## Oceanographic assessment of the planktonic communities in the northeastern Chukchi Sea

**Report for Survey year 2010** 

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#### Oceanographic assessment of the planktonic communities in the northeastern Chukchi Sea: Report for Survey year 2010

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#### EXECUTIVE SUMMARY

Surveys of the planktonic communities over the Klondike, Burger and Statoil survey areas were completed twice during August and September of 2010, plus an October survey in Burger. Chlorophyll and nutrient concentrations suggest that August sampling captured remnants of the spring phytoplankton bloom in both the Klondike and Burger areas; concentrations of nutrients and chlorophyll then declined but showed patches of elevated concentration, particularly at depth. In total, 77 taxonomic categories of zooplankton, including 10 meroplanktonic larval categories, were observed during the 2010 field year. The greatest taxonomic diversity was observed within the copepods (25 species, plus juvenile categories), followed by the cnidarians (11 species), with all species typical for the region and largely of sub-arctic Pacific origin. An average abundance of 16712 individuals  $m^{-3}$  and 115.0 mg DW  $m^{-3}$  was captured by the 150  $\mu$ m net and an average of 158 individuals m<sup>-3</sup> and 33.7 mg DW m<sup>-3</sup> captured by the 505  $\mu$ m net. The contribution by meroplankton forms to both abundance and biomass was substantial. Both holozooplankton and meroplankton abundance and biomass were much higher in 2010 than in previous years, especially for larger bodied animals. In 2010, Klondike zooplankton could generally be separated from Burger and Statoil based on community structure, with a temporal evolution of the community structure apparent at each area, and detectable differences in community structure between each study year. Differences in ice-melt timing, water temperatures, northward transport of water masses, nutrients and chlorophyll are believed to influence the large inter-annual difference observed in the planktonic communities over the past 3 years.

#### INTRODUCTION

#### Purpose of Study and Rationale

Chukchi Lease Sale 193 occurred in February 2008, followed by the completion of the first year of a 4-year multidisciplinary environmental studies program initiated by ConocoPhillips in cooperation with Shell Exploration & Production Company, and Statoil USA Exploration & Production Inc. The 2010 field effort represents a third year of data collection that will aid in the preparation of a defensible NEPA document in support of exploratory drilling. Pelagic biological oceanography forms one aspect of the baseline studies program, because the productivity of the water column determines the flux of energy to the seafloor, as well as productivity transferred through zooplankton to higher trophic levels such as fish, seabirds and marine mammals. Alterations to water column productivity as a result of inter-annual variability, long-term climate change or human activity, could have direct impact on the ecosystem, including the more visible vertebrates. The data collected through this studies program, combined with historical and region-wide data will provide us with direct observations of community composition and biomass, the only means to compare temporal variation in biological communities to environmental change.

#### **Objectives of Study**

The major objective of this study is to describe the spatial and seasonal characteristics of the plankton (phytoplankton and zooplankton) communities, with specific detail in the three study areas. Planktonic communities are strongly coupled to the underlying physical oceanography, with major differences in water-masses generally reflected in the plankton. The study areas are near the historical transition between Alaska Coastal waters and Bering Shelf waters, both of which have unique assemblages of zooplankton. Simultaneous measurement of the physical, chemical, and biological oceanographic setting is therefore essential to forming an understanding of the patterns and the range of seasonal and inter-annual variability characteristic of the region. A secondary goal, sampling of zooplankton in areas of observed bowhead whales feeding was not exercised due to the absence of such situations.

#### Brief History of Planktonic Biological Oceanography in Chukchi Sea

The Chukchi Sea represents a complex ecosystem at the Pacific Ocean's gateway into the Arctic where climate variation combines with the complex interplay of several distinct water masses of Pacific origin with those of the central Arctic Ocean and its continental-shelf seas. Large quantities of Pacific nutrients, phytoplankton and zooplankton enter the region through the Bering Strait, in a complicated mixture of water masses (i.e. Alaska Coastal, Bering Shelf, and Anadyr Water), each with unique assemblages and quantities of zooplankton (Springer *et al.*, 1989; Coyle *et al.*, 1996; Hopcroft *et al.*, 2010). It has been estimated that 1.8 million metric tons of Bering Sea zooplankton are carried into the Chukchi Sea annually (Springer *et al.*, 1989) and that this, along with the entrained phytoplankton communities, are responsible for the high productivity of the Chukchi Sea in comparison to adjoining regions of the Arctic Ocean (e.g. Plourde *et al.*, 2005).

During the ice-free season, the southern Chukchi zooplankton fauna is primarily Pacific in character. During summer, the Pacific inflow is diluted by Coastal Arctic waters carried along

by the East Siberian Current and water carried in from the deeper waters of the Canada Basin or Chukchi Plateau (Grebmeier *et al*., 1995). Nonetheless, Pacific species are carried northward as far as the eastern side of Wrangel Island (Hopcroft *et al.*, 2010), as well as to the shelf break in the northeastern Chukchi Sea (Lane *et al.*, 2008). The influx of these "rich" Pacific waters determines the reproductive success of both the imported and resident zooplankton communities (Plourde *et al.*, 2005; Hopcroft and Kosobokova, 2010). Both inter-annual and long-term variation in climate affect the relative transport of these various water masses and hence the composition, distribution, standing stock, and production of zooplankton and their predators within the Chukchi Sea.

A regional and basin-wide review of Arctic zooplankton, their composition, seasonal life cycles, and trophic interactions was completed nearly two decades ago (Smith and Schnack-Schiel, 1990). A more recent effort emphasizing the Russian literature for just the Bering Sea has also been completed (Coyle *et al.*, 1996), as well as a review of zooplankton in polynyas (Deibel and Daly, 2007). The most current review is specific to the Chukchi and Beaufort Seas and has an extensive review of the literature for zooplankton as well as other groups (Hopcroft *et al.*, 2008). Comparison of studies prior to the 1990s is hampered by lack of standardized sampling techniques, many of which used only a single net of 303 to ~600 µm mesh that missed the majority of the zooplankton community numerically, and a substantial proportion of the community biomass and diversity. Pacific-Arctic studies have now standardized on 150 µm mesh nets (e.g. Kosobokova and Hirche, 2000; Ashjian *et al.*, 2003; Lane *et al.*, 2008; Kosobokova and Hopcroft, 2010) that more completely sample the numerically dominant copepods in the genera *Oithona, Oncaea, Microcalanus* and *Pseudocalanus (ibid;* Conover and Huntley, 1991; Auel and Hagen, 2002; Hopcroft *et al.*, 2010), although passage of the early developmental stages of these small species still occurs (Hopcroft *et al.*, 2005).

Over the past decade, biological oceanographers have assembled a relatively complete list of zooplankton species inhabiting the Chukchi Sea, with species diversity dominated by copepods (e.g. Sirenko, 2001; <u>http://www.marinespecies.org/arms/index.php</u>). Nonetheless, prior to the lease sale, we lacked comprehensive estimates of the abundance, biomass and relative composition of the zooplankton in the Chukchi Sea, and in particular their seasonal and inter-annual variability. In this regard, recent publications by RUSALCA (Russian American Long-term Census of the Arctic), SBI (Shelf-Basin Interactions) and Arctic Ocean Biodiversity (ArcOD) programs provide excellent regional context with which to compare the result of this program.

It is now clear that to a large extent, the spatial distribution of zooplankton communities in the Chukchi Sea is tied to the different water masses present in this region (Hopcroft *et al.*, 2010). While copepod crustaceans generally dominate zooplankton communities in most ocean regions, both larvaceans and meroplankton contribute significantly to community abundance and biomass (Lane *et al.*, 2008; Hopcroft *et al.*, 2009, 2010a,b). Similarly, a relatively diverse group of predatory jellyfish, and a single species of chaetognaths remain important predatory components of the zooplankton community (Ashjian *et al.*, 2003; Lane *et al.*, 2008; Hopcroft *et al.*, 2005, 2009, 2010a,b). Arguably the greatest strength of this study has been the observation of the seasonal progression of the planktonic communities, and a consistent sampling framework to highlight the extent of spatial and inter-annual variability within these communities.

