isolated from the rest of the Chukchi Sea by a well-defined front ~50 km from the coast that extends northward from Bering Strait to the Lisburne Peninsula (Weingartner, 1997). Off Cape Lisburne, this flow might continue northward and spread westward (Weingartner et al., 2005), which explains our depth-integrated distribution of ACW. Transport inferred from sediment deposition also indicates potential northwest flow of ACW to Herald Shoal (Naidu and Mowatt, 1983).

The typical flow pattern of BSW is northward through the Bering Strait and spread out across the Chukchi Shelf (Winsor and Chapman, 2004) as observed in 2004. This water mass continues northward to enter the Arctic Ocean through three pathways, one of which is Herald Canyon (Weingartner et al., 2005). The BSW seen in the present study in both bottom and depth-integrated water masses is the summertime Bering Sea-origin water (Coachman et al., 1975) seen along the eastern edge of Herald Canyon in 2004 (Pickart et al., 2010).

In addition to the BSW, two other water masses were found in the vicinity of Herald Valley in summer 2004. Winter Water (Pickart et al., 2005, 2010) is the subsurface very cold and salty water on the west of side Herald Canyon that remains from the preceding winter (Coachman et al., 1975). WW is formed by rapid cooling and ice production in polynyas (Weingartner et al., 1998, 2005) on the western side of Wrangel Island; the cold water mass is transported into the Chukchi Sea by anti-cyclonic circulation around the island (Pickart et al., 2010). At the head of Herald Canyon, summer water on the eastern side and Winter Water on the western side are separated by a very sharp front (Pickart et al., 2010). It is clear that the front is a horizontal separation, but the separation is not necessarily vertical. The dense WW never extends to the surface, an indication that multiple water masses are present at a single station (Pickart et al., 2010). The ranges of temperatures and salinities we classified in the WW from depth-integrated values were warmer and fresher than those from the bottom. RCW is not considered part of WW (Pickart et al., 2010). The extremely cold and moderately salty RCW is derived from the upper layers of the Arctic Ocean (Weingartner, 1997) or from shelf water transformed into a deep water mass the previous winter

