

## **ECOSYSTEM CONSIDERATION INDICATORS FOR BERING SEA AND ALEUTIAN ISLANDS KING AND TANNER CRAB SPECIES**

E.A. Chilton, K.M. Swiney, J.D. Urban, and J.E. Munk

U.S. Department of Commerce  
National Oceanic and Atmospheric Administration  
National Marine Fisheries Service  
Alaska Fisheries Science Center  
301 Research Court, Kodiak, AK 99615

### **Summary of updates from the May 2011 SAFE**

Although the presentation of the final draft ecosystem chapter to the Crab Plan Team (CPT) is scheduled for May, the CPT asked for an update to this chapter before the final BSAI crab SAFE report is submitted to the Council in the fall.

*The CPT team discussed how ecosystem indicators would be useful in stock assessments and that it would be useful to compile information on how (if any) these indicators relate to crab stocks. The team recommends the author compile proposed ecosystem indicators and conduct a literature search on reference information to evaluate these in relation to crab stocks for September to facilitate team discussion of appropriate indicators.*

Two physical and two biological environmental indicators have been proposed as ecosystem indicators in the *Current Status of Ecosystem Indicators on 2010/2011* section of this document with supporting literature for BSAI crab stocks.

### **Summary of updates from the September 2010 SAFE**

The timing of the ecosystem chapter presentation to the Crab Plan Team (CPT) has been changed from September to May in order to include the most current environmental data as well as annual survey data from the previous summer. The *Current Status of Ecosystem Indicators in 2010/2011* has been updated with the 2010 summer survey data as well as the most recent environmental data available (winter 2011).

- Variability in benthic production in the EBS was examined and compared to male mature biomass of commercial crab stocks.

- An overview of the temporal changes in flatfish and other crab predators in the EBS along with mature male crab biomass is provided.
- Ecosystem indicators were selected in the *Current Status of Ecosystem Indicators in 2010/2011* section as they appear to correlate with patterns in crab abundance.
- The effects of bottom trawling on the benthic substrate are discussed in *Effects of Fishing Gear on Seafloor Habitat* section.
- Current ecosystem related research with respect to commercial crab stock in the the BSAI is listed in the *Current Status of Ecosystem Indicators in 2010/2011* section along with future research suggestions.

### **Responses to Comments from the Science and Statistical Committee (SSC)**

#### October 2010 SSC Comments

1. *The SSC commends the authors on advancing this section and has some recommendations for future consideration. The current section includes data through 2008-2009. It would be useful to add more current data, to the extent practicable.*

We agree with the SSC suggestion and have changed the timing of the ecosystem chapter presentation to the CPT from September to May in order to include the most current environmental data as well as annual survey data from the previous summer. The final Ecosystem chapter will be submitted to the NPFMC and the SSC after the September CPT meeting.

2. *The SSC also continues to encourage crab stock assessment authors to use the information within their individual stock assessments.*

This request is the intended outcome of this chapter. We will continue to work with the stock assessment authors to develop appropriate ecosystem indicators and information which may be useful to the stock assessment authors.

3. *There would be value in re-examining the prey used at all age classes of crab.*

We agree with making this important distinction in crab prey identification. Specific prey species consumed by EBS crabs are not well known and must be established before prey availability and trends can be determined. Some recent work at AFSC has begun on identifying prey items in adult Tanner crab stomachs. It is often difficult to identify masticated and semi-digested remains in crab stomachs; therefore genetic ID of Tanner crab stomach content is being pursued by the Kodiak Laboratory in collaboration with the AFSC Pathology Program.

*4. In the vicinity of the Pribilof Islands, there should be a concentrated effort to determine prey use by potential predators of crab, in particular PIBKC, to see if predation might be a contributor to the failure of this stock to meet rebuilding targets, particularly given the spatial changes in flatfish predators that may have occurred.*

Pacific cod have been identified as a primary king crab predator, especially after molting when the crab carapaces are soft and malleable while larval crab have been found in flatfish diets. Time series analysis of BKC year classes compared with Pacific cod and yellowfin sole year classes have not revealed any significant correlation between groundfish predation or competition and the decline in BKC stocks (Zheng and Kruse 2006). Given the recent change in flatfish distribution, future investigation would be beneficial and is listed as a future research priority in this document.

*5. In discussing recent trends in crab and the Bering Sea ecosystem, authors should recognize that the period 2000-2010 is comprised of two very different pentades: a warm one from 2001-2005 and a cold one from 2007-2010, with 2006 intermediate in conditions. Averaging over 2000-2010 for many aspects of the marine environment may prove misleading.*

We agree with your suggestions and apologize for any confusion that may have occurred by the impression of combining the two temperature pentades in the last decade. A majority of the trends discussed in this chapter recognize the two separate time periods with the different temperatures schemes.

## **Responses to Comments from the Crab Plan Team**

### September 2010 CPT Comments

*1. The CPT acknowledged the hard work in putting together this document by Liz and her colleagues. Suggestions were made from the CPT as to how to focus the chapter for future versions. One major recommendation was to remove crab stock assessment information and to focus on ecosystem issues.*

Thank you for the feedback, although the authors would like to acknowledge much of the initial ecosystem summary was developed by the CPT in their individual stock assessments. The overarching theme from the CPT at the September 2010 meeting was to focus this chapter on ecosystem issues common to crab stocks in the Bering Sea/Aleutian Islands and prevent duplication of information addressed in the individual stock assessment chapters. Under that direction, we have removed specific details or data relating to the individual crab stocks such as population assessments or bycatch mortality unless these data relate to an ecosystem trend or highlight a relationship with other ecosystem indicators.

*2. With regards to research priorities, which were taken from last year's Crab Plan Team minutes, the suggestion was to focus research priorities within this document on ecosystem issues.*

From this point forward, the section *Current crab ecosystem research and future priorities* will list the most current ecosystem oriented crab research as well as provide an opportunity for the CPT to describe future research priorities on crab ecosystem issues.

### **Ecosystem SAFE overview**

The objectives of this chapter are to assess the BSAI ecosystem trends, identify and provide annual updates of ecosystem status indicators and research priorities for BSAI crab stocks, and to update management status indicators. A summary of the most recent ecosystem trends affecting BSAI crab is summarized below with additional information detailed in the ecosystem considerations chapter.

#### *Recent trends in the 2010 ecosystem indicators (physical & biological)*

- The 2010/ 2011 winter in the Bering Sea was not as cold as expected from La Niña
- Sea ice coverage was not as extensive in January through March of 2011 compared to the previous five years although the sea ice edge advanced in April 2011
- Benthic invertebrate biomass has remained stable relative for the last five years, dominated by purple-orange sea star (*Asterias amurensis*) and other echinoderms.
- Groundfish biomass is increasing in the EBS, especially as Pacific cod biomass doubled from 0.42 t in 2009 to 0.86 t in 2010.

ECOSYSTEM CONSIDERATION INDICATORS FOR BERING SEA AND ALEUTIAN ISLANDS KING AND TANNER CRAB SPECIES .....	1
Summary of updates from the May 2011 SAFE.....	1
Although the presentation of the final draft ecosystem chapter to the Crab Plan Team (CPT) is scheduled for May, the CPT asked for an update to the ecosystem indicators be made to this chapter before the final BSAI crab SAFE report is submitted to the Council in the fall.....	1
Summary of updates from the September 2010 SAFE.....	1
Responses to Comments from the Science and Statistical Committee (SSC).....	2
Responses to Comments from the Crab Plan Team.....	3
Ecosystem SAFE overview.....	4
Introduction.....	7
Ecosystem Assessment .....	8
Purpose.....	8
Crab Life History .....	8
Physical Environment of the BSAI Ecosystem .....	8
<i>North Pacific Climate Historic Overview</i> .....	9
<i>Sea Ice Trends in the Eastern Bering Sea</i> .....	10
<i>Pelagic Habitat</i> .....	11
<i>Benthic Habitat</i> .....	12
<i>Ocean Acidification</i> .....	13
Biological Environment of the BSAI Ecosystem .....	14
<i>Crab Prey</i> .....	14
<i>Competitive Interactions</i> .....	16
<i>Predation by Groundfish, Marine Mammals and Seabirds</i> .....	18
<i>Predator Population Trends</i> .....	20
Physical and Biological Environmental Impacts on Crab Biology .....	21
<i>Recruitment of King and Tanner Crab</i> .....	21
<i>Growth</i> .....	23
<i>Maturity</i> .....	24
<i>Natural Mortality</i> .....	24
Current Status of Ecosystem Indicators in 2010/2011 .....	26
Purpose.....	26
Physical Environment of the BSAI Ecosystem in 2010/2011 .....	26
<i>North Pacific Climate</i> .....	26
<i>Sea Ice Cover and EBS Climate</i> .....	26
<i>2010 Summer Bottom and Surface Temperatures in the eastern Bering Sea</i> .....	26
<i>2010 Summer Bottom and Surface Temperatures in Norton Sound and Aleutian Islands</i> .....	27
Biological Environment of the BSAI Ecosystem .....	27
<i>Status of BSAI Epifaunal Prey and Competitors in 2010</i> .....	27
<i>Status of Crab Predators in 2010</i> .....	27
<i>Current Crab Ecosystem Research and Future Priorities</i> .....	28
Ecosystem-based Management Indicators.....	30
Purpose.....	32
Fishery-Specific Impacts on the Physical Environment .....	32

<i>Effects of Crab Fishing Gear on Seafloor Habitat</i> .....	32
<i>Management Enacted Efforts</i> .....	32
<i>Effects of groundfish Fishing Gear on Seafloor Habitat</i> .....	33
Fishery-Specific Impacts on Biological Environment.....	34
<i>Directed Fishery Contribution to Competitor and Predator Mortality</i> .....	34
<i>Directed Fishery Contribution to Discards and Offal Production</i> .....	35
<i>Groundfish and Scallop Fisheries By-Catch of Commercial Crab</i> .....	35
Fishery-Specific Impacts on Crab Biology.....	35
<i>Directed Fishery Effects of the Target Catch Relative to Predators</i> .....	35
<i>Directed Fishery Effects on Target Crab, Age-At-Maturity and Reproduction</i> .....	36
Literature Cited.....	38

## Introduction

The purpose of the Crab Ecosystem Consideration Indicators (CECI) report is to consolidate ecosystem information specific to the crab stocks in the Bering Sea and Aleutian Islands (BSAI) Fishery Management Plan. The BSAI Fishery Management Plan covers 10 stocks of crab representing five species: red king crab (*Paralithodes camtschaticus*; RKC), blue king crab (*Paralithodes platypus*; BKC), golden king crab (*Lithodes aequispinus*; GKC), southern Tanner crab (*Chionoecetes bairdi*), and snow crab (*Chionoecetes opilio*). The CECI report will serve as an appendix to the BSAI King and Tanner Crab Stock Assessment and Fisheries Evaluation (SAFE) document.