#### **METHODS**

#### Survey Design

The 2010 schedule consisted of three multi-week cruises occurring between August and mid October collecting data and samples at 3 survey areas around the historic Klondike and Burger wells (Fig. 1). Sampling conducted during 2010 occurred within of a 30 x 30 NM box at the Klondike and Burger surveys, with a grid of 5x5 stations, at ~7.5 nm spacing, plus a somewhat irregular rectangle of 22 stations at similar spacing within the Statoil survey. Bottom depth over both survey areas was similar and relatively constant, varying between approximately 35 and 45 m. Inorganic macronutrients, phytoplankton (as chlorophyll) and zooplankton were sampled on each cruise, concurrent with collection of CTD measurements.

#### **Collection Procedures**

Phytoplankton were assessed as chlorophyll *a* concentration from samples collected with a Seabird 55 CTD rosette (Weingartner and Danielson, 2010) on upcasts at 6 depths per station: 0, 5, 10, 20, and 30 m, plus 3m above the sea floor. Samples were filtered under low pressure onto Whatman GF/F filters and frozen for post-cruise analysis (Parsons *et al.*, 1984). Nutrient samples were taken from the same Niskin bottles as chlorophyll, frozen immediately and analyzed post-cruise (Whitledge *et al.*, 1981; Gordon *et al.*, 1993).

Smaller zooplankton was collected routinely by a pair of 150  $\mu$ m mesh Bongo nets of 60 cm diameter hauled vertically from within 3 m of the bottom to the surface at 0.5 m s<sup>-1</sup>. The volume of water filtered was measured by Sea-Gear flowmeters in each vertical net. To target larger, more mobile zooplankton, a set of 60 cm diameter 505  $\mu$ m Bongo nets was deployed in a double oblique tow with the ship moving at 2 knots. General Oceanic flowmeters installed in each Bongo net were used to estimate the volume of water filtered. Upon retrieval, at primary stations, both samples were preserved in 10% buffered formalin, while at secondary stations one sample of each mesh size was preserved in 10% formalin, and the other in 95% ethanol (required for molecular identification). When present, large cnidarians and ctenophores were removed, sized, identified and discarded prior to sample preservation.

#### Analytical Procedures

Frozen filters were extracted for chlorophyll *a* in 95% acetone and concentrations determined fluorometrically post-cruise (Parsons *et al.*, 1984) using a Turner Fluorometer. Measurements can be used to calibrate *in vivo* fluorescence profiles measured at stations. Integral chlorophyll concentration was calculated by assuming each depth represented the concentration to the midpoint depth between each sampling interval. Frozen nutrient samples were measured post-cruise using an Alpkem Rapid Flow Analyzer (Whitledge *et al.*, 1981) and conformed to WOCE standards (Gordon *et al.*, 1993).

Formalin preserved samples were processed for quantitative determination of species composition, and prediction of biomass, at 13 stations for Klondike and Burger and at 11 stations for Statoil. During taxonomic processing, all larger organisms (primarily shrimp and jellyfish) were removed, enumerated and weighed (to  $\pm 10 \ \mu g$ ), then the sample was Folsom split until the smallest subsample contained about 100 specimens of the more abundant taxa. Specimens were identified, copepodites staged, enumerated, and measured (Roff and Hopcroft, 1986). Each larger

subsample was examined to identify, measure, enumerate and weigh the larger, less abundant taxa, particularly in the 505  $\mu$ m net which typically captures the largest taxonomic diversity. A minimum of 300 individual organisms were identified from each collection. When necessary, specimens were compared to the voucher set housed at UAF, and periodic cross-comparison occurred between the 2 co-authors processing samples. Larval fish were excluded from analysis, and passed to the fisheries ecology team for their analysis.

For some congeneric species, where earlier copepodites could not be distinguished, they have been grouped with the sibling species. Adults were identified to the species level. In the case of Calanus, excessive lipid storage in most samples made it difficult to view the ocellus which would distinguish C. marshallae from C. glacialis, and other features used to separate the adults are difficult to routinely employ, thus these species were grouped for consistency. The larger C. hyperboreus was distinguished by size (e.g. Unstad and Tande, 1991; Hirche et al., 1994). The weight of each specimen was predicted from species-specific relationships, or from those of a morphologically similar species of holozooplankton (Table 1). Such relationships were unavailable for merozooplankton. Notably, although a relationship has been published for Oithona similis (Sabatini and Kiørboe, 1994), its slope of 2.16 is unrealistically shallow and thus overestimates weights for early stages, hence we use that for a congeneric species of similar body form. Where necessary, ash-free dry weight (AFDW) was converted to dry weight (DW) assuming 10% ash (Båmstedt, 1986). A Carbon weight (CW) to DW conversion does not exist for larvaceans, so we assumed it to be 40% of DW for *Oikopleura vanhoeffeni*, as is typical of many copepods (Båmstedt, 1986). For Acartia longiremis where CW was 50% of DW, weights were more consistent with other relationships determined for this genus (e.g. Uye, 1982).

In addition to a descriptive summary, community patterns were explored using the Primer (V6) software package which has been shown to reveal patterns in zooplankton communities (e.g. Clarke and Warwick 2001; Wishner *et al.*, 2008). Data sets were power transformed (4<sup>th</sup> root), and the Bray-Curtis similarity index between stations was calculated employing all taxonomic categories that contributed at least 3% to any sample in that dataset. Significant groups within the hierarchical clustering were established with the SIMPROF routine, and these clusters were superimposed on the 2D and 3D plots of the multi-dimensional scaled (MDS) datasets, as well as spatial plots of the data. Relationships between zooplankton community composition and other variables were explored with Primer's BEST routine using normalized physical data (above and below the thermocline) and integral chlorophyll data.

#### **Quality Control Procedures**

In the field, samples were always collected in duplicate, so any discrepancy in the flowmeter readings become readily apparent. The Sea Gear meters used on the vertical nets are rigged not to spin during descent, but can be problematic - when measured values were unreasonably large they were constrained to 40 m distance. Replicate samples are not routinely analyzed, but served as insurance in the event one sample is compromised. Where necessary, specimens were compared to the voucher set housed at UAF, and periodic cross-comparison occurred between the co-authors processing samples.

**Table 1.** Relationships employed to predict weight from length for the holozooplankton encountered in the study region. Where species-specific relations were not employed we used relationships from: \* *T. japonica*, \*\* *Oithona nana*, <sup>+</sup> *F. pellucida*, <sup>++</sup>*Pseudocalanus*. DW- dry weight, AFDW- ash-free dry weight, CW- carbon weight, TL-total body length, PL- prosome length, CL- carapace length