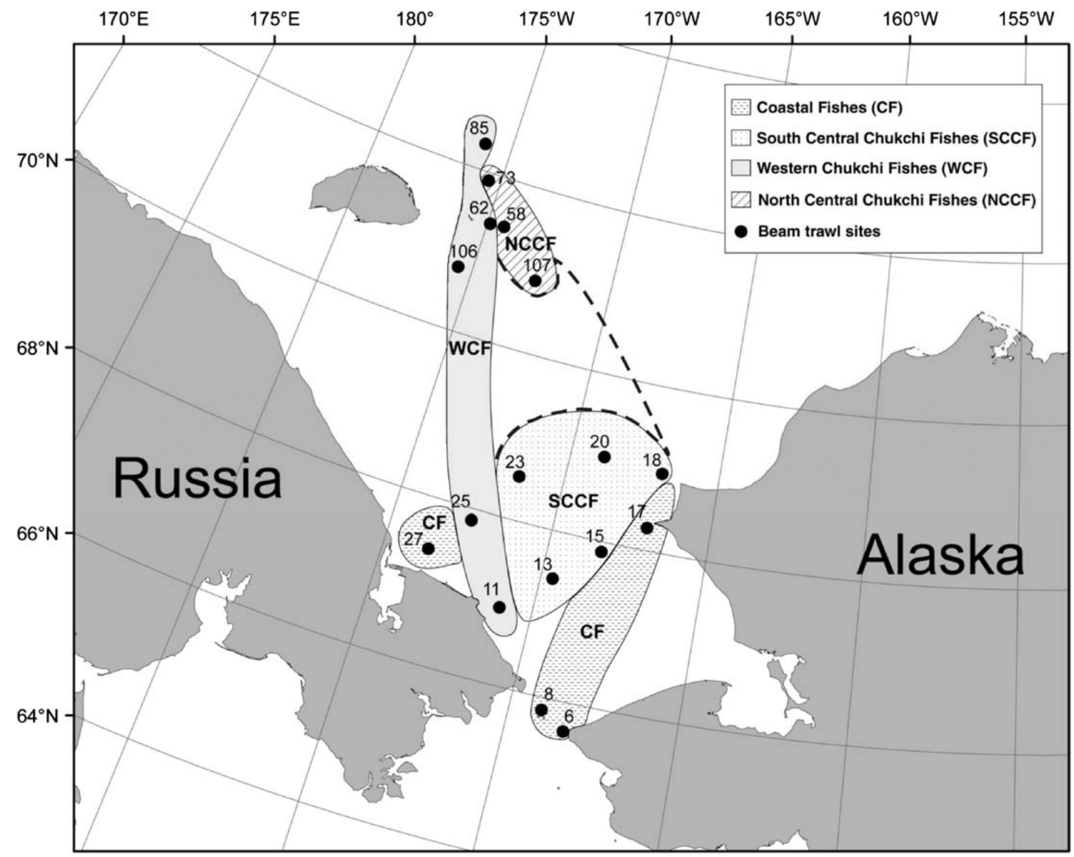

Fig. 9. Geographic designations of small demersal fish assemblages for all fishing stations. Dashed line represents connection of sub-assemblages into one larger assemblage.

(Weingartner et al., 2005) and is found in shallower water (<50 m) than WW to the west of Herald Canyon where no sampling for fish occurred.

Fortunately an earlier study was available to compare with the 2004 demersal fish assemblages in the Chukchi Sea. Cluster analyses identified six demersal fish assemblages from 48 samples of bottom fishes over a constrained area in the northeast Chukchi Sea in 1990–1991 (Barber et al., 1997). Our four assemblages of demersal fishes in 2004 were formed from only 17 sample locations that spatially were dispersed over a broader geographical area of the Chukchi Sea than those of Barber et al. (1997). Despite different sampling scales, i.e. relatively nearshore versus the open Chukchi including Russian waters, 14 years difference (1990 versus 2004), and disparate net and mesh sizes (32- versus 4-mm liner), the most important environmental factors determining the demersal fish assemblages in both 1990 and in 2004 were bottom salinity and sediment type. We did not sample northeast of Cape Lisburne and thus cannot confirm or refute Barber et al.'s (1997) contention that these assemblages are the result of wind reversal affecting ACW and mixing southern Chukchi Sea and Arctic Ocean fishes.

The ACW was thought to restrict both adult (Smith et al., 1997a) and larval (Wyllie-Echeverria et al., 1997) Bering flounder (*Hippoglossoides robustus*) near the coast as far as 71°N in 1990. Our closer examination of their results revealed that adult Bering flounder only were south of 69°N near the coast (Smith et al., 1997a), in what we and they called ACW, and larval Bering flounder were