The objectives of this chapter are to assess the BSAI ecosystem trends, identify and provide annual updates of ecosystem status indicators and research priorities for BSAI crab stocks, and to update management status indicators. The format and organization of the CECI chapter are adapted from the Ecosystem Considerations Appendix to the BSAI and Gulf of Alaska Groundfish SAFE documents and the North Pacific Marine Science Organization (PICES) workshop on integrating ecological indicators of the North Pacific (Kruse et al. 2006). In order to avoid duplication of effort, sections in this document may occasionally refer to detailed reports from the Groundfish Ecosystem Considerations Appendix on topics specifically impacting crab ecology.

Beamish and Mahnken (1999) addressed incorporating the dynamics of an ecosystem, i.e. multispecies interactions and environmental variations, into stock assessments and resource management by discussing the need to understand natural influences which regulate a species as well as the influence from humans. Ecosystem-based management in the BSAI crab fisheries involves accounting for other influences on the target species beyond directed fishing. To address these influences, the CECI is composed of three main sections. First, the **Ecosystem Assessment** portion of the document provides a historical overview of the physical and biological environment of the BSAI ecosystem utilized by crab species as well as aspects of crab life history such as survival, recruitment, growth, maturity and natural mortality which are known to be impacted by changes in the BSAI ecosystem. The second section of the CECI, **Current Status of Ecosystem Indicators**, provides current information and updates on the status of the physical and biological components of the BSAI ecosystem. Physical components include pelagic and benthic habitat variables while biological components include prey availability and their abundance as well as distribution and abundance of competitors and predators. This section updates current research and identifies future research priorities for BSAI crab stocks with respect to ecosystem interactions. The final section, the **Ecosystem-based Management Indicators**, provides trends which could indicate early warning signals of direct fishery effects on crab-oriented BSAI ecosystem components, warranting management intervention or providing evidence of the efficacy of previous management actions. Specific indicators include the magnitude of directed fishery effects on BSAI habitat and resulting management efforts, and spatial and temporal removals of the target catch affecting other biological predators. In this section, we also review potential fishery effects on crab biology such as changes in age and size at maturity, and reproduction.

## Ecosystem Assessment

### Purpose

This section provides a historic overview of the physical and biological components in the BSAI ecosystem that are utilized by crab species at specific life stages. Three major crab life history stages, larval, juvenile and adult, utilize distinct components of the physical environment, both pelagic and benthic, as well as exhibit unique species interactions within the biological environment as prey, competitors and predators. The duration of the major life history stages are specific to each crab species (Fig. 1).

### *Crab Life History*

Larval stages are distributed according to vertical swimming abilities, the oceanographic currents, and mixing or stratification of the water column. Generally, the larval stages occupy the mixed layer near the sea surface except golden king crab larvae, which are fully lecithotrophic (yolk-nourishing) and are considered demersal (Shirley and Zhou 1997). Egg extrusion and hatching in RKC and BKC are relatively synchronous, although alternate year hatching has been observed in BKC (Somerton and MacIntosh 1985). Larval hatching in GKC is asynchronous with no apparent seasonal mating period in mature adults (Shirley 2006). After molting through multiple larval stages, crab settle on the seafloor. Settlement on habitat with suitable shelter, food, and temperature is imperative for survival of settling crab. Young of the year RKC and BKC require nearshore shallow habitat with significant cover that offers protection (e.g., sea stars, anemones, macroalgae, shell hash, cobble, and shale). Early juvenile stage Tanner and snow crab also occupy shallow waters and are found on mud habitat. Juvenile GKC have been observed on structure-forming sessile invertebrates growing on the sea floor, such as corals, sponges and sea-whips, which provide protection (Stone 2006).

King crab reproduction occurs between a soft-shelled female and hard-shelled male while Tanner and snow crab females exhibit a terminal molt and can store sperm to fertilize subsequent clutches or mate while hard-shelled. Tanner and snow crab mate in the middle shelf of the EBS while RKC and BKC mate in relatively shallow (< 50 m) nearshore areas (Somerton and MacIntosh 1985; Loher and Armstrong 2005; Orensanz et al. 2007). Golden king crab mate in deepwater canyons, along the slope of the EBS and on isolated seamounts (Shirley 2006). All crab species are highly vulnerable to predation and damage during molting. The benthic environment or habitat occupied by molting and mating crab differs from that occupied by mature crab during the remainder of the year.

### Physical Environment of the BSAI Ecosystem

The Bering Sea is semi-enclosed with a total area of 2.3 million km<sup>2</sup>, of which 44% is continental shelf, 13% is continental slope, and 43% is deep-water basin. The Aleutian Islands (AI) lie in an arc that forms a partial geographic barrier to the exchange of northern Pacific marine waters with EBS waters. The AI continental shelf is narrow compared with the EBS shelf, ranging in width on the north and south sides of the islands



from about 4 km or less to 46 km; the shelf broadens in the eastern portion of the AI arc. The AI archipelago comprises approximately 150 islands and extends about 2,260 km in length (Johnson 2003) (Fig. 2).

#### *North Pacific Climate Historic Overview*

Variation in climate and ocean dynamics have been implicated as important factors influencing crab recruitment in Alaska, with cold periods partially explaining strong recruitment events (Zheng and Kruse 2000). Air temperature anomalies over the last four decades in the EBS are characterized by a 1971-1976 cold period, a 1977-1988 warm period, a weaker cold period from 1989-1998, followed by warm years in 2000-2005 with a transitional year in 2006 to the cold period from 2007 to the present (Schumacher et al. 2003, NPFMC 2008). Overland et al. (1999) found three shifts of wintertime climate forcing patterns identified as: 1) 1967-1976 a positive Aleutian Low and mixed Arctic Oscillation, 2) 1977-1988 a negative Aleutian Low and negative Arctic Oscillation, and 3) 1989-1998 a mixed Aleutian Low and positive Arctic Oscillation. The negative Aleutian Low and negative Arctic Oscillation period from 1977-1988 is coincident with the warm period in the EBS while the mixed Aleutian Low and positive Arctic Oscillation in 1989-1998 is coincident with a colder period (Hare and Mantua 2000).

Bering Sea air temperatures have been warmer on average in the past decade (2000-2010) compared to the pre-1977 air temperatures. During this period, however, fluctuations included cooler air temperatures in the winter and spring 2007. (Wang et al. 2008). The last five years, 2006-2010, have been the coldest average surface air temperatures on St. Paul Island since pre-1978 conditions. Moderate El Niño conditions developed in the fall and winter of 2009/2010, resulting in a slight warming of the water temperatures in the Bering Sea (Overland et al. 2009).

A low Aleutian Low Pressure Index (ALPI) and relatively cool sea surface temperatures (SST) in the fall of 2008 contributed to a cold winter in the Bering Sea and extensive sea ice conditions persisted into the spring of 2009 with a prominent cold pool ( $< 2^{\circ}\text{C}$ ) residing on the middle shelf well into the summer (Bond and Overland 2009). The SST in the Aleutian Islands in the fall of 2008 was relatively warm compared to seasonal norms, then cooled to near normal temperatures by the summer of 2009. Southern wind anomalies prevailed throughout much of the winter of 2008/2009 in the western Aleutians followed by northern wind anomalies in the summer of 2009 compared to southeastern wind anomalies occurring for most of the winter and spring of 2009 in the eastern Aleutians. This difference in prevailing wind direction resulted in suppressed storm activity in the eastern Aleutians and along the Alaska Peninsula (Bond and Overland 2009).

It is generally acknowledged that the global climate is changing and those changes are driving marine ecosystems toward conditions not seen in historic times. The effects on BSAI crab stocks will be both direct and indirect due to changes in temperatures, winds, storm intensity, salinity, stratification, pH, and abundance of suitable physical habitat. There is, however, considerable uncertainty over the spatial and temporal distribution of the effects of changing climate on marine ecosystems (Brander 2010, Hoegh-Guldberg

and Bruno 2010). In the EBS, increases in air temperature, storm intensity, storm frequency, southerly wind, humidity, and precipitation are anticipated. The increased precipitation, plus snow and ice melt, leads to an increase in freshwater runoff (Barange and Perry 2009). The only atmospheric change showing a decrease is sea level pressure, which is associated with the northward shift in the storm track. Ocean circulation decreases are likely to occur in the major current systems: the Alaska Stream, Near Strait Inflow, Bering Slope Current, and Kamchatka Current. Competing effects make changes in the Unimak Pass inflow, the shelf coastal current, and the Bering Strait outflow unknown. Changes in hydrography should include increases in sea level, sea surface temperature, shelf bottom temperature, and basin stratification. Decreases should occur in mixing energy and shelf break nutrient supply, while competing effects make changes in shelf stratification and eddy activity unknown. Ice extent, thickness, and brine rejection are all expected to decrease (Barange and Perry 2009).