Species	Regression	Units	Source
Themisto abyssorum/pacifica*	DW=0.0049·TL <sup>2.957</sup>	mm, µg	lkeda & Shiga, 1999
Themisto libellula Acartia longiremis Calanus glacialis/marshallae	DW=0.006·TL <sup>2.821</sup> CW=1.023·10 <sup>-8</sup> PL <sup>2.906</sup> log <i>DW</i> =4.034·log <i>PL</i> -11.561	mm, µg µm, µg µm, µg	Auel & Werner, 2003 Hansen <i>et al</i> ., 1999 Liu & Hopcroft, 2007
Centropages abdominalis Eucalanus bungii Eurytemora hermani Metridia pacifica Neocalanus plumchrus/flemingeri	log DW = 3.00·log PL-7.89 LogDW=3.091·logPL-0.0026 logDW = 2.96·logPL-7.60 logDW = 3.29·logPL-8.75 log <i>DW</i> =3.56·log <i>PL</i> -2.32	μm, μg mm, μg μm, μg μm, μg mm, mg	Uye, 1982 Hopcroft <i>et al.</i> , 2002 Middlebrook & Roff, 1986 Liu & Hopcroft, 2006b Liu & Hopcroft, 2006a
Neocalanus cristatus Paraeuchaeta spp.	LogDW=4.001.logPL-11.776 AFDW=0.0075.PL <sup>3.274</sup>	μm, μg mm, mg	Kobari <i>et al</i> ., 2003 Mumm, 1991
Pseudocalanus spp. Oithona similis** Oncaea spp.** Oikopleura vanhoeffeni Fritillaria borealis <sup>+</sup> Other calanoids <sup>++</sup> Micro– calanus, Jaschnovia	log <i>DW</i> =-2.85·log <i>PL-</i> 7.62 logAFDW=3.16·logPL-8.18 logAFDW=3.16·logPL-8.18 logC=3.20·logTL-8.93 logDW=3.21·logTL-9.11 log <i>DW</i> =-2.85·log <i>PL-</i> 7.62	µm, µg µm, µg µm, µg µm, µg µm, µg µm, µg	Liu & Hopcroft, 2008 Hopcroft <i>et al.</i> , 1998 Hopcroft <i>et al.</i> , 1998 Deibel, 1986 Fenaux, 1976 Liu & Hopcroft, 2008
Ostracods Thysanoessa inermis (T. rachii)	AFDW=0.0228·PL <sup>2.3698</sup> Log DW=2.50·logCL-1.162	mm, mg mm, mg	Mumm, 1991 Pinchuk & Hopcroft, 2007
Evadne & Podon Tomopteris Eukrohnia hamata Parasagitta elegans Aglantha digitale & other jellies	$logDW=4.0 \cdot logTL-10.5 DW=0.005 \cdot L^{2.25} DW=0.00032 \cdot PL^{3.00} DW=0.000064 \cdot PL^{3.30} DW=0.00194 \cdot PL^{3.05} $	μm, μg mm, mg mm, mg mm, mg mm, mg	Uye, 1982 Matthews & Hestad, 1977 Matthews & Hestad, 1977 Matthews & Hestad, 1977 Matthews & Hestad, 1977

#### RESULTS

#### Nutrients and chlorophyll

Chlorophyll concentrations were variable within each survey over the study, with some larger peaks observed at some stations during the first cruise (Fig. 2). Nonetheless, the magnitude of these peaks was only moderate at best, and declined on subsequent cruises at Klondike and Statoil, but surprisingly not at Burger (Table 2). On all cruises, chlorophyll was extremely low in the upper 10m, but frequently increased below this, often with an obvious subsurface maximum (Fig. 3, 5, 7, 9, 11, 13, 15). Overall these observations suggest that sampling had occurred post-spring phytoplankton bloom, perhaps catching the tail end of it during the first cruise. It is unclear what mechanisms sustained the chlorophyll observed at Burger throughout the sampling season.

*Table 2.* Average integral chlorophyll concentration (mg m<sup>-2</sup>) at the Klondike, Burger and Statoil survey grids during 2010.

Cruise	Klondike	Burger	Statoil
August	46.1	42.7	66.3
September	26.2	40.2	26.3
October		42.2	

Nitrate, silicate and phosphate were virtually absent from surface waters even during the first cruise, generally increased toward the seafloor, and were somewhat irregular in their profiles within each grid (Fig. 3-16). All nutrients were low over the Klondike survey on the first cruise (Fig. 3, 4), and virtually disappeared on the second cruise (Fig 9, 10). Even on the first cruise, nutrient concentrations at depth were generally higher at Burger and Statoil than Klondike, with notable deep pools of nitrate and silicate remaining present at Burger on all cruises (Fig 5, 6, 11, 12, 15, 16). In contrast, Statoil subsurface nitrate and silicate were high during the first cruise (Fig. 7, 8), but only low to moderate during the second cruise (Fig. 13, 14).

#### Zooplankton

In total, 75 taxonomic categories of zooplankton, including 11 meroplanktonic larval categories, were observed during the 2010 field year. An average abundance of 16712 individuals m<sup>-3</sup> and 115.0 mg DW m<sup>-3</sup> was captured by the 150  $\mu$ m net and an average of 158 individuals m<sup>-3</sup> and 33.7 mg DW m<sup>-3</sup> captured by the 505  $\mu$ m net. The greatest diversity was observed within the copepods (24 species, plus juvenile categories), followed by the cnidarians (12 species). The relative importance of taxa varies depending on which net is considered, and if abundance or biomass are used for such assessment. For the 150  $\mu$ m nets, abundance was dominated by the bivalve larvae, followed by the *Pseudocalanus* copepod species complex, the cyclopoid copepod *Oithona similis*, the small larvacean *Fritillaria borealis*, copepod nauplii, barnacle larvae (nauplii and cyprids), polychaete larvae, the pteropods *Limacina helicina*, the larvacean *Oikopleura vanhoeffeni*, and the copepod *Calanus glacialis/marshallae*, all averaging more than 100 m<sup>-3</sup>. Biomass in the 150  $\mu$ m nets was dominated by several of these taxa, plus rarer species of larger individual biomass. Among the top ten biomass, followed by *Calanus* 

*Table 3.* Zooplankton species observed during 2010, in the Klondike, Burger and Statoil surveys, along with their average abundance and biomass across all samples examined. Data is presented for both vertical 150  $\mu$ m collections and the 505  $\mu$ m oblique tows. 'Trace' refers to taxa observed only once or twice during analysis.

	150 µm net		505 µr	505 µm net	
	Abundance	Biomass	Abundance	Biomass	
	(indiv m⁻³)	(mg DW m⁻³)	(indiv m <sup>-3</sup> )	(mg DW m⁻³)	
Copepods					
<i>Acartia</i> spp.	150.48	0.020	0.00	0.000	
Acartia longiremis	82.72	0.375	0.50	0.004	
Acartia hudsonica	2.08	0.007	0.00	0.000	
Eurytemora pacifica	0.41	0.003	0.01	0.007	
Calanus hyperboreus	0.00	0.000	trace	0.001	
Calanus glacialis/marshallae	123.62	16.543	62.39	10.991	
Centropages abdominalis	54.10	0.153	1.35	0.027	
<i>Clausocalanus</i> sp. (juvenile)	0.20	0.001	0.00	0.000	
Epilabidocera amphitrites	0.00	0.000	0.02	0.004	
Eucalanus bungii	14.12	0.892	5.41	0.377	
Heterorhabdus sp. (juvenile)	trace		0.00	0.000	
Metridia pacifica	13.45	0.167	1.99	0.110	
<i>Microcalanus</i> sp. (juvenile)	2.80	0.011	0.00	0.000	
Neocalanus flemingerii	2.16	1.580	1.29	0.634	
Neocalanus plumchrus	0.40	0.139	0.02	0.012	
Neocalanus cristatus	0.15	0.971	0.22	1.411	
Pseudocalanus male	42.15	0.300	0.02	0.000	
Pseudocalanus spp. (juvenile)	1555.33	3.796	0.31	0.005	
Pseudocalanus minutus	25.54	0.381	2.22	0.046	
Pseudocalanus acuspes	51.14	0.537	1.16	0.021	
Pseudocalanus newmanii	127.21	0.707	0.08	0.001	
Pseudocalanus mimus	0.62	0.011	0.01	0.000	
Scaphocalanus sp. (juvenile)	trace		0.00	0.000	
Scolecithricella minor	0.00	0.000	0.01	0.000	
Spinocalanus spp. (juvenile)	trace		0.00	0.000	
Tortanus dicaudatus	0.12	0.000	0.04	0.001	
Oithona similis	1552.62	1.980			
Triconia (Oncaea) borealis	8.55	0.014			
Harpacticoida	14.26	0.090			
Calanoida nauplii	1138.80	0.968			
Cyclopoida nauplii	140.49	0.043			
Larvaceans					
Oikopleura vanhoeffeni	198.35	5.689	5.86	0.263	
Fritillaria borealis	1424.77	0.048	17.62	0.003	
Pteropods					
Limacina helicina	426.91	2.162	1.35	0.141	
Clione limacina	0.12	0.052	0.06	0.025	
Cladocerans					
Evadne nordmanni	1.67	0.021	1.17	0.038	
Podon leuckartii	67.79	0.619	0.19	0.004	