collected farther north and offshore (Wyllie-Echeverria et al., 1997), in the gap in our sampling area between stations 20 and 107. We seldom found larval Bering flounder in the ACW where they had been collected in the 1990s, but rather found them offshore and much farther to the west and north. Small demersal and larval Bering flounder were captured in BSW while a few larvae and most of the eggs were in WW, farther west than examined by 1990 collections. We therefore disagree with Wyllie-Echeverria et al. (1997) that Bering flounder larvae are only in the Chukchi Sea because they were transported by the ACW. Because Bering flounder eggs were in the WW, a water mass not adjacent to the ACW, we believe that Bering flounder spawn in the Chukchi Sea.

Because characteristics of water masses vary temporally and spatially, it can be difficult to interpret associated fish distributions. In 1990–1991, adult Arctic cod (*Boreogadus saida*) were collected in the entire collection range, alongshore and offshore in the northeastern Chukchi Sea, with greatest abundance in BSW south of 69°N (Gillespie et al., 1997). That area was near our station 17, which was one of the few stations at which demersal Arctic cod were not captured in 2004 (Mecklenburg et al., 2007). Larval Arctic cod were captured north of the adults in ACW and RCW in 1990–1991 (Wyllie-Echeverria et al., 1997). In contrast to the 1990s, during 2004 larval Arctic cod were captured farther west, south, and north in different water masses, i.e. in BSW and WW. Interannual changes in distribution of fishes in the Chukchi Sea have been associated with influx of warm ACW (Gillespie et al., 1997; Smith et al., 1997a, 1997b). Though our analysis does not indicate that the ACW is affecting the distribution of these species, water temperature clearly influences larval fish assemblages.