When considering the effect of climate change on BSAI crab stocks, differing time scales will have different management implications (Brander 2010). At short time scales (i.e., 1-5 years), the effects of long-term climate change can be relatively unimportant but the frequency of extreme conditions such as abnormally warm winters with minimal ice cover in the Bering Sea or a regime shift can have major consequences on the recruitment of a particular year class of crab. At medium-term time scales (~ 5-25 years) which span several generations of crab, changes in climate affect the basic productivity of the marine ecosystem (King 2005) and consequently crab rebuilding plans and biological reference points used in the assessment process. The long term impact of climate change on crab stocks will undoubtedly be very large, but the uncertainty associated with that change is also very large. Responses may be nonlinear and have greater impact on populations that may be less resilient (Brander 2007).

#### *Sea Ice Trends in the Eastern Bering Sea*

The extent and timing of the retreat of sea ice in the Bering Sea determines the strength and fate of the spring phytoplankton bloom which in turn can have a major impact on the survival of larval crab and the whole food web structure (Hare et al. 2007). The extent of sea ice coverage is variable and related to the location of the Aleutian Low and Siberian High which typically produce northeast winds in the winter that freeze the seawater and push the ice southwestward (Stabeno et al. 2001). During 1971-1976, extensive ice coverage on the Bering Sea shelf extended south and west, beyond the slope, and remained around St. Paul Island for more than a month in the spring. During the next cold phase from 1989-1998, 2-4 more weeks of ice were observed at the 59°N parallel than during the previous decade (Schumacher et al. 2003).

The Ice Retreat Index, defined by Overland et al. (2008) as the number of days with sea ice coverage after March 15<sup>th</sup> within the vicinity of king crab mooring 2A (KC-2A, Fig. 2), increased in 2006-2010 compared to the previous five years. This increase drives the recent trend in colder water temperatures and high ice coverage, if the ice cover is not extensive or retreats early in the spring, a shift occurs from ice-edge blooms to later open-water blooms (Hunt et al. 2010). The Ice Cover Index represents the average ice concentration from Jan 1 to May 31<sup>st</sup> in a 2° x 2° box (56-58°N, 163-165°W) for 1978-2008 relative to the 1981-2000 mean index of 7.15 (SD = 4.01) (Overland 2008). The

presence of sea ice in 2007 (Fig. 3) along with below normal ocean temperatures likely resulted in the first ice-edge bloom since 1999 (Wang et al. 2008).

The seasonal melt and retreat of the sea ice edge leaves low saline and less dense water at the surface and the increased warming creates a stratified water mass of cold, dense seawater at the bottom of the seafloor. This cold pool ( $< 2^{\circ}\text{C}$ ) extends over a large portion of the EBS and has extended into Bristol Bay during the summer months, particularly in 1999-2000 and again in 2007-2010 as shown by bottom temperatures recorded at KC-2A (Fig. 4). As a response to changing water temperatures, the ecosystem in the Bering Sea is shifting northward (Overland and Stabeno 2004). Changes in the location of the cold pool alter the composition of the arctic and subarctic marine communities, but the response among taxa is variable and difficult to predict (Aydin and Mueter 2007; Mueter and Litzow 2008).

Wang et al. (2010) predict an approximately 40% reduction in Bering Sea sea ice coverage by 2050. Long-term changes in sea ice cover may affect benthic communities because much of the production from retreating ice edge spring blooms sink to the bottom, but if these blooms do not occur there may not be sufficient phytoplankton falling to the benthos to support abundant communities (Lovvorn et al. 2005).

#### *Pelagic Habitat*

During their larval stages, crab utilize the pelagic habitat of the Bering Sea and Aleutian Islands (Fig. 1, except Golden King Crab-see *Crab Life History* above). The pelagic habitat is vast and dynamic but many aspects of this habitat affecting larval survival are poorly understood. Kinney et al. (2009) presented an updated description of the general circulation of the Bering Sea and Aleutian Islands based upon recent modeling. The Alaskan Stream is the strongest current in the region and brings water from the North Pacific through Unimak Pass and Amukta Pass northward into the Bering Sea. The Alaska Coastal Current also supplies water from the North Pacific to the Bering Sea through Unimak Pass. The shelf break region is characterized by the Bering Slope Current which extends from the eastern Aleutian Islands along the shelf break toward the coast of Siberia near Cape Navarin and flows to the northwest (Fig. 2).

The shelf of the Bering Sea is divided into three depth domains each with distinct circulation patterns and hydrographic (temperature and salinity) characteristics. The coastal shelf domain (0-50 m) is characterized by one well mixed layer. In the middle shelf domain (50 to 100 m), a two-layer temperature and salinity structure exists because of wind which mixes the upper water column and tidal currents which mix the lower layer. In the outer shelf domain (100 to 180 m), a three-layer temperature and salinity structure exists due to wind mixing the upper water column, tidal currents mixing the lower layer and a middle layer that is not well mixed (Stabeno et al. 2001). The majority of the Norton Sound bathymetry is dominated by shallow depths, between 0 and 50 m, with one well mixed layer influenced by the freshwater driven Alaska Coastal Current as it flows north to the Bering Strait (Fig. 2).

Snow crab and RKC larvae have been shown to have strict survival tolerances to extremes in salinity (Shirley and Shirley 1989, Charmantier and Charmantier-Daures

1995) but the effects on survival due to variable salinity in the BSAI have not been demonstrated. Along the edge of the EBS shelf in the Alaska Stream, a low salinity tongue-like feature (less than 32.0) protrudes westward towards the EBS slope. On the south side of the central AI, nearshore surface salinities can reach as high as 33.3, as the higher salinity EBS surface water occasionally mixes southward through the AI passes. Proceeding south and west, a minimum of approximately 32.2 is usually present over the slope in the Alaska Stream and values rise to above 32.6 in the oceanic water offshore with salinity increasing towards the west as the influence of fresh water from the land decreases (Ladd et al. 2005).

High primary productivity along the shelf edge is maintained by vertical nutrient supply to the subsurface layer and shelf to slope exchange occurring with an increase in the Bering Slope Current transport and eddy fluctuations (Mizobata and Saitoh 2004). Vertical mixing of nutrient-rich deep Bering Sea water can enhance productivity in regions of the Bering Sea including around St. Lawrence Island and the Pribilof Islands (Stabeno et al. 2008, Kinney et al. 2009). Eddies along the southern edge of the Aleutian Islands influence the advection of both nutrients and water temperatures into the Bering Sea (Maslowski et al. 2008; Okkonen 1996). Cold, deep-water, high in nutrients, moves through the Aleutian Island passes and mixes with surface water in the Bering Sea. Water within these deep gullies and passes is highly mixed, resulting in low productivity, but as this water moves northward and becomes stratified, high-nutrient water is brought to the surface of the Bering Sea (Ladd et al. 2005).

#### *Benthic Habitat*

McConnaughey and Smith (2000) and Smith and McConnaughey (1999) synthesized the available sediment data for the EBS shelf. These data were used to describe four habitat types (Fig. 5). The first, situated around the shallow eastern and southern perimeter and near the Pribilof Islands, has primarily sand substrates with a little gravel. The second, across the central shelf out to the 100 m contour, has mixtures of sand and mud. A third, west of a line between St. Matthew and St. Lawrence Islands, has primarily mud (silt) substrates, with some mixing with sand. Finally, the areas north and east of St. Lawrence Island, including Norton Sound, have a complex mixture of substrates. The AI region has complicated mixes of substrates, including a significant proportion of hard substrates (pebbles, cobbles, boulders, and rock), but data are not available to describe the spatial distribution of these substrates.

Juvenile BKC have a mottled color pattern that blends into the background epifauna and, specifically, shell hash habitat may be important to juvenile BKC as a refuge from predators. Juvenile BKC likely require cover afforded by shell hash due to a lack of long spines and the lightly mottled carapace blends in with shell hash (Armstrong et al. 1985; Palacios et al. 1985). Survival in juvenile BKC is linked to the abundance of shells of certain mollusk species, including mussels (*Modiolus modiolus*), scallops (*Chlamys sp.*), rock oysters (*Pododesmus macrochisma*), and hairy tritons (*Fusitriton oregonensis*) (Palacios et al. 1985). This type of epifauna is scarce in offshore, sandy environments. Habitat of adult BKC is primarily composed of hard substrate such as cobble, gravel and rock found in the shallow (< 50 m) waters surrounding St. Matthew and the Pribilof Islands (Zheng et al. 1997).

Juvenile RKC have been shown to prefer nearshore habitats of high complexity (Dew 1990; Loher and Armstrong 2000) which includes a well-developed community of living substrate, such as hydroids, bryozoans and sponges. Juvenile RKC at the early post-settlement stage (< 10 mm CL) have strong preferences for structurally complex habitat with biogenic structure that provide foraging opportunities as well as protection from predation (Pirtle and Stoner 2010). Adult RKC move to soft bottom substrates further offshore (Rodin 1989). Tanner and snow crab juveniles are reported to prefer homogenous mud substrate (Dionne et al. 2003) or mud, silt, and sand (Rosenkranz et al. 1998). Adults prefer a similar habitat, with Tanner crab found primarily in a sand-mud substrate (Zhou and Shirley 1998) and snow crab generally occurring in the northwestern area of the Bering Sea although their ranges overlap (Slizkin 1989). Juvenile GKC have been seen associated with hexactinellid sponges *Aphrocallistes vastus* and *Heterochone calyx* (Stone 2006), while adults are associated with cold-water corals including *Primnoa* (Krieger and Wing 2002).