Table 3 continued	150 µm net		505 µm net	
-	Abundance	Biomass	Abundance	Biomass
Euphausiids				
Euphausiid calyptopis	4.78	0.010	0.57	0.011
Euphausiid juvenile	1.31	0.121	1.36	0.134
Thysanoessa inermis	0.00	0.000	0.00	0.007
Thysanoessa raschii	4.78	0.010	0.33	1.015
Thysanoessa spinifera	1.31	0.121	0.01	0.000
Shrimps and Mysids				
Hippolytidae (juvenile)	8.29	9.099	0.17	0.148
Eualus gaimardii	0.24	1.244	0.03	0.034
Mysis polaris	0.00	0.000	0.00	0.002
Amphipods				
Themisto abvssorum/pacifica	0.00	0.000	0.01	0.011
Themisto libellula	0.93	5,727	0.02	0.224
Hyperoche medusarum	0.00	0.006	0.02	0.011
Hyperia galba/medusarum	0.00	0.000	0.01	0.003
Ctenophores				
Beroe cucumis	0.00	0.048	0.00	0.000
Mertensia ovum	1.22	3.817	0.23	0.874
Cnidarians				
Aeginopsis laurentii	12.96	0.293	0.07	0.001
Aglantha digitale	51.85	6.060	17.29	4.184
Bougainvillia supercilliaris	0.00	0.000	0.00	0.008
Catablema vesicarium	2 23	8 705	0.03	0.030
Euphysa flammea	0.00	0.000	0.01	0.000
Obelia longissima	0.92	0 139	0.02	0.004
Rathkea octonunctata	1 13	0.005	0.02	0.000
Sarsia tubulosa	0.00	0.000	0.02	0.020
Melicertum octopunctata	0.04	0.092	0.14	0 138
I Inidentified chidaria	0101	0.002	0.01	0 106
Aurelia aurita	0.00	0.000	0.01	0.100
Cvanea canillata	0.00	0.000	0.01	0.397
Chrysaora melanaster	0.01	0.001	observed	0.001
Chaetognaths			00001104	
Parasaditta elegans	80 75	29 081	11 59	11 937
TOTAL Holozoonlankton	7397	102 9	135.3	33.5
Bivalvia Janvae	8011.80	2 504	10010	
Bornacla cyprid	220 51	2.304	1.01	0.010
Barnacle cypriu Barnacle pauplii	120.02	0.307	10.45	0.019
Decencido zoco	139.93	0.274	19.40	0.075
Decapoda zoea	0.01	0.010	0.60	0.011
Pagunidae zoea	1.17	0.004	0.00	0.024
Decapoua megalopa Delvebasta lanvas	0.00	0.010	0.09	0.015
	003.10	3.009	0.76	0.029
Ophuroid larvae	94.79	0.010		
Asteroid dipinnaria	3.52	0.007		
Echinod larvae	60.44	0.040		
Bivalvia larvae	8011.89	2.504	00 F	
Total Merozooplankton	9315	12.1	22.5	0.2
TOTAL Zooplankton	16712	115.0	157.8	33.7

glacialis/marshallae, juvenile Hippolytid decapods, the medusae Catablema vesicarium and Aglantha digitale, the amphipod Themisto libellula, barnacle larvae (nauplii and cyprids), the larvacean Oikopleura vanhoeffeni, and finally polychaete larvae.

In contrast, the top 10 abundance ranking for the 505 µm nets was led by the copepod *Calanus marshallae/glacialis* (nearly half of the holozooplankton), barnacle larvae (cyprids plus nauplii), the larvacean *Fritillaria borealis*, the medusae *Aglantha digitale*, the chaetognath *Parasagitta elegans*, the larvacean *Oikopleura vanhoeffeni*, the copepods *Eucalanus bungii*, the *Pseudocalanus* species complex, *Metridia pacifica*, and finally juvenile euphausiids. Biomass in the 505 µm nets was dominated by the chaetognath *Parasagitta elegans*, and the copepod *Calanus marshallae/glacialis*, with only the medusae *Aglantha digitale*, *Neocalanus cristatus* and the euphausiid *Thysanoessa raschii* contributing more then 1 mg DW m<sup>-3</sup>. The top ten biomass ranking was rounded out with the ctenophore *Mertensia ovum*, the copepod *Neocalanus flemingerii*, the jellyfish *Cyanea capillata*, the copepod *Eucalanus bungii*, and the larvacean *Oikopleura vanhoeffeni* 

Summarizing the averages for each cruise by major taxonomic groups, in terms of abundance copepods and meroplankton appear to dominate in numbers, with large spikes in overall numbers (including nauplii) in the 150  $\mu$ m net during the second cruise (Fig. 17). Larvaceans appear somewhat variable but stable in number, while pteropods made major increases during the second cruise. It is notable that based on the 505  $\mu$ m net copepod numbers were relatively stable between cruises, as were chaetognaths, but cnidarians increased significantly on the second cruise. In terms of biomass, there were pronounced differences in magnitude for two major taxa when compared across the sampling season, where chaetognaths and copepods co-dominated the biomass for all three study areas during the sampling season, with the contributions from the remaining taxa highly variable (Fig. 18). Chaetognaths, euphausiids, cnidarians, and the "other" group category contribute relatively little in terms of abundance, but make notable contributions to biomass, in both nets.

Changes in the relative contributions of the different groups are more striking when viewed at the station level (Fig. 19 & 21). For the 150 µm nets, Burger and Statoil appear relatively similar with abundances being dominated by meroplankton, copepods and larvaceans where Klondike is dominated by both copepods and larvaceans (Fig. 19). The survey grids appear to diverge on the second cruise, with meroplankton dramatically increasing in number over all three sites. Contribution of copepods remained relatively stable throughout the entire season over the study area with slight decreases occurring in Klondike during the second cruise and increases in Burger by October. In terms of biomass, in the 150 µm nets, chaetognaths, hydrozoans and copepods dominated overall, with typically greater contributions by larvaceans at Klondike than Burger and Statoil (Fig. 20). For the 505 µm nets, abundance was significantly dominated by copepods over the entire sampling season, reaching a peak in abundance in Burger in the third cruise. By the second cruise copepod abundance remained high but meroplankton numbers significantly dropped off and were replaced by hydrozoans. Larvacean abundance seemed to move northeast into Burger during the second cruise and then dropped off by the time sampling commenced over Burger in October (Fig. 21). In contrast, the distribution of biomass in the 505 μm nets was distinctly different from the 150 μm nets, with chaetognaths and copepods prominent over the three sites during the entire sampling season. Cnidarian biomass peaked during the second cruise in Statoil and by the third cruise chaetognath and copepod biomass continued to dominate in Burger (Fig. 22).