In 2004, larval fishes clustered into species assemblages that were related to general direction of water flow. Though the number of ichthyoplankton assemblages was less than that zooplankton assemblages in 2004 (Hopcroft et al., 2010), they shared some geographical similarities with zooplankton assemblages in 2004 (Hopcroft et al., 2010). Both ichthyoplankton and zooplankton had assemblages that connect Bering Strait (Station

Table 3
Average CPUE (#/10 m^2) of eggs, larval and juvenile fishes caught by plankton net within each water mass and station. ACW = Alaska Coastal Water; BSW = Bering Sea Water; WW = Winter Water.

Bongo water mass	ACW					BSW								WW					Total caught	Standard length range (mm)
Station	6	17	18	20	107	8	10	11	13	15	23	25	58	27	62	73	85	106		
Maximum fishing depth (m)	25	37	29	26	22	35	51	30	40	40	45	29	55	22	48	44	81	37		
Bottom depth (m)	50	40	48	54	40	48	57	43	51	59	56	49	60	44	77	71	101	73		
Osmeridae (smelts)	–	–	2.3	–	–	–	4.3	–	–	–	–	–	–	–	–	–	–	–	2	8.0–15.0
Gadidae (cods)[d]																				
Gadidae eggs[d]	–	–	–	–	–	–	13.0	–	–	–	–	–	–	–	–	–	–	–	3	–
Gadidae[d]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6.5	4.5	6	–
Boreogadus saida[d]	–	–	–	1.9	–	–	4.3	13.3	3.0	9.4	–	2.9	–	35.1	69.4	–	63.9	168.0	301	10.0–25.0
B. saida juveniles[d]	–	–	–	1.9	–	–	–	–	–	–	2.3	–	–	–	–	–	5.8	–	4	27.0–41.0
Eleginus gracilis juvenile[d]	–	–	–	–	–	–	–	–	–	–	2.4	–	–	–	–	–	–	–	1	33.5
Theragra chalcogramma[d]	–	–	–	–	6.7	–	–	–	–	4.7	–	–	–	–	–	–	–	–	3	9.0–18.0
Cottidae (sculpins)[d]																				
Gymnocanthus spp.[d]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	5.8	1.8	2	20.0–22.6
G. tricuspis juvenile[d]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2.0	–	–	1	32.0
G. tricuspis[d]	–	–	–	–	–	–	4.3	–	–	–	–	3.3	–	–	–	–	–	–	2	12.3–29.0
Icelus sp.[d]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.8	1	17.0
Agonidae (poachers)[d]																				
Aspidophoroides monopterygius	–	–	–	–	–	2.5	–	2.4	–	5.2	–	–	–	–	–	–	–	–	3	22.0–36.5
Ulcina olrikii[d]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3.2	–	–	–	1	28.0
Liparidae (snailfishes)[d]																				
Liparis spp.[d]	–	–	–	–	–	2.7	4.3	7.6	–	7.5	10.7	–	–	–	–	–	–	–	20	4.5–18.8
L. fabricii[d]	–	–	–	1.8	–	–	–	9.5	–	–	6.6	–	–	2.2	–	–	5.8	–	13	12.0–21.0
L. gibbus[d]	–	–	–	–	–	–	7.4	11.8	4.7	12.7	4.4	2.9	–	4.3	2.8	2.0	12.6	3.6	36	8.0–27.5
L. tunicatus[d]	–	–	–	–	–	–	4.3	–	–	–	–	–	–	–	–	–	–	–	1	16.0
Stichaeidae (pricklebacks)[d]																				
Leptoclinus maculatus	–	–	–	–	–	–	4.3	–	–	–	–	–	–	–	–	2.3	–	–	2	17.0–18.5
Lumpenus spp.[d]	–	–	–	–	–	–	11.1	5.5	–	5.2	–	–	–	–	–	2.0	–	1.8	8	13.0–39.0
L. fabricii[d]	–	–	–	–	–	–	–	–	–	–	–	–	–	4.4	3.2	2.0	–	–	4	23.0–37.0
Stichaeus punctatus[d]	–	–	–	–	–	–	–	–	–	–	2.3	–	–	–	2.8	–	–	–	3	18.0–27.0
Ammodytidae (sand lances)																				
Ammodytes hexapterus	–	–	–	–	–	–	–	–	–	4.7	2.3	–	–	–	–	–	–	–	3	5.7–8.0
Pleuronectidae (flatfishes)[d]																				
Pleuronectidae eggs[d]	4.7	–	–	–	–	2.7	–	–	–	–	–	–	–	–	–	–	–	–	4	–
Pleuronectidae[d]	–	–	–	1.8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	7.0
Hippoglossoides robustus eggs[d]	–	–	–	–	–	–	7.4	–	–	–	–	–	–	2.2	19.8	–	43.8	53.5	89	–
H. robustus[d]	–	–	–	3.7	–	–	–	–	–	–	6.0	–	2.1	–	–	–	5.8	–	12	6.5–20.0
Limanda spp. eggs[d]	9.7	–	11.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	17	–
L. aspera[d]	33.4	13.4	16.1	5.6	–	–	–	2.6	–	–	–	2.9	–	–	–	–	–	–	67	3.0–10.5
L. proboscidea	–	–	2.3	–	–	–	–	–	–	––	–	–	–	–	–	–	–	–	1	25.0
Hippoglossus stenolepis	–	–	–	–	–	2.5	3.7	–	–	–	–	–	–	–	–	–	–	–	2	22.0
Total caught	56	9	20	11	2	4	17	37	4	14	25	4	2	42	64	5	45	254	615	3.0–41.0