Changes in bottom water temperatures impact the amount of benthic habitat available to crab species. Over the last three decades, distribution of mature female snow crab in the EBS shifted in relation to changing water temperatures. Increased water temperatures in the mid-1980s resulted in a shift of mature female snow crab to the northwest EBS shelf while the more recent temperature decrease in the last decade did not result in a return of mature females to their historical distribution (Orensanz et al. 2004). See *Recruitment of King and Tanner Crab* section below for more details.

The Bristol Bay mean bottom water temperature collected over the last decade in early June on the NMFS Alaska Fisheries Science Center (AFSC) EBS bottom trawl survey ranged from lows of 1.8°C (SD = 1.6) in 2010 to 2.2°C (SD = 0.7) in 2006 compared to warmer temperatures ranging from 3.5°C (SD = 0.3) in 2001 to 4.3°C (SD = 0.5) in 2005. These cold temperatures in the summer reflect the extent of the sea ice coverage from 2006 to 2010 compared to the warmer bottom water temperatures from 2001 to 2005.

Based on data collected during the biennial AI bottom trawl survey from 1994 to 2006 and standardized to a median date of July 10<sup>th</sup>, water temperatures both at the surface and in deeper depths were warmest in 1997, followed by 2004 compared to the other years (Martin 2010). Average bottom water temperatures collected on the Norton Sound trawl survey in late summer have fluctuated between 9.0 °C to 5.6 °C over the last two decades, with an average of 7.1°C bottom water temperature from the most recent Norton Sound triennial bottom trawl survey in 2008 (Hamazaki et al. 2005; Soong 2008).

### *Ocean Acidification*

Since the start of the industrial revolution in the late 18<sup>th</sup> century, anthropogenic activities, including the burning of fossil fuels and the production of cement have released CO<sub>2</sub> into the atmosphere and the world's oceans have taken up approximately 30% of this CO<sub>2</sub> (Feely et al. 2004; Sabine et al. 2004). When CO<sub>2</sub> dissolves in seawater, the pH is lowered and is known as ocean acidification. The pH of the world's ocean have lowered by approximately 0.1 units since the industrial revolution and is predicted to drop by 0.7 units over the next two and a half centuries (Caldeira and Wickett 2003). In the North Pacific Ocean the saturation depth is relatively shallow due to the cold

temperature and age of advected deep water masses. This combination of factors means that these waters may become constantly undersaturated for aragonite by mid-century and for calcite by the end of the century (Fabry et al. 2009; Feely et al. 2009). This rapid decline in ocean pH will likely have strong effects on marine species and substantially alter marine ecosystems (Doney et al. 2009; Raven et al. 2006)

### Biological Environment of the BSAI Ecosystem

#### *Crab Prey*

Information on BSAI crab food habits is limited; however, it is known that crab diets vary with life stage and in general crab are opportunistic omnivorous feeders, eating a wide variety of microscopic and macroscopic plants and animals. Red king crab, BKC, Tanner and snow crab larvae are planktonic feeders and consume both phytoplankton and zooplankton including diatoms, algae and copepods (Bright 1967, Paul et al. 1979, Abrunhosa and Kittaka 1997). Golden king crab larvae are considered lecithotrophic which are non-feeding and survive on yolk reserves (Shirley and Zhou 1997). The glaucothoe stage of RKC and BKC, their last larval stage, is non-feeding (Epelbaum et al. 2006).

Increased primary production could result in increased phytoplankton and zooplankton prey items for crab larvae. Nutrient supply and productivity in the Bering Sea is related to ice coverage, currents and eddies (see above, *Sea Ice Trends in the Eastern Bering Sea*). When sea ice coverage over the southeast Bering Sea shelf occurs in March/April, a strong phytoplankton bloom occurs. In the absence of sea ice, the bloom does not occur until May/June and is typically weaker (Stabeno et al. 2001). For example, timing of the expansion and contraction of EBS sea ice coverage in 1997 was favorable for a phytoplankton bloom but not in 1998 or 1999 (Rho et al. 2005). The premature contraction of the sea ice coverage in 1998 and 1999, combined with strong mixing due to high winds, may have prevented the development of density-driven stratification, and resulted in higher nitrate concentrations with a lack of an obvious spring bloom (Rho et al. 2005).

Changes in the zooplankton community in the eastern Bering Sea may have an effect on RKC, BKC, Tanner and snow crab larvae which consume both phytoplankton and zooplankton. A decline of the euphausiid *Thysanoessa raschii* throughout the middle domain of the EBS shelf as well as coastal areas was discovered in the diet of short-tailed shearwaters during the late 1990s (Hunt et al. 2002). More recently, declines in summer zooplankton biomass have been linked to the warm years of 2001-2005 in the eastern Bering Sea (Renner et al. 2008). Part of the decrease in biomass over the middle shelf was most likely due to decreases in the abundance of *Calanus marshallae*, the only “large” copepod found in that area, and euphausiids (Renner et al. 2008). After a six year period of relatively low biomass, the EBS zooplankton began increasing on the middle shelf during the cold period of 2006-2008 (Napp and Yamaguchi 2008) and more recently, the biomass of *Calanus* spp. increased 10 fold by 2009 compared to the previous warm years. Unfortunately, due to a reduction in ship time, no samples were collected on the EBS shelf in 2010.

Juvenile and adult crabs are opportunistic omnivorous scavengers. Juveniles consume benthic prey such as diatoms, foraminifera, copepods, algae, sponge, bryozoans, hydroids, polychaetes, small bivalves, snails, seastars, ophiuroids, echinoids, barnacles, crab, and sediment; detritus may also be a major component of their diet (Feder et al. 1980, Feder and Jewett 1981, Paul 1982). Cannibalism has been documented for juvenile RKC held in laboratory settings while examining early post-settlement juveniles and habitat preference (Stevens and Swiney, 2005; Stoner et al. 2010). The predominant prey of adult red king crab are bivalves, barnacles, polychaetes, hydroids, gastropods, amphipods, crabs, brittle stars, sand dollars and sea urchins (reviewed in Jewett and Onuf 1988). The predominant prey of adult Pribilof Islands blue king crab are fish, barnacles, hydroids, brittle stars, bivalves, crabs, polychaetes, sea stars, and amphipods (ADFG unpublished data). Stomach contents of Tanner crab near Kodiak Island had predominantly arthropods by weight (primarily juvenile Tanner crab); followed by fish and mollusks (Jewett and Feder 1983).

Adult snow crab in the EBS eat polychaetes, bivalves, detritus and other benthic prey (Aydin et al. 2007), which is similar to the most frequently occurring prey of adult snow crab from the Newfoundland shelf of polychaetes, shrimp, crab, small crustaceans, infaunal clams, and fishes (Squires and Dawe 2003). The diet of snow crab in the northern Bering Sea includes the most dominate prey available and changes ontogenetically, with smaller snow crab (< 50mm CW) eating amphipods and thin shelled bivalves while larger prey were found in the larger snow crab diets, such as bivalves, gastropods, polychaetes, brittle stars, and decapod crustaceans, (Lovvorn 2010). Additionally, cannibalism was found to provide a major food source for adult snow crab in the Gulf of the St. Lawrence (Lovich and Sainte-Marie 1997).

A small number of BKC (28) and RKC (32) stomachs were collected by Alaska Department of Fish and Game (ADF&G) on the 2003 Pribilof Islands pot survey with prey analysis conducted by a marine taxonomist at the University of Alaska Fairbanks (unpublished data). Information on the distribution of the most frequently observed prey items from this study such as teleost tissue, barnacles, hydroids, Ophiuroidea (brittle stars), gastropod fragments, and polychaetes around the Pribilof Islands is limited.

The most complete description of benthic infaunal prey distribution in the EBS, such as polychaetes, other worms, and bivalves, comes from grab samples collected in 1975 and 1976 (Halflinger 1981), followed by a description of polychaete assemblages collected from a small section of the south-eastern portion of the Bering Sea in 2006 (Yeung et al. 2010). Polychaete families were associated with sediment type or benthic substrate based on their functional ecology such as burrowers in mud and sand or mobile species distributed on hard substrate. Coyle et al. (2007) compared late 1950s to mid 1970s benthic infaunal data from the southeastern Bering Sea shelf and found a trend toward higher overall infaunal biomass during the mid 1970s among carnivores, omnivores, and surface detritivores. The 1970s data was collected during a cold period which suggests a link between temperature and infaunal biomass. During cold periods, infaunal biomass is predicted to increase due to elevated carbon flux to the benthos and a reduction in groundfish predators due to cold bottom water (Coyle et al. 2007).

On the annual EBS bottom trawl survey, the catchability of most epibenthic crab prey is low but still accounted for 23% of the total demersal animal biomass (15.4 million t) in 2007, 24% (14.3 million t) in 2008 and 13% (0.70 million t) in 2009 (Acuna and Lauth 2008; Lauth and Acuna 2009; Lauth 2010). The majority of the invertebrates in 2009 were asteroid seastars, brittle stars, and sea urchins at 1.5 million t followed by crustaceans at 0.71 million t (Lauth 2010).