Looking more closely at the species and genus level, faunal differences become apparent between the cruises and survey areas. For the 150 µm nets, the copepods, Pseudocalanus spp., Calanus marshallae/glacialis, Oithona similis, Centropages abdominalis, Metridia pacifica, Oncaea borealis and Acartia spp. all showed an increase in overall abundance during the second cruise in August, with significant increases occurring for Acartia, C. abdominalis, O. similis as well as copepod nauplii (Figs. 24 & 25). The larvacean Fritillaria borealis was the second most dominant zooplankton category behind O. similis, with abundances reaching a two fold increase in Klondike in August over September and then numbers drop off in Burger by October. The chaetognath Parasagitta elegans increased in numbers by the second cruise and remained stable during the remainder of the season, where the cnidarian Aglantha digitale and pteropod Limacina helicina were rather variable in abundance throughout the season but showed a large increase in numbers from the first to the second cruise in both Klondike and Statoil (Fig. 25). Barnacle nauplii peaked in abundance at the beginning of the season and then markedly decreased during the second and third cruises, while barnacle cyprids were greatest in Burger and Statoil during the first cruise and then dropped off to more uniform and stable numbers for the duration of the sampling season. Bivalve larvae saw an extensive amplification of individuals during the second cruise in Klondike and Statoil and by the third cruise saw a relatively lower but substantial contribution of numbers over Burger (Fig. 26). Species wide, Klondike exhibited the most dramatic increases in absolute numbers during the September cruise.

For the 505 µm net, abundances were lower for all species of zooplankton than observed in the 150 µm net (Fig. 27, 28, & 29). The more robust data on these larger species in the 505 µm nets showed the neritic *Calanus marshallae/glacialis*, as well as *Acartia* spp. and *Pseudocalanus* spp., to be relatively uniform throughout the study area during the entire sampling season (Fig. 27). The copepod *Eucalanus bungii*, the chaetognaths *Parasagitta elegans*, the pteropod *Limacina helicina* and the cnidarian *Aglantha digitale* all showed similar patterns to the 150 µm net (Figs. 27 & 28). Meroplankton for decapods, euphausiid calytopsids and Hippolytidae peaked in abundance during the first cruise, mainly in Burger and Statoil, and euphausiid juveniles became more abundant in the latter part of the season (Fig 29).

Cluster analysis of sample Bray-Curtis similarity on the 150  $\mu$ m abundances suggested 16 distinct clusters (and 2 strays) within the samples, with ~4 major clusters emerging at the 70-80% similarity level (Fig. 30). The first Klondike cruise tends to cluster relatively distinctly from the other survey grids, while the second Klondike cruise shows some overlap with the western edge of Burger and Statoil, and the transition stations. Not surprisingly, within a cruise the adjoining Burger and Statoil grids tend to cluster together, and somewhat distinctly, while the October survey of Burger is scattered across the major clusters. In general, these grouping are also supported by the multidimensional scaling (MDS) of the data (Fig. 31). MDS plots also suggest collections are moving along a temporal trajectory between the first and second cruise although it is not apparent in the 2-D MDS (compared to the 3-D) that the third Burger survey is moving along a unique trajectory. Clustering analysis of the 505  $\mu$ m zooplankton abundances produced more fractured clusters (Fig. 32), but again supported the somewhat distinct community structure of Klondike, but also the distinctness of the third Burger survey, all again supported by the MDS analysis (Fig. 33). As in previous year's Primer's BEST routine indicated that consecutive day of sampling as well as temperature, salinity or fluorescence alone, or in

combination, explains a relatively limited amount of the observed variation (max Spearman's r < 0.4 for either net).

#### Inter-annual comparisons

A comparison across the three years by sampling month does not show large differences between abundances in August (Fig. 34), although there is the suggestion of fewer copepods in 2008. In terms of biomass, there were significantly more chaetognaths in August 2010 than prior years and fewer larger copepods in 2008 than in subsequent years (Fig. 35). During September, there were massive increases in copepods, meroplankton and enidarian abundance in 2010 compared to previous years (Fig. 36), with these increases along with those of chaetognaths and the 'other' category also apparent for biomass (Fig. 37). In October, larvacean abundance was greatest in 2009, and copepod abundance lowest in 2008 (Fig. 38), while biomass again showed, a progressive increase in copepods and chaetognaths across years (Fig. 39).

Looking at the species-level details, in the 150 µm net abundances of the copepod genera *Acartia, Pseudocalanus, Oithona, Calanus* and *Metridia* appear to have increased across years, while the tiny copepod *Oncaea*, and the larvacean *Fritillaria* peaked in 2009, and both *Centropages* and *Oikoplerua* abundances were depressed in 2009 (Fig. 40). Within the meroplankton, barnacle larvae (nauplii plus cyprids) declined across months but showed no clear inter-annual pattern, while polychaete larvae – and particularly bivalve larvae – exploded in 2010 (Fig. 41). In the 505 µm nets, the large copepod *Calanus marshallae/glacialis* was several fold more abundant in 2010 than previous years, while *Eucalanus* was nearly absent during 2009, as were *Neocalanus* species to a lesser extent (Fig. 42). The filter-feeding larvaceans *Oikopleura* and *Fritillaria* had reciprocal patterns, with *Fritillaria* most abundant in 2008 and 2010, while *Thysanoessa* euphausiids were variable, but least abundant in 2010, the ctenophore *Mertensia ovum* was not observed in 2008, and the chaetognath Parasagitta elegans was generally more abundant in 2010 then prior years (Fig. 44)

Comparison of the copepod size spectra between nets and season provides an interesting means of examining the observed patterns. Base on the 150  $\mu$ m collections (Fig. 45) 2010 has far more copepods in all size categories than 2008 and 2009, with 2008 being lowest in individuals above 1.5 mm prosome length. These differences are most pronounced in terms of biomass than abundance. The visible modes in the spectra between 1.5 and 4 mm reflect the stages of *Calanus glacailis/marshallae*, with still larger data contributed by *Neocalanus* species and *Eucalanus bungii*. The 505  $\mu$ m collections typically provide much more robust data for copepods above ~1.2-1.5 mm (Hopcroft *et al.*, 2001), and should progressively extrude copepods of decreasing size (Fig. 46). Only the 2010 data shows the expected pattern, with 2009 showing a mode below 1.2 mm and 2008 with an unexpectedly large peak below 1 mm, indicating the 505  $\mu$ m net was retaining copepods that it should not have been.

The zooplankton communities appear to be distinctly different between all three years with little overlap in their clustering and distinct domains for multidimensional scaling of both 150  $\mu$ m (Fig. 47) and 505  $\mu$ m (Fig. 48) abundances. Interestingly, the 2008 data shows higher within-year similarity than 2009 for the 150  $\mu$ m samples, while the opposite is true for the 505  $\mu$ m samples, suggesting one of the greatest differences between years was the larger zooplankton species.

#### DISCUSSION

#### Chlorophyll and Nutrients

Phytoplankton pigments and their spatial or temporal variations during the spring and summer are related to water-column irradiance and nutrient concentration (Hill et al., 2005; Lee et al., 2007). High concentrations of nutrients in the surface waters during spring are typically depleted rapidly during bloom conditions along the ice edge, or in open water where stratification limits replenishment of nutrients from below the mixed layer to the surface. Thus, observations north of our study area near the shelf break (Hill *et. al.*, 2005) show low chlorophyll concentrations and moderate nutrients prevail during the ice-covered period. These give way to depleted surface nutrients and subsurface chlorophyll peaks of 2-12 mg m<sup>-3</sup> during the spring bloom, consistent with our observations. Further removed from our study area, concentration peaks in excess of 200 mg m<sup>-2</sup> have been observed, although values below 50 mg m<sup>-2</sup> are also common (Lee *et al.*, 2007).