Total caught is the number of individuals, and length range is the minimum and maximum size of each taxon. Taxa also caught by bottom trawl are indicated by superscript d.

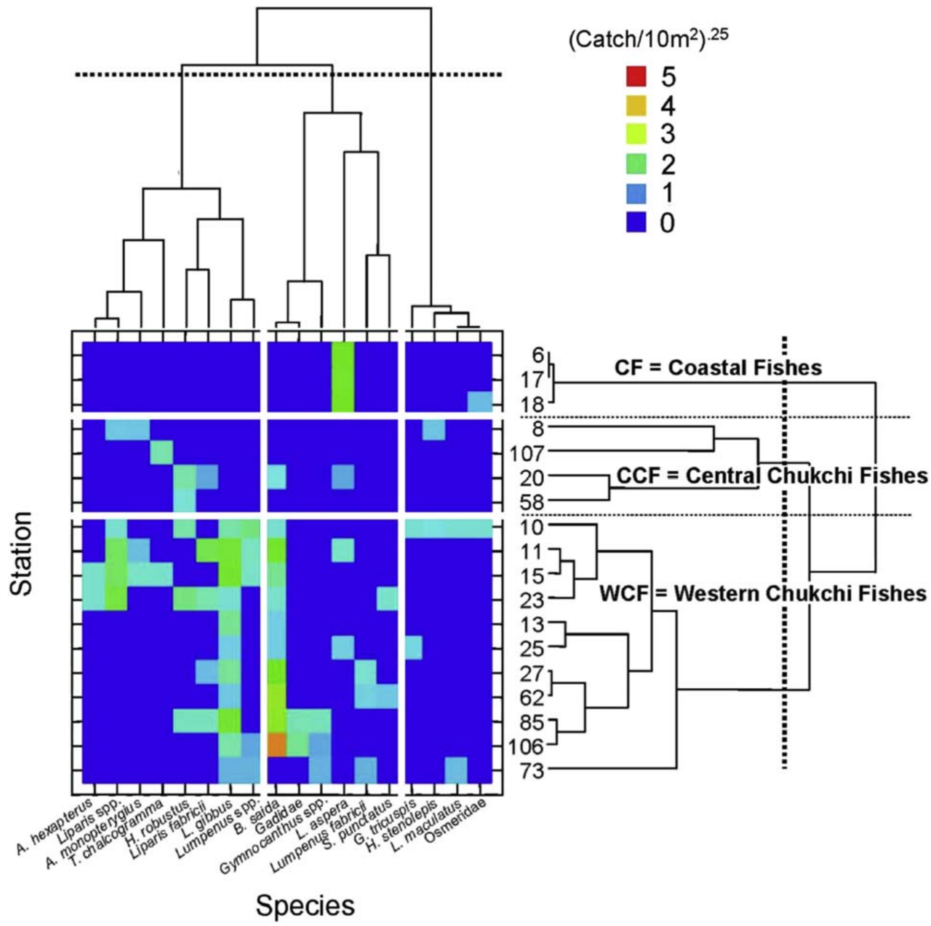

Fig. 10. Two-way joining analysis of species/station clusters showing abundance of ichthyoplankton. Heavy white lines indicate groupings. Station groups have geographic designations.

8) through offshore of Cape Lisburne (Station 20) to Herald Shoal (Station 107), indicative of a northwestward flow in the eastern Chukchi Sea.

Community structure of epibenthic invertebrates in the Chukchi Sea is similar to that of demersal fishes. Benthic communities are defined as inshore, like the Coastal Fishes, and offshore, like the Central Chukchi Fishes (Feder et al., 1994). Separation of offshore northern and southern benthic groups in the northeastern Chukchi Sea (Feder et al., 1994) occurs at 70–71°N where a hydrographic front intersects the bottom (Johnson, 1989); that separation of groups is attributable to carbon biomass associated with lower bottom water temperature and higher salinity of BSW (Feder et al., 1994). Furthermore water mass differences are reflected in benthic food web structure (Iken et al., 2010). As seen for benthic communities in 1986 (Feder et al., 1994), the small demersal fish in 2004 clustered north (NCCF) and south (SCCF) of 70–71°N. This persistent north-south division affects both benthic and demersal fish communities.

5. Conclusions and outlook

The present and future effects of climate change on Chukchi Sea fish assemblages are not well understood (Genner et al., 2004). Climate change will affect demersal and planktonic fish assemblages in the Chukchi Sea because the physical habitat that shapes those assemblages will be altered. In addition to obvious changes in temperature, salinity and nearshore sediment, it is likely that the Chukchi Sea ecosystem will switch from being benthic-dominated to being pelagic-dominated (Grebmeier et al., 2006). Such a dramatic shift would be expected to be reflected in fish assemblages as well.

Knowledge of the baseline relationship among fishes and water masses will provide the background on which to build future monitoring efforts. If Chukchi Sea water masses shift in horizontal or vertical extent with storm events or season, or merge in northerly locations, both of which are indicated by physical measurements (Weingartner et al., 2005; Pickart et al., 2010), the implications for seasonal or long-term effects on fish assemblages are great. Climate change in the western Arctic will likely also cause increased water temperature, precipitation and river runoff, and reduced salinity, all of which will affect current structure, flow patterns and strengths (ACIA, 2004).

Predicting the response of entire fish assemblages to these changes is not possible with knowledge currently available because not all fish species within an assemblage will react equally to oceanographic variability (Bertness et al., 1999). Some Arctic fishes are expected to expand northward and flourish while others will contract northward and diminish (ACIA, 2004). Changes in distributions of species would result in a restructuring of fish assemblages in the Chukchi Sea. In the characterization of a fish assemblage, absent taxa as well as present taxa are important, and a climate change effect on even the least abundant species could have large impacts on species assemblages. Effects of climate change such as these can only be quantified as measurements against existing conditions. This research provides a necessary baseline of demersal and planktonic fish distributions throughout the broad expanse of the Chukchi Sea, before further changes occur.