Variability in benthic production in the EBS, such as changes in epibenthic prey and benthic-foraging invertebrates, has been suggested as an important ecosystem indicator of productivity for commercial crab stocks, as crab are primarily benthic predators and crab production is likely influenced by benthic production. Invertebrates identified on the EBS bottom trawl survey from 1982 to present provide the most complete dataset available of trends in the benthic community. Asteroid seastars and brittle stars have been identified as crab prey and, excepting crab, are also the most abundant epifaunal invertebrates sampled by the AFSC EBS bottom trawl survey. The purple–orange sea star (*Asterias amurensis*) is distributed along the middle and coastal shelf domain of the EBS while the notched brittle star (*Ophiura sarsi*) is found primarily in the middle shelf domain, two areas which are also important for commercial crab stock on the EBS shelf. The mean CPUE of the purple–orange sea star caught on the EBS bottom trawl survey increased during the warm years of 2001–2005 followed by a decrease in 2006 and continuing in the cold years of 2007–2009, with a slight increase in 2010 (Fig. 6). Slight changes in the mean CPUE of the notched brittle star during the same time period does not appear to be associated with the two temperature regimes in the EBS although the mean CPUE is greatly reduced in 2009 and at the lowest level in 2010 (Fig. 6).

### *Competitive Interactions*

Forage fish are planktonic feeders and may be competitors or predators for larval crab. Abundance trends of forage fish species for the EBS have been examined using data obtained on the AFSC EBS bottom trawl survey from 1982–2009. In general, abundance estimates of stichaeids and Pacific sand lance (*Ammodytes hexapterus*) were higher from 1982–1998 and lower from 1999–2009. Eulachon (*Thaleichthys pacificus*) abundance has been variable from 1982–2009 with the lowest years of abundance observed in 1985, 1989, 2008 and 2009 and the highest abundance years were 1984, 1991, and 1997 while capelin (*Mallotus villosus*) abundance has been low except for 1993 (Gaichas and Bolt 2009; Lauth 2009).

Abundance indices of other planktonic feeders in the EBS such as juvenile sockeye salmon (*Oncorhynchus nerka*), age-0 walleye pollock (*Theragra chalcogramma*), and age-0 Pacific cod (*Gadus macrocephalus*) were estimated from surface trawl data collected in the fall of 2002–2007 on the Bering-Aleutian Salmon International survey (BASIS). In warm water years, 2002–2005, juvenile sockeye salmon and age-0 pollock abundance increased and were widely distributed throughout the EBS shelf compared to decreased abundances in cold water years, 2006 and 2007, when juvenile sockeye salmon were primarily found in the inner Bristol Bay waters and age-0 pollock were restricted to the middle domain of the EBS. The abundance of age-0 Pacific cod fluctuated throughout the six year period with a relatively high number caught in 2005 and again in 2006 (Farley et al. 2008).



The 2008-2009 age-0 pollock year classes estimated from the EBS bottom trawl survey at 440 and 701 million fish respectively, decreased significantly compared to the 2007 estimate of 1,665 million fish (SAFE: Ianelli et al. 2009). The 2008-2009 year class of age-0 Pacific cod has been estimated to be a large year class by the Pacific cod stock assessment model, although the year class has only been observed once and the estimate is bounded by large confidence intervals (SAFE: Grant et al. 2009).

Benthic-foraging epibenthic invertebrates are likely competitors with juvenile and adult king, Tanner and snow crab for food. Examination of epibenthic invertebrate catches from the AFSC EBS bottom trawl survey 1982-2002 found distinct inshore and offshore communities that are separated by an oceanographic front occurring at the 50 m isobath. The biomass of the inshore community is dominated by seastars and the offshore community is dominated by snails, hermit crabs and snow crab (Yeung and McConnaughey 2006). Variations in this inshore and offshore community structure occur with a reduction in the spatial extent of the inshore community when mean bottom temperatures in the survey area were higher than normal the preceding summer. During these events, epibenthic invertebrates such as red king crab in Bristol Bay shifted from inshore communities to either offshore or undefined communities (Yeung and McConnaughey 2006). Yeung and McConnaughey (2006) concluded that epibenthic communities in the EBS may be rearranged by mobile epibenthic invertebrates, primarily crab, migrating offshore toward cooler water in warm years.

Marine benthic snails from the genus *Neptunea* are ubiquitously distributed throughout the EBS shelf and represent a significant element of the motile benthic epifauna in the EBS benthic ecology (Smith and Armistead *in review*). As a carnivorous benthic forager (Shimek 1984), *Neptunea* species are a good candidate for reflecting changes in benthic productivity. While some *Neptunea* have been identified to species on the EBS trawl survey over the last thirty years, analysis of confidence in the consistent identification of *Neptunea* to the species level resulted in a low confidence report while identification of *Neptunea* to the family level resulted in a high confidence report (Stevenson and Hoff 2009). Changes in the mean CPUE of *Neptunea* snails caught on the EBS bottom trawl survey were negligible during the last two pentades within 2000-2010, although higher CPUE were observed from 1987 through 1992 (Fig. 6). The motile benthic epifauna as a whole has been assessed as a stable foraging guild in the more recent time period of 2005-2010 with mean biomass, catch and exploitation rates within  $\pm$  one standard deviation of 1977-2010 levels (SAFE; Zador and Gaichas 2010).

Comparisons of two of the most abundant benthic epifaunal species, the purple–orange sea star and the notched brittle star, and *Neptunea* from the Buccinidae family with mature male biomass of Tanner, snow and Bristol Bay RKC from 1982 to 2010 did not elucidate any trends in benthic productivity or highlight a relationship between these benthic species (Fig. 7). Further analysis of the relationship between these epibenthic organisms on a smaller spatial scale would be beneficial and is listed as a future research priority in this document.

Benthic foragers such as flatfish, skates, and other invertebrates including crab species may compete with juvenile and adult crab for food. Juvenile flatfish including rock sole

(*Lepidopsetta* spp.), yellowfin sole (*Limanda aspera*), Pacific halibut (*Hippoglossus stenolepis*) and flathead sole (*Hippoglossoides elassodon*) consume polychaetes, bivalves, snails, and crustaceans (Holladay and Norcross 1995). Adult flatfish and skates consume benthic prey such as snails, clams, shrimp, crabs, fish, brittlestars, and polychaetes (Yang 2003). Refer to the *Predation by Groundfish, Marine Mammals and Seabirds* section for population trends as these species are both competitors and predators of crab.

#### *Predation by Groundfish, Marine Mammals and Seabirds*

During each life history stage, from the pelagic larvae to benthic adults, crab are consumed by different predators contributing in part to the natural mortality of these species. Other factors contributing to natural mortality in crab are discussed in the *Physical and Biological Environmental Impacts on Crab Biology* below. For king crab, numerous planktivorous fishes prey on Paralithodid larvae (Livingston et al. 1993; Weststad et al. 1994). The size of Paralithodid prey in yellowfin sole and walleye pollock stomachs indicates they feed on larval and very early juvenile king crab (Livingston et al. 1993). Juvenile king crab may fall prey to Arrowtooth flounder (*Atheresthes stomias*), Irish lords (*Hemilepidotus* sp), snailfish (*Liparis* sp.), and octopus (*Enteroctopus dofleini*) (Livingston and Goiney 1983) but as the crab grow larger, they begin to exceed the mouth gape of many of these predators. Juvenile RKC experienced mortality due to cannibalism by older RKC in laboratory experiments (Stevens and Swiney 2005). However, juvenile king crab are usually found in shallow, nearshore waters (RKC, and BKC) or deepwater canyons (GKC) and outside of the annual bottom trawl survey area where a majority of the stomach samples are collected for food habits analysis, thus the potential of juvenile king crab as prey in these collections is greatly reduced.

A high number of early juvenile Tanner and snow crab age 0 to age 1 are consumed by Pacific cod in the eastern Bering Sea (Lang et al. 2005). It was estimated that cod removed up to 94% of age 1 Tanner crab and up to 57% of snow crab in the Bering Sea in a single year (Livingston 1989). A seasonal study in the Gulf of Alaska showed the primary prey item of Pacific cod were early juvenile Tanner crab ( $\leq 45$  mm CW), both by weight and number (Urban 2010). Over the last thirty years, an increase in Tanner and snow crab mature male biomass from the EBS trawl survey is evident with a decrease in the Pacific cod biomass. When the Pacific cod biomass is time lagged three years to represent the juvenile crab predation, a more prominent trend reflects the impact these predators have on the smaller size classes which results in an increase or decrease in recruitment to maturity (Fig. 8). A similar trend of declining Bristol Bay RKC recruitment was found with increasing Pacific cod and yellowfin sole biomass (Zheng and Kruse 2000, 2006). The affect of yellowfin sole as a predator of juvenile Tanner and snow crab is not evident in this time series using a three-year lag on the predator, although yellowfin sole could be competing with adult Tanner and snow crab for the same prey (Fig. 9).

Other groundfish species such as; Alaska plaice (*Pleuronectes quadrituberculatus*), Arrowtooth flounder, flathead sole, northern rock sole (*Lepidopsetta polyxystra*), Pacific halibut, and yellowfin sole, also consume juvenile snow and Tanner crab, based on

stomach contents data (Lang et al. 2003). Tanner crab were observed as a small percentage in the diet of Big skates (*Raja binoculata*), Aleutian skates (*Bathyrāja aleutica*), Bering skate (*Bathyrāja interrupta*) and Alaska skates (*Bathyrāja parmifera*) collected on the AFSC Aleutian Island bottom trawl survey in 1994, 1997, 2000 and 2002 (Yang 2007). These predators may have an impact on the recruitment of juvenile Tanner and snow crab.

Pacific cod and large sculpins prey on adult king, Tanner and snow crab (NPFMC 2003, Aydin et al. 2007) but adult crab are relatively invulnerable to predation except after molting when they are in a soft shell state (Blau 1986, Livingston 1989, Loher et al. 1998). Because molting typically occurs in the spring and stomach samples are collected during the summer EBS and AI surveys, records of predation on adult crab occur infrequently in the AFSC food habits database.

Records of predation on golden and blue king crab are rare. The Resource Ecology and Ecosystem Modeling Program at AFSC collected stomachs on the EBS bottom trawl survey from over 100 species, yet BKC were found only in Pacific cod, walleye pollock and yellowfin sole stomachs. From 1981 to 2005, 5 Pacific cod, 27 walleye pollock and 8 yellowfin sole contained BKC prey from a total of 13,831 stomach samples with Pacific cod having the largest amount of BKC by weight (AFSC, REEM food habits database). One golden king crab was found in a white-blotched skate (*Bathyrāja maculata*) stomach from the 612 samples collected from along the Kuril Islands and southeast Kamchatka during 1996 (Orlov 1998). Simenstad et al. (1977) assessed the AI marine food web in the vicinity of Amchitka Island and reported 6 instances of GKC and RKC in 69 halibut stomachs examined from inshore areas.

Coincident with the decline of Pribilof Islands blue king crab in the early 1980s, the abundance of Pacific cod and flatfish species increased dramatically in the late 1970s and early 1980s and has generally been high ever since; the influx of rock sole in the Pribilof Islands area has been particularly high (NPFMC 2003). A cause and effect relationship between the decline in BKC stock and the increase in the stocks of groundfish that are predators of and competitors with king crab remains speculative. Time series analysis of BKC year classes compared with Pacific cod, yellowfin sole, and rockfish (*Sebastes* spp.) year classes have not revealed any correlation between groundfish predation or competition and the decline in BKC stocks. Increases in Pacific cod and yellowfin sole biomass was associated with lower RKC recruitment (Zheng and Kruse 2000; Zheng and Kruse 2006). Correlations between Pacific cod biomass and Bristol Bay RKC recruitment with recruitment time lags from ages 0 to 3 and yellowfin sole biomass with recruitment time lags from ages 0 to 2 were statistically significant (Zheng and Kruse 2006). The spatial distribution of yellowfin sole and Bristol Bay RKC overlap in the southeastern section of Bristol Bay and this area of overlap has not changed substantially over time. This research is discussed in more detail in *Recruitment of King and Tanner Crab* section.

As benthic foragers, Arctic ice seals, such as bearded seals (*Erignathus barbatus*) and ribbon seals (*Phoca fasciata*), could be both competitors as well as predators of snow crab. Bearded seals are primarily found on ice floes in circumpolar arctic and subarctic

waters migrating as far south as 57°N with the advancing ice edge in the spring. Ribbon seals stayed in the ice-free waters out towards the shelf break in the late spring and summer, after the ice edge begins to retreat (Cameron and Boveng 2009; Cameron et al. 2009). Bearded seals feed at depths less than 200 m with a diet composed of shrimp, crabs, clams and gastropods such as whelks while ribbon seals primarily eat groundfish, shrimp and some crustacean species (Lowry et al. 1980; Cameron et al. 2009).

The short-tailed shearwater (*Puffinus tenuirostris*) represents a major portion of the marine bird biomass in the southeastern Bering Sea. In the late 1990s the bird's diet was examined after a rapid decline of the species in the southeastern Bering Sea. The expected prey species, euphausiids (*Thysanoessa raschii*), was not predominant after 1997. The birds were feeding primarily on Pacific sandlance in the summer as well as crab zoea and copepods in the inner domain of the EBS (Hunt et al. 2002).

### *Predator Population Trends*

Estimates from EBS bottom trawl surveys show a steady increase in Pacific cod biomass from the late 1970s through the mid 1980s, fluctuating from 1988 through 1994 (peak observed) then steadily declining with the 2008 estimate of 403,125 metric tons being the lowest on record (Thompson et al. 2009). Although recent biomass estimates of Pacific cod have been declining, there has been an increase in the number of smaller sized fish, suggesting the emergence of a strong year class (Acuna and Lauth 2008). Yellowfin sole biomass was at low levels during most of the 1960s and early 1970s after a period of high exploitation then increased and peaked in 1984. Although the biomass has been in slow decline, it has remained stable in recent years (SAFE: Wilderbuer et al. 2009). The abundance of EBS pollock remained at a fairly high level from 1982 through 1988. The stock is characterized by peaks in the mid 1980s and mid 1990s with a substantial decline by 1991 and the lowest point occurring at present. The stock has continued to decline substantially since 2003 due to apparently poor recruitment between 2000 and 2005 although the 2006 and 2008 year classes showed positive signs of recruitment (SAFE: Ianelli et al. 2009). Biomass estimates of EBS skate species have not been reported with the exception of Alaska skate, which is the dominant skate on the EBS shelf between the 50 and 200 m isobaths (Stevenson 2004). Alaska skate biomass fluctuated from 1982 through 1986, increased from 1986 through 1990 (peak), decreased from 1991 through 1999, and demonstrated an increasing trend from 353 thousand t in 1999 to 480 thousand t in 2007, followed by a dramatic decrease to 362 and 351 thousand t in 2008 and 2009, respectively (SAFE: Ormseth et al. 2010) (Fig. 10). Other skate species found in the EBS have no reliable estimates of biomass due to lack of survey data and are managed using average catch data.

Abundance trends of Pacific halibut showed an increase in biomass from 1982 through 1988 with a decrease in 1989. An upward trend with some fluctuation was observed through 2001 followed by a decrease in 2002. Low commercial and survey catch rates from the International Pacific Halibut Commission support a general decline in abundance estimates of Pacific halibut in the eastern Bering Sea (Clarke and Hare 2008). In 2006-2007, the under-40 cm halibut size class dominated the overall catch, but in 2008, the 40-79 cm size class regained that position (Sadorus and Lauth 2009). This indicates an increase in recruitment of Pacific halibut, although a majority of the 2009

biomass estimate of 130 million t in the eastern Bering Sea was dominated by smaller age classes (Hare 2010).

Early biomass estimates of bearded seal in the EBS and Chukchi Sea ranged from 250,000 to 300,000 animals. Surveys flown from Shishmaref to Barrow, Alaska, during May-June 1999 and 2000 provided preliminary results indicating densities up to 0.652 seals km<sup>2</sup>. These densities cannot be converted into an abundance estimate, however, without information on the proportion of the population hauled out during the survey (Cameron and Boveng 2009). Surveys conducted in the 1970s estimated the Bering Sea population of ribbon seals between 60,000 to 100,000 animals. More recent population estimates are not currently available.

### Physical and Biological Environmental Impacts on Crab Biology

#### *Recruitment of King and Tanner Crab*

Recruitment trends for RKC in Alaska are correlated with decadal shifts in climate and physical oceanography. Strong year classes for eastern Bering Sea RKC were observed when temperatures were low, and weak year classes occurred when temperatures were high, but temperature alone cannot explain year class strength trends for RKC (Zheng and Kruse 2000). In Bristol Bay, there is a relationship between RKC brood strength and the intensity of the Aleutian Low atmospheric pressure systems; during low pressure the brood strength is reduced (Tyler and Kruse 1996; Zheng and Kruse 2000). Gish (2006) suggested that the lack of king crab recruitment in the Pribilof Islands area may be the result of a large-scale environmental event affecting abundance and distribution.

The spatial distribution of mature females prior to larval release and locations of crab larvae settlement appear to be important for the recruitment success of crab in the EBS (Zheng and Kruse 2006). Both of these life history stages are affected by changes in the pelagic and benthic environment of the BSAI ecosystem. Bottom water temperatures may be important in structuring the distribution of ovigerous RKC (Loher and Armstrong 2005; Chilton et al. 2010). Female RKC were found primarily in central Bristol Bay during 1980-1987 and 1992-2006 (Zheng and Kruse 2006). The distribution centers of mature females moved south slightly during 1988-1991 but did not reach the southern locations previously occupied in the 1970s. Distribution of ovigerous RKC in the southeastern Bering Sea shifted from the eastern edge of Bristol Bay to the northeast, central shelf area during the late 1970s and early 1980s and this distribution change coincided with increased early summer bottom temperatures (Loher and Armstrong 2005). When the cold pool extended onto the Bristol Bay shelf area in 2006-2009, the summer distribution of ovigerous RKC had moved from the central area of Bristol Bay to the nearshore areas along the Alaska Peninsula (Chilton et al. 2010).

Snow crab recruitment in the EBS is also affected by temperature and ice cover, as well as spawning locations, settlement location and cod predation. Parada et al. (2010) developed a larval trajectory model based on female snow crab reproductive index, a ROMS oceanographic model, bottom temperatures collected during NMFS surveys, ice

cover, chlorophyll-a, a cod predation index and larval recruitment patterns data from 1978-2003. In cold years, retention occurs in areas off the Pribilofs and St. Matthew Islands, whereas transport is generally north in warm years. Larval settlement occurs over a larger area in cold years than in warm years, and is always focused in the northwest section of the EBS.

Strong year classes of Bristol Bay Tanner crab are associated with warm seawater temperatures during gonadal development and embryo incubation along with northeast winds during the larval stages (Rosenkranz et al. 2001). Northeast winds may promote upwelling and provide Tanner crab larvae with food while advecting larvae to regions of preferred settling habitat (Rosenkranz et al. 1998; Rosenkranz et al. 2001).

Recruitment of king, Tanner and snow crab may be affected by ocean acidification because acidified waters can impact the development (Findlay et al. 2009, Parker et al. 2009), development time (Findlay et al. 2009), viability (Kurihara et al. 2004a), and even behavior (Ellis et al. 2009) of the embryos of marine invertebrates (though see Arnold et al. 2009). Further, acidified waters can reduce fertilization success (Parker et al. 2009), the hatching success of embryos (Kurihara et al. 2004a), and the fecundity of females (Kurihara et al. 2004b). No experiments examining the effects of ocean acidification specifically on crab reproduction or recruitment have been published to date; however, research on RKC is progressing at the Kodiak Laboratory, see Current Crab Ecosystem Research and Future Priorities section.

*Ocean acidification and Bristol Bay red king crab recruitment-current modeling work*  
Contributed by Dusanka Poljak, University of Washington

Zheng and Kruse (2006) noted that the abundances of eastern Bering Sea (EBS) crab stocks, including red king crab in Bristol Bay (BBRKC), are driven greatly by recruitment variability. When recruitment is density-dependent, spawning biomass can explain some of the variation in recruitment through the stock recruitment relationship (Ricker, 1954; Beverton and Holt, 1957), with the remaining variation due to environmental factors such as temperature, wind, barometric pressure, or perhaps eventually ocean acidification (OA). Zheng and Kruse (2003) also found a high correlation among year classes, which implies environmental effects on recruitment. Environmental factors may affect food availability, larval timing and transport, growth, survival and consequently recruitment strength (Shepherd et al., 1984).

Given OA, North Pacific waters may become constantly undersaturated for aragonite and for calcite ions by the mid-century (Fabry et al. 2009, Feely et al. 2009). In addition, with increasing acidity, concentration of hydrogen ions will increase. Calcifying organisms need more energy to create their shells when the concentration of hydrogen ions increases because hydrogen ions are released when carbon shells are created. OA may slow down or stop process of shell construction in molting crab, which may reduce larval growth and fitness (Walther et al, 2010).

Survival of pre-recruitment stages of Bristol Bay red king crab (BBRKC) is being modeled under two OA scenarios to construct scenarios regarding trends in recruitment to

the first size-classes in the stock assessment model. The implications of these trends for management will then be evaluated. The recruitment model considers all juvenile RKC life stages, with the final stage being the recruitment to the first size-class in the stock assessment model. It is assumed that individual animals in a stage, given that they survive, have to spend a certain amount of time in that stage before then can move to the next stage. Survival rates per stage are modeled using fecundity and recruitment data. Probabilities to stay in or progress to the next stage are a function of pH, hence, OA. The changes over time in pH were calculated by fitting a linear relationship to predictions of ocean pH for 2000 ( $\text{pH}_{2000}=8.069$ ) and 2100 ( $\text{pH}_{2100}=7.824$ ) (Caldiera and Wickett, 2003; Orr et al., 2005). Uncertainty in the model is accounted for by conducting a large number (1,000) of simulations where the reference values for annual survival and stage duration are drawn independently from beta and uniform distributions respectively.

The simulations estimate time-trajectories of recruitment for two scenarios: (a) pH is decreasing linearly over time, and (b) pH is constant over time. The first scenario identifies potential thresholds in response to changing pH. The second scenario shows likely trends in recruitment given no changes to pH values in the future. The two scenarios bound likely recruitment trends in the future for use in the later modeling, i.e., simulating catches of BBRKC based on a population model which mimics that used for stock assessment purposes.

### *Growth*

Changes in both the physical and biological environment of the BSAI ecosystem utilized by crab species may have an effect on the individual growth of commercial crab species. Several studies have examined the direct effect of changing temperatures on the length of intermolt periods in juvenile Tanner crab and GKC (Paul and Paul 1996; Paul and Paul 2001a; Paul and Paul 2001b). Growth of juvenile RKC from Bristol Bay was found to be slower than that of juvenile RKC collected from Unalaska and Kodiak Island in the Gulf of Alaska (Loher and Armstrong 2000). One hypothesis for the protracted juvenile phase in Bristol Bay was related to water temperatures differences. Colder bottom temperatures in Norton Sound have been associated with the smaller size at maturity observed in RKC when compared to the Pribilof Islands and Bristol Bay RKC stocks (Blau 1990; Otto et al. 1990). The affects of temperature on juvenile blue king crab growth and intermolt period is currently being examined at the Kodiak Laboratory see *Current Crab Ecosystem Research and Future Priorities* section.

Ocean acidification has highly variable and species-specific effects on marine species (Kroeker et al. 2010). Calcification rates in marine calcifiers frequently decrease with decreasing pH (e.g. Gao et al. 2009, Comeau et al. 2010a, Comeau et al. 2010b, Rodolfo-Metalpa et al. 2010a), although the response is not always linear or negative (e.g. Rodolfo-Metalpa et al. 2010b). Crustaceans, in particular, may increase calcification rates under reduced pH conditions (Egilsdottir et al. 2009, Ries et al. 2009); however, increasing calcification rates may come at a high energetic cost (Wood et al. 2008). Embryos and larvae may be particularly vulnerable, although, again, the effects are variable. Acidification can increase development time (Findlay et al. 2009), decrease survival (Dupont et al. 2008, Parker et al. 2009, Watson et al. 2009), decrease growth (Talmage & Gobler 2009, Gazeau et al. 2010, Walther et al. 2010), cause malformations

(Comeau et al. 2010a, Parker et al. 2010), alter behavior (Ellis et al. 2009), and reduce settlement (Cigliano et al. 2010) in the embryos and larvae of marine species, although some species are unaffected (Arnold et al. 2009). The Kodiak Laboratory is currently investigating the affects of ocean acidification on growth and calcification rates of juvenile red king crab, blue king crab and Tanner crab as well and calcification of adult Tanner crab and red king crab, see *Current Crab Ecosystem Research and Future Priorities* section.

### *Maturity*

Causes for differences in size of maturity have not been well studied for EBS crab species, but are often attributed to temperature or oceanographic processes. Female snow crab in the EBS can reach maturity at four different instars and reach maturity at smaller sizes at high latitudes in colder water and larger sizes at warmer low latitudes (Orensanz et al. 2007). Otto et al. (1990) found that among red king crab stocks, female size of maturity was lowest for Norton Sound, the northernmost stock studied, which may suggest that size of maturity is inversely correlated with latitude and temperature. However, the Pribilof Islands and Bristol Bay are located at approximately the same latitude, and while the Pribilof Islands are slightly colder, the size of maturity in females is lower for Bristol Bay red king crab than Pribilof Islands crab (Otto et al. 1990). Furthermore, size of maturity among red king crab females is nearly identical for Bristol Bay and Adak stocks, but Adak is south of Bristol Bay and is warmer. Size at maturity for male and female EBS golden king crab decreases with increasing latitude which may be due to temperature differences resulting in a decrease in growth rate in colder water (Somerton and Otto 1986). Size at maturity of male and female golden king crab is lower at Bowers Ridge than Seguam Pass, two areas that occur over a narrow range of latitude with similar temperatures (Otto and Cummiskey 1985). Oceanographic processes may account for differences in maturity between these areas. Seguam Pass is characterized by strong currents and turbulent mixing of North Pacific and Bering Sea waters and may be more productive than Bowers Ridge which is characterized by gentle currents (Otto and Cummiskey 1985).

### *Natural Mortality*

Several factors may influence the natural mortality of commercial crab stocks other than senescence. Predation on commercial crab stocks or mortality due to disease should also be considered, particularly when those factors are also influenced by the same physical and biological environment of the BSAI ecosystem utilized by crab species. Crab predation is addressed in the *Predation by Groundfish, Marine Mammals, and Seabirds* section of this document while the effects of disease and parasitism on crab mortality are discussed here.

Mortalities are an obvious end-point of disease and parasitism, but these factors may affect individuals by less obvious means. Disease and parasitism may reduce growth rates and/or fecundity. Reproductive capability may be affected at several levels; failure of the ovary to develop or mature completely, and loss or failure of embryos to develop to hatching. Currently, several diseases and/or parasites are known to affect North Pacific crabs at all levels.



Potentially fatal diseases that may affect *Paralithodes* spp. and *Lithodes aequispinus* populations include a herpes-like viral disease of the bladder and antennal gland (Sparks and Morado 1986a, Bower et al. 1994), a pansporoblastic microsporidian (*Thelohania* sp.) which infects the hepatopancreas, ovary and muscle tissue, and produces a cottage cheese appearance in the abdominal cavity (Morado 2010), and a parasitic barnacle or rhizocephalan (*Briarosaccus* sp.) (Sparks and Morado 1986b; Hawkes et al. 1985). Symbiotic snailfish, *Careproctus* spp., deposit eggs into golden king crab gill chambers which interferes with respiration by compressing the gills, causing necrosis, and may lead to mortality (Somerton and Donaldson 1998). Otto et al. (1990) found three of 243 Bristol Bay RKC egg clutches containing nemertian worms, which are known predators of embryos. Although the amphipod *Ischyrocerus* sp. feeds on the eggs of king crab and could have a significant impact on fecundity they are usually never abundant enough to be a major predator (Kuris et al. 1991).

Bitter crab syndrome (BCS) in Tanner and snow crab is a fatal disease caused by a parasitic dinoflagellate of the genus *Hematodinium*, which infects the hemolymph (Meyers et al. 1990) and is widely distributed throughout the North Pacific (Meyers et al. 1996). The meat of crab infected with *Hematodinium* is not a public health concern but has a chalky texture and bitter taste, and is not marketable (Taylor and Khan 1995). Heavily infected crab may be identified by the opaque, white appearance of the ventral side of the abdomen and legs, and the milky white color of the hemolymph. The AFSC Fisheries Resources Pathobiology group has been monitoring BCS since 1988, detecting BCS in EBS Tanner and snow crab for more than 20 years with no clear trends in prevalence. The overall occurrence of BCS in snow crab has been about 3.5% with a low of < 1% to a high > 20% in 2003 since monitoring began (pers. comm. F. Morado, NOAA Fisheries). Tanner and snow crab stock recruitment may be affected as BCS is more common in crab less than 50 mm and is present throughout much of their distribution range. Some recent collections and analysis suggest that only one species of *Hematodinium* infects both North Pacific snow and Tanner crabs although other research indicates there may be more than one species of *Hematodinium* based on the frequency and distribution of occurrence in Tanner crab (Jensen et al. 2010). The long-term effect of this syndrome on affected crab populations is only now being investigated. The disease is more prevalent in the western Bering Sea Tanner crab stock than in the eastern stock (Tanner crab stocks divide by longitude 166°W). Siddeek et al. (2010) determined recovery of the western stock would be delayed by 2-3 years because of BCS when compared to the eastern stock. However, this delay was negligible when compared to the impact of the disease on the Stephens Passage, southeast Alaska Tanner crab stock which under any scenario would not recover under either a medium and long-term recovery plan.

Another disease detected in EBS Tanner crab is black mat syndrome, a systemic fungal infection caused by *Trichomarix invadens*, which penetrates the carapace and affects the epidermis and muscle (Sparks and Hibbits 1979). It has only been observed in *C. bairdi* and seldom encountered in the Bering Sea, thus it is not considered an issue of concern in the EBS (pers. comm. F. Morado, NOAA Fisheries).

## **Current Status of Ecosystem Indicators in 2010/2011**

### Purpose

The purpose of this section is to present current physical and biological environmental data within the BSAI ecosystem utilized by crab species and examine the trophodynamic interactions between crab and lower/upper trophic levels using information from the most recent publications or survey and research data. Current ecosystem oriented research projects and future research priorities for BSAI crab stocks are also presented here. One objective of the CECI is to identify key ecosystem status indicators relating to variability in BSAI crab stocks. Two physical and two biological environmental indicators have been proposed in this document as ecosystem stocks indicators with supporting literature for BSAI crab stocks.

### Physical Environment of the BSAI Ecosystem in 2010/2011

#### *North Pacific Climate*

Despite the appearance of the 2009/2010 El Niño, the North Pacific experienced cooler than normal ocean temperatures in the northern and eastern sections mainly due to the cooler pre-existing state of the North Pacific. A relatively weak Aleutian Low occurred based on the arrival of La Nina in the spring/summer of 2010 which created a negative Pacific Decadal Oscillation for the North Pacific (Bond and Guy 2010).

#### *Sea Ice Cover and EBS Climate*

The Bering Sea climate conditions are driven by local and North Pacific processes throughout the winter into spring, which are uncoupled from the warming trends and sea ice loss observed in the Arctic. Both air and water temperatures in 2009/2010 contributed to extensive sea ice coverage in 2010 persisting into late spring which resulted in one of the largest summer cold pools encountered in the EBS. Reversing the trend of the relatively cold years of 2006-2010, the winter of 2010-2011 returned to warmer temperatures, especially the late winter months. The maximum air temperatures recorded at St. Paul Island were above the long-term average of 1947-2011, during three out of four days in January to March of 2011 (Fig. 11). The extent of the sea ice coverage was reduced in January to March of 2011 compared to the previous five years although the ice edge did extend further south in April 2011.

#### *2010 Summer Bottom and Surface Temperatures in the eastern Bering Sea*

Bottom temperatures measured during the 2010 EBS standard trawl survey ranged from -1.6° to 6.4°C (Fig. 12a) while sea surface temperatures ranged from 0.5°C to 9.7°C (Fig. 12b). These temperatures were collected at 20 nmi intervals as the survey progressed from east to west, beginning on 7 June 2010 in the northeast corner of Bristol Bay and moving westward towards the shelf edge finishing on 4 August 2010. A cold pool of water < 2°C was prevalent between the 50 m and 100 m isobaths in the middle shelf and southwestern portion of Bristol Bay area with cool temperatures persisting at the nearshore stations along the Alaska Peninsula. Bottom temperatures ranging from 2.5° to

3.9°C were evident between the 100 m and 200 m isobaths in the southwestern section of the survey area of the EBS, while cooler water temperatures ranging from 1.3° to 2.7°C persisted in the northwestern area between the 100 m and 200 m isobaths and the waters surrounding St. Matthew Island. Sea surface temperatures followed a similar pattern although colder temperatures were seen in Bristol Bay and the inner shelf of the EBS. Sea surface temperatures increased with increasing depths on the shelf but could be an artifact of the sample design where outer shelf stations were sampled later in the summer.

#### *2010 Summer Bottom and Surface Temperatures in Norton Sound and Aleutian Islands*

The mean bottom temperature per tow in the NBS area ranged from -1.6° to 12.3°C (Fig. 13a). These temperatures were collected at 20 nmi intervals as the survey progressed from southeast to northwest, beginning on 23 July just north of Nunivak Island and finishing just south of the Bering Straits on 9 August 2010. A cold pool of water < 2°C was prevalent west and south of St. Lawrence Island with cooler temperatures persisting at stations along 50 m isobath and deeper. Warmer bottom temperatures were evident in Norton Sound and in shallow waters along the Alaskan coastline, south of Norton Sound. Surface water temperatures followed a similar pattern in Norton Sound and along the Alaskan coastline with a cooler band of surface water east of St. Lawrence Island (Fig. 13b). Water temperatures collected on the 2010 AI bottom trawl survey were similar to data collected in 2006, with warmer surface water temperatures in the eastern and western ends of the AI trawl survey (Unimak Island and Adak Island) while cooler water temperatures were observed in the central area of the trawl survey near Seguam Island (Martin 2010).

### Biological Environment of the BSAI Ecosystem

#### *Status of BSAI Epifaunal Prey and Competitors in 2010*

The 2010 total demersal biomass of the eastern Bering Sea estimated from the annual EBS bottom trawl survey was 15.6 million t, with benthic invertebrates representing 25% (3.9 million t) and composed primarily of echinoderms such as sea stars, sea urchins, and sea cucumbers at 1.7 million t (Lauth *in review*). The biomass of benthic invertebrates increased compared to 2009 levels.

#### *Status of Crab Predators in 2010*

The current biomass and abundance estimates for a group of likely crab predators common on the eastern Bering Sea shelf are reported by Lauth (*in review*) for the 2010 EBS bottom trawl survey, and are summarized in the next paragraph. The overall trend in crab predator abundance in the EBS appears to be increasing in comparison to previous years, especially with an increase in the biomass of Pacific cod which are known predators on juvenile Tanner crab (Urban 2010). The distribution of both Pacific cod and walleye pollock on the 2010 EBS bottom trawl survey was associated with areas outside of the cold pool and in water temperatures warmer than 0°C (Lauth *in review*).

The 2010 biomass estimate of 0.86 million t for Pacific cod has increased by 100% compared to 2009 estimate of 0.42 million t, most likely due to growth of the highly

abundant younger year classes observed in the 2009 survey. The total biomass of walleye pollock for the entire survey area in 2010 was 3.75 million t, which was 63% higher than the 2009 biomass estimate of 2.28 million t. Yellowfin sole biomass increased to 2.37 million t in 2010 from 1.7 million t in 2009 while the estimated biomass of northern and southern rock sole (*L. bilineata*) increased by 18% to 2.06 million t in 2010 compared to 1.74 million t in 2009. Estimates of biomass for Arrowtooth flounder increased to 0.53 million t in 2010 compared to 0.41 million t in 2009, while the biomass estimate for Pacific halibut in the eastern Bering Sea was 0.198 million t in 2010 compared to 0.178 million t in 2009 (Lauth *in review*). Pacific halibut is one of the few crab predators with a decreasing abundance, but is still well above the values seen in the past 20 years although there has been a recent increase in the number of small halibut suggesting a strong year class (Hare 2010).

The estimated biomass of Alaska skate increased slightly to 367 thousand t in 2010 from 351 thousand t in 2009 and biomass estimates for other individual skate species in the BSAI region are not available. The total biomass estimate for the aggregated skate complex in the EBS for 2010 is 385 thousand t (SAFE: Ormseth et al 2010).

#### *Current Crab Ecosystem Research and Future Priorities*

This section of the CECI provides an opportunity to highlight current ecosystem oriented crab research such as funded proposals without published results or recent presentations at scientific meetings as well as identify gaps in the data and future research priorities.

The Crab Plan Team creates a list of crab specific research priorities on an annual basis that is forwarded to the North Pacific Fishery Management Council (NPFMC) for inclusion into a larger document. Several of these priorities have evolved into research projects funded by various entities including but not limited to AFSC and NMFS, the North Pacific Research Board (NPRB), the University of Alaska and other Universities. Crab specific research priorities are also developed at the annual December Interagency Crab Meeting held in Anchorage where a diverse number of research biologists from ADF&G, University of Alaska Fairbanks, University of Alaska Southeast, and AFSC present data from current projects and discuss potential collaborations (Webb and Woodby 2008). Currently, a number of crab ecosystem projects are being pursued which have developed from the research priorities discussed at these meetings.

Current crab ecosystem research includes

- Assessing inter-annual and seasonal variability in Bristol Bay red king crab fecundity in warm and cold years
- Investigating snow crab