During all the 2010 surveys, low nutrient and chlorophyll concentrations were persistent in surface waters, with even subsurface nutrients and most chlorophyll notably depleted at all depths for Klondike on both surveys. In contrast, Burger and Statoil showed subsurface nutrients and chlorophyll in August, which declined at Statoil but not Burger in September. In aggregate these observations suggest Klondike was sampled post-bloom in August while the bloom was still underway at Burger and Statoil. It is unclear how the high subsurface nutrients and chlorophyll persisted throughout the season, but they are clearly coupled. Differing transport rates between the survey areas likely contribute to some of the observed differences. A compilation of chlorophyll values from the 1974-1995 period (Dunton *et al.*, 2005) suggest large gradients of chlorophyll occur through the Chukchi Sea, with their values in our study area approximately 80-200 mg m<sup>-2</sup>. Our 2010 observations overlap the lower end of that range in 2010, but generally fall below it.

#### Zooplankton composition

The Chukchi Sea displays a similar level of diversity, but high biomass compared to the adjoining East Siberian (Jaschnov, 1940; Pavshtiks, 1994) and Beaufort (e.g. Horner, 1981) seas. In contrast, the Chukchi Sea has lower diversity than is present in the adjoining vertically-structured central Arctic basins where depths can exceed 3000 m (e.g. Kosobokova and Hirche, 2000; Kosobokova and Hopcroft, 2010). As was observed during the 2008 field program, most copepod species observed in this study were common to the subarctic Pacific Ocean and/or the Bering Sea rather than specific to the Arctic (Brodsky, 1950, 1957) due to the generally northward advection of waters thought Bering Strait (e.g. Weingartner *et al.*, 2005). In contrast to all other planktonic groups, the hydrozoan medusae assemblage is more arctic in character, presumably because they are released to the water column by the benthic life-stage further south in the Chukchi. Nonetheless, the species composition is generally similar to that observed during the summer ice-free period in this region when similar-sized finer collecting meshes are employed (e.g. Springer *et al.*, 1989; Kulikov, 1992; Hopcroft *et al.*, 2010), or similar coarser nets are compared (e.g. Wing, 1974; English and Horner, 1977).

In contrast, our estimates 16712 individuals  $m^{-3}$  and 115.0 mg DW  $m^{-3}$  (~3.45 g DW  $m^{-2}$ ) captured by the 150  $\mu$ m net, and the average of 158 individuals  $m^{-3}$  and 33.7 mg DW  $m^{-3}$  (~1.01

g DW m<sup>-2</sup>) captured by the 505 μm net are comparable to previous studies from the Chukchi Sea, although they are 5-6 fold larger than observations from the study area in 2008 and 2009. In waters to the south and west of the Klondike and Burger survey areas an average of 5760 individuals m<sup>-3</sup> and 42 mg DW m<sup>-3</sup> in were recently determined using identical techniques with a 150 μm vertical net (Hopcroft *et al.*, 2010). There is also a broad range of older biomass estimates for the region, ~2 g DW m<sup>-2</sup> for herbivorous zooplankton in summer north and south of the Bering Strait (Springer *et al.*, 1989), 2.5-5.5 g DW m<sup>-2</sup> on the US side of the Chukchi Sea or 1.3 g DW m<sup>-2</sup> spanning both sides of the Chukchi (Turco, 1992a, b). Furthermore, 14.8 g WW m<sup>-2</sup> (Kulikov, 1992) and 356 mg WW m<sup>-3</sup> (14.2 g WW m<sup>-2</sup> - Pavshtiks, 1984) for all mesozooplankton spanning the Chukchi Sea are also somewhat lower, if we assume DW is 10-15% of WW (Wiebe *et al.*, 1975). Our 2010 observations generally exceed the range of recent observations (3-58 mg DW m<sup>-3</sup>) to the north of the Klondike and Burger survey areas near the shelf break (Lane *et al.* 2008; Llinás *et al.*, 2009), as well as values for the upper 50 m (42 mg DW m<sup>-3</sup>) further into the adjoining basin (Kosobokova and Hopcroft, 2010).

In terms of composition, the species observed in this study have all been reported previously for this region, but not consistently within a single publication. Our 505 µm data is directly comparable to data from the ISHTAR (Inner Shelf Transfer and Recycling) program (Springer et al., 1989; Turco, 1992a,b), who noted the predominance of Calanus marshallae/glacialis, *Pseudocalanus* spp., *Acartia longiremis* and *Oikopleura* among the herbivorous grazers. In addition to awareness of differences between collecting mesh size, detailed comparison to many previous studies also requires an awareness of changes in taxonomic resolution, and taxonomy itself (e.g. Pseudocalanus - Frost, 1989; Neocalanus - Miller, 1988; Calanus - Frost, 1974). Even today routine morphological separation of several of these species is difficult (Llinás, 2007; Lane et al., 2008). Other holoplanktonic crustacean groups, such as euphausiids and cladocerans, present less of a taxonomic challenge, although they are not always reported to the species level. Non-crustacean groups have been recorded with variable resolution and proficiency in previous studies. This study is consistent with a emerging realization that considerable populations of larvaceans, specifically the large arctic *Oikopleura vanhoeffeni* and the much smaller *Fritillaria* borealis, are present in the northern Bering and Chukchi Sea (e.g. Kulikov, 1992; Lane et al., 2008; Hopcroft et al., 2010) at times reaching high biomass (Springer et al., 1989; Shiga et al., 1998, Hopcroft et al., 2010).

The dominant predators in terms of abundance and biomass were the chaetognaths, exclusively *Parasagitta elegans*, consistent with other studies from the region (e.g. Cooney, 1977; Neimark, 1979; Springer *et al.*, 1989; Kulikov 1992; Lane *et al.*, 2008; Hopcroft *et al.*, 2010). Consistent with these studies there was considerable biomass in both small and large gelatinous organisms: *Aglantha digitale* and *Rathkea octopunctata* being most common, but with larger species periodically captured but poorly quantified. Finally, suspension-feeding meroplanktonic larvae of benthic organisms were extremely common throughout the sampling region. High abundance of meroplankton is typical of summer-time data in this region (e.g. Cooney, 1977; Neimark, 1979; Springer *et al.*, 1989; Kulikov, 1992; Hopcroft *et al.*, 2010), and knowledge of their abundance and distribution is relevant to understanding recruitment to the rich benthic communities in this region (Bluhm *et al.*, 2009), and relation to the work by Blanchard *et al.* Given their apparently large contribution to the zooplankton biomass in the survey areas, relationships between the size and weight for meroplanktonic groups need to be better quantified to more fully appreciate their role in this region.

#### Community patterns

The spatial distribution of the zooplankton communities in the Chukchi Sea has been frequently tied to the different water masses in this region. Such patterns were first recognized by Russian researchers as early as the 1930s (Stepanova, 1937a,b), and are to a large extent a continuation of patterns observed in the northern Bering Sea (see review by Coyle *et al.*, 1996). These patterns were reiterated by later Russian studies (e.g. Pavshtiks, 1984) that identified at least three water types in the region. Although the first years of the ISHTAR program were restricted to sampling in US waters, the oceanic Anadyr waters, continental shelf and low-saline nearshore waters were also recognized (Springer *et al.*, 1989). Cross-basin studies by the international BERPAC (Bering-Pacific) program also identified three zooplankton clusters within the Chukchi Sea, but failed to articulate their species assemblages or associate them with specific water masses (Kulikov, 1992). Recent sampling to the south also confirms strong ties to water masses (Hopcroft *et al.*, 2010).

Despite the relative proximity of the survey areas, as in previous years we were frequently able to separate them based on community structure, and also able to determine a temporal evolution to the communities as well. Although temperature, salinity and fluorescence (as an index of chlorophyll) could be statistically correlated to the observed community structures, the amount of variation explained within a year was relatively low. Also as in previous years, the study area appears to have little influence from the Alaska Coastal Current (i.e. Hopcroft *et al.*, 2010), but coastal species (i.e. *Podon* and *Evadne*, *Acartia hudsonica*, *Eurytemora* species) were observed in low numbers throughout our study area. Integration of the surveys' biological and physical data and broader scale observations anticipated during 2011 should help resolve some of the questions about the footprint of the various water masses.

#### Inter-annual comparison

The most striking feature of the zooplankton community for 2010 were the large increase in the several key "herbivorous" copepod species (*Calanus* and *Pseudocalanus*), the microzooplankton predatory copepods (*Acartia* and *Oithona*), all categories of meroplankton, the omnivorous euphausiids, and the planktonic predators upon these groups. It is particularly notable that overall increases in copepod abundance and biomass occurred in the large lip-rich species that should be of greatest value to those vertebrates feeding on zooplankton. Large increases in planktonic predators – most notably the ctenophore *Mertensia ovum*, the cnidarian *Aglantha digitale*, and the arrow worm *Parasagitta elegans* – are a direct response to the increased availability of their prey. Under these relatively optimal conditions, few major species declined in 2010, the notable exception is the larvacean *Fritillaria borealis*. The huge spikes in meroplankton abundance observed in September also suggest the benthos received a considerable supply of food earlier in the season.

The copepod size-frequency analysis completed this year re-enforces our belief last year that there were significantly more large-bodied copepods in 2009 than 2008, and even more again in 2010. While the 150  $\mu$ m nets are free of bias, this analysis has highlighted a bias present in the first 2 years of 505  $\mu$ m net data, related to the excess retention of smaller-bodied copepods (and other groups). This problem was particularly pronounced in 2008, when large numbers of larvaceans, especially *Oikopleura* (and their mucus houses), were present and the 505  $\mu$ m tows were longer than in subsequent years. The large quantities of houses trapped on the mesh of the plankton nets then retained zooplankton that should have passed through, and thus increased the

counts of copepods in that net by 35-40 individuals m<sup>-3</sup> (80%), and are likely responsible for most *Fritillaria* (~33 individuals m<sup>-3</sup>) retained plus an unknown number of some meroplankton groups. The bottom line was there was extremely little in the way of large zooplankton present and available for higher trophic levels in 2008. In 2009, the high numbers of *Fritillaria* (and their mucus houses) again caused a detectable retention bias, but it was on the order of only 1-2 individuals m<sup>-3</sup> for the copepods, but may explain the high numbers of *Fritillaria* retained by the 505 µm nets. The impact on biomass are much less than for abundance (because small animals weigh little) and was probably about 0.24 mg DW m<sup>-3</sup> (11%) of the copepods in 2008, and trivial in 2009.

At present we believe the inter-annual variability observed for the planktonic communities from 2008-2010 is related to a combination of physical parameters as observed at the study area and the intensity of physical transport from the Bering Strait (Fig. 49). Sea surface temperatures in 2008 were low throughout the entire season at Burger (i.e. generally below 1°C) but warmed over the season at Klondike reaching between 3 and 6°C (Weingartner and Danielson, 2010). Overall this retarded zooplankton growth and development, resulting in lower abundances and smaller body sizes across major taxa. In 2009 ice retreat was earlier than the previous year and sea surface temperatures (SSTs) were already 5-7°C at Klondike and slightly cooler at Burger by the first cruise. Temperatures declined slowly over subsequent 2009 cruises, but there was notably more "heat" in the system during 2009 (Weingartner and Danielson, 2010) and 2010 (Weingartner and Danielson, 2011). Warmer temperatures should have allowed more rapid growth and reproduction, allowing for greater zooplankton abundances in 2009 (i.e. the 2 fold increase in 150 um net abundances). This appears to have supported more energy rich largerbodied zooplankton earlier in the 2009 season, however the chronically low concentration of chlorophyll and nutrients suggest zooplankton was probably food-limited throughout much of the season. During 2010 ice retreat was slow, but not as slow as 2008, while water temperatures warmed rapidly to as much as 8°C. Like 2008 we appear to have captured some of the spring bloom signal in 2010, but unlike 2009, nutrients persisted in the system at Burger and Statoil maintaining intermediate concentrations of chlorophyll upon which zooplankton could feed and grow. Furthermore, the extent and duration of ice-free zones during May-July also shows significant inter-annual variability (Weingartner, per comm.) and may be important in 'priming' the productivity of the zooplankton communities prior to our period of observation.

Changes in the abundance and relative contribution of crustacean and non-crustacean zooplankton – in particular larger-bodied copepods and euphausiids – can help us to interpret the degree of dissimilarity expressed from clustering and MDS between 2008, 2009, and 2010. Specifically, we believe several larger key species became progressively more abundant from 2008-2010 because the "productive" season started earlier in the later years yielding oceanographic conditions (i.e. temperature) that were more optimal for their growth and/or reproduction, either locally or in the source waters "down stream" of the study area. These factors placed populations of larger crustacean zooplankton in the survey areas sooner, at a time when they could be usefully exploited by fishes, planktivorous seabirds and other higher trophic levels. These differences likely contributed to the contrasting seabird populations observed between the 2008 and 2009 field years (Gall and Day, 2010), but do not explain why seabirds failed to capitalize better on the 2010 zooplankton.

#### CONCLUSIONS

Significant differences in water temperatures and timing of the phytoplankton bloom in 2008-2010, resulted in large differences in both seasonally and spatially averaged zooplankton community values. It is likely that both the intensity of transport of zooplankton from more southern waters, and downstream productivity are also important. In addition to confirming the known importance of crustacean zooplankton to higher trophic levels (i.e. seabirds), these surveys are establishing the unappreciated importance of both larvaceans and meroplankton in the northeastern Chukchi Sea. Sampling during three years of the ice-free period in the Chukchi Sea has allowed us to recognize the level of inter- and intra-annual variability of a plankton community primarily Pacific in faunal character. Surveys during 2011 will further help to refine the scales of spatial variability and our appreciation of inter-annual variability.

Data collected during the 1980s by the ISHTAR program (Turco, 1992a,b) suggests that large seasonal and inter-annual difference can occur in the northern Bering and southern Chukchi Seas, however their observations are problematic to fully interpret because they lacked a consistent set of stations on which to standardize their data. A major strength of this program is the use of a consistent sampling design capable of capturing differences in both timing and intensity of the planktonic communities and other ecosystem components. Observations concurrent with this study's September 2009 surveys conducted by NOAA's RUSALCA program show some interesting consistencies within their preliminary data (e.g. high abundances of the pteropod *Limacina helicina*, and low abundances of the larvacean *Oikopleura vanhoeffeni* in 2009). Physical, chemical and zooplankton data was collected near our study area by another NOAA program in 2010, and additional sampling by agencies is anticipated during 2011. A more complete and rigorous comparison of these datasets will be undertaken during the coming year, as well as comparison to other concurrent sampling efforts in the region.

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*Fig. 1.* Locations of the Klondike, Burger and Statoil survey grids in the northeastern Chukchi Sea. Survey grids are approximately  $900 \text{ NM}^2$ .

# Chlorophyll *a* (mg m<sup>3</sup>)



Fig. 2. Integrated chlorophyll a observed at the Klondike, Burger and Statoil areas during 2010.



*Fig. 3.* Chlorophyll and nitrate profile concentrations observed at the Klondike survey area during the August cruise 2010 (WWW1002).



*Fig. 4.* Silicate and phosphate profile concentrations observed at the Klondike survey area during the August cruise 2010 (WWW1002).



*Fig. 5.* Chlorophyll and nitrate profile concentrations observed at the Burger survey area during the August cruise 2010 (WWW1002).



# *Fig. 6.* Silicate and phosphate profile concentrations observed at the Burger survey area during the August cruise 2010 (WWW1002).



*Fig.* 7. Chlorophyll and nitrate profile concentrations observed at the Statoil survey area during the August cruise 2010 (WWW1002).



## Statoil August 2010

*Fig. 8.* Silicate and phosphate profile concentrations observed at the Statoil survey area during the August cruise 2010 (WWW1002)



Klondike September 2010

*Fig. 9.* Chlorophyll and nitrate profile concentrations observed at the Klondike survey area during the September cruise 2010 (WWW1003).



Klondike September 2010

*Fig. 10.* Silicate and phosphate profile concentrations observed at the Klondike survey area during the September cruise 2010 (WWW1003).



## Burger September 2010

*Fig. 11.* Chlorophyll and nitrate profile concentrations observed at the Burger survey area during the September cruise 2010 (WWW1003).


#### **Burger September 2010**

*Fig. 12.* Silicate and phosphate profile concentrations observed at the Burger survey area during the September cruise 2010 (WWW1003).



## Statoil September 2010

*Fig. 13.* Chlorophyll and nitrate profile concentrations observed at the Statoil survey area during the September cruise 2010 (WWW1003).



### Statoil September 2010

*Fig. 14.* Silicate and phosphate profile concentrations observed at the Statoil survey area during the September cruise 2010 (WWW1003).



*Fig. 15.* Chlorophyll and nitrate profile concentrations observed at the Burger survey area during the October cruise 2010 (WWW1005).



# *Fig. 16.* Silicate and phosphate profile concentrations observed at the Burger survey area during the October cruise 2010 (WWW1005).



*Fig. 17.* Contribution of the major groups to the community abundance at each survey grid during 2010 as determined for both plankton nets. Error bars are standard error of the means.



*Fig. 18.* Contribution of the major groups to the community biomass at each survey grid during 2010 as determined for both plankton nets. Error bars are standard error of the means.



*Fig. 19.* Relative contribution of major taxonomic groups to the community abundance captured by the 150  $\mu$ m net at each survey grid during 2010.



Fig. 20. Relative contribution of major taxonomic groups to the community biomass captured by the 150 µm net at each survey grid during 2010.



*Fig. 21.* Relative contribution of major taxonomic groups to the community abundance captured by the 505  $\mu$ m net at each survey grid during 2010.



Fig. 22. Relative contribution of major taxonomic groups to the community biomass captured by the 505 µm net at each survey grid during 2010.

#### 150 µm



*Fig. 23* Abundance of the dominant copepod species or genera during each survey grid in 2010 as captured by the 150  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 24.* Abundance of the dominant copepod species/stages, and non-copepod crustaceans during each survey grid in 2010 as captured by the 150  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 25.* Abundance of the dominant cnidarians, chaetognaths, larvaceans and pteropods during each survey grid in 2010 as captured by the 150  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 26.* Abundance of the dominant meroplankton during each survey grid in 2010 as captured by the 150  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig.* 27. Abundance of the dominant copepods during each survey grid in 2010 as captured by the 505  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 28.* Abundance of the dominant non-crustacean zooplankton during each survey grid in 2010 as captured by the 505  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 29.* Abundance of the dominant non-copepod zooplankton during each survey grid in 2010 as captured by the 505  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 30.* Station similarity as determined by hierarchical clustering of fourth-root transformed zooplankton abundance for the 150  $\mu$ m net. Red lines connect stations that are not statistically unique (P<0.05). Stations color-coded by survey grid to aid interpretation. Stations numbers are last two digits of sample ID number.



*Fig. 31.* Multidimensional scaling of zooplankton community abundances for the 150  $\mu$ m net based on clustering performed in Fig. 30. Axes are arbitrary, spacing of samples represents the best 2-D projection of the distance in similarity between each sample. Stations color-coded by survey grid to aid interpretation.



*Fig.* 32. Station similarity as determined by hierarchical clustering of fourth root-transformed zooplankton abundance for the 505  $\mu$ m net. Red lines connect stations that are not statistically unique (P<0.05). Stations color-coded by survey grid to aid interpretation. Stations numbers are last two digits of sample ID number.



*Fig. 33.* Multidimensional scaling of zooplankton community abundances for the 505  $\mu$ m net based on clustering performed in Fig. 32. Axes are arbitrary, spacing of samples represents the best 2-D projection of the distance in similarity between each sample. Stations color-coded by survey grid to aid interpretation.



*Fig. 34.* Contribution of the major groups to the community abundance during August at each survey grid spanning the 2008-2010 season as determined for both plankton nets. Error bars are standard error of the means.



*Fig. 35.* Contribution of the major groups to the community biomass during August at each survey grid spanning the 2008-2010 season as determined for both plankton nets. Error bars are standard error of the means.



*Fig. 36.* Contribution of the major groups to the community abundance during September at each survey grid spanning the 2008-2010 season as determined for both plankton nets. Error bars are standard error of the means.



*Fig. 37.* Contribution of the major groups to the community biomass during September at each survey grid spanning the 2008-2010 season as determined for both plankton nets. Error bars are standard error of the means.



*Fig. 38.* Contribution of the major groups to the community abundance during October at each survey grid spanning the 2008-2010 season as determined for both plankton nets. Error bars are standard error of the means.



*Fig. 39.* Contribution of the major groups to the community biomass during October at each survey grid spanning the 2008-2010 season as determined for both plankton nets. Error bars are standard error of the means.



*Fig. 40a.* Abundance of the dominant copepod and larvacean species during each survey grid spanning the 2008-2010 seasons as captured by the 150  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles.



*Fig. 40b.* Abundance of the dominant copepod and larvacean species during each survey grid spanning the 2008-2010 seasons as captured by the 150  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles.



*Fig. 40c.* Abundance of the dominant copepod and larvacean species during each survey grid spanning the 2008-2010 seasons as captured by the 150  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 41.* Abundance of the dominant meroplankton during each survey grid spanning the 2008-2010 seasons as captured by the 150  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 42.* Abundance of the dominant copepod species during each survey grid spanning the 2008-2010 seasons as captured by the 505  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 43.* Abundance of the dominant larvacean species and euphausiids (juveniles plus adults) during each survey grid spanning the 2008-2010 seasons as captured by the 505  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.



*Fig. 44.* Abundance of the dominant cnidarian, ctenophore and chaetognath species during each survey grid spanning the 2008-2010 seasons as captured by the 505  $\mu$ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25<sup>th</sup> and 75<sup>th</sup> percentile. Whiskers are the 10<sup>th</sup> and 90<sup>th</sup> percentiles and the single points are the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Features may be absent where number of samples with occurrence is low.





*Fig. 45.* Average size-spectra of the copepod community captured by the 150  $\mu$ m net for each survey year. Data is sorted into 50  $\mu$ m wide bins, gaps reflect an absence of data in that bin within the portion of samples examined.




*Fig. 46.* Average size-spectra of the copepod community captured by the 505  $\mu$ m net for each survey year. Data is sorted into 50  $\mu$ m wide bins, gaps reflect an absence of data in that bin within the portion of samples examined.



*Fig.* 47. Spatial distribution Bray-Curtis similarity clusters for the zooplankton communities collected by the 150  $\mu$ m nets in 2008 (filled symbols), 2009 (open symbols) and 2010 (line symbols). Symbol color is constant for each station/month combination.



*Fig. 48.* Spatial distribution Bray-Curtis similarity clusters for the zooplankton communities collected by the 505  $\mu$ m nets in 2008 (filled symbols), 2009 (open symbols) and 2010 (line symbols). Symbol color is constant for each station/month combination.

## 2008 Late ice retreat and low SST



*Fig. 49.* Possible mechanism driving inter-annual differences in zooplankton communities. Modified from G.L. Hunt.