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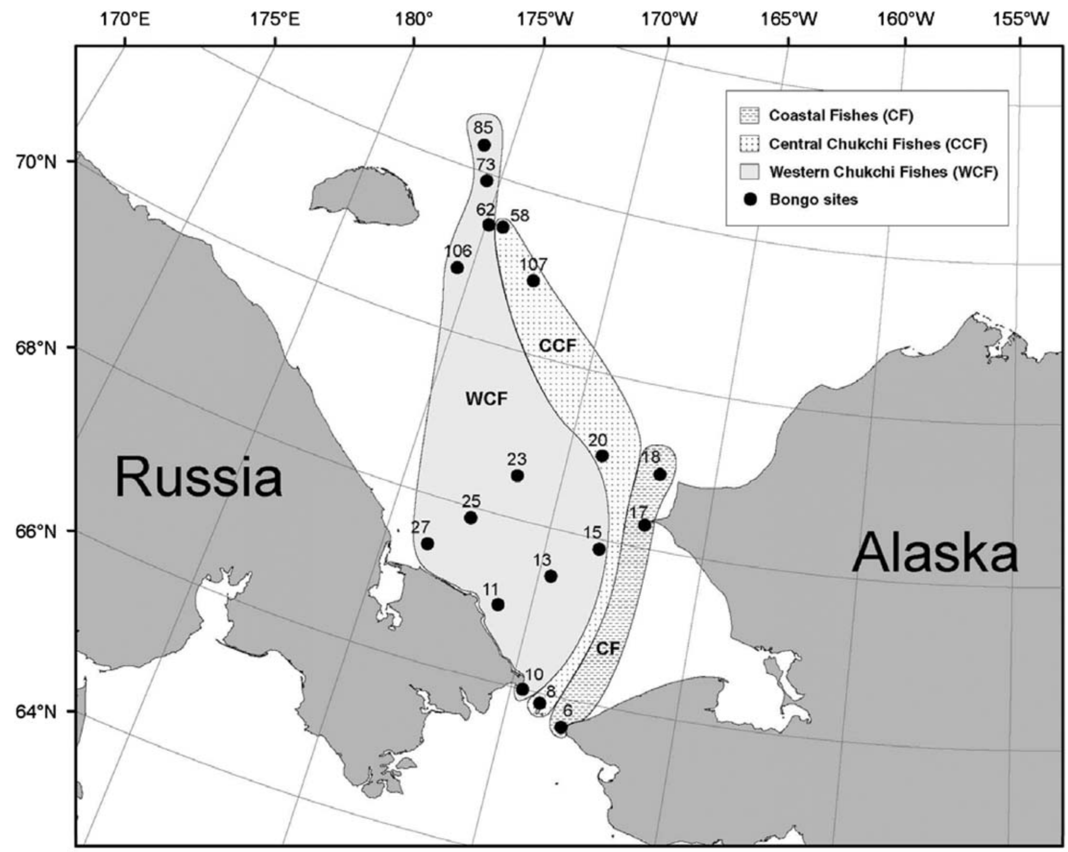

Fig. 11. Geographic designation of ichthyoplankton assemblages for all stations.

The recently approved Arctic Fisheries Management Plan bans commercial fishing in the Chukchi Sea (NPFMC, 2008). That ruling was based, in part, on the lack of adequate assessment of the effects of climate change on the region. Baseline data are needed for ecosystem-based fisheries management and designation of essential fish habitat (UCOP, 2004). Collections of fishes in 2004 had geographic gaps in sample locations that need to be filled, particularly between 69°N and 71°N, to determine where or if there is a division between the North and South Central Chukchi Fish groups. Establishment of this baseline is essential to monitoring northward migration of fish species with climate change and to developing models to predict changes in fish assemblages. Continued investigations of oceanographic conditions and faunal distribution, including larval and later-stage fishes, supported by the RUSALCA program, are planned to address these issues through cruises in the western and eastern Chukchi Sea in summer 2009 and 2012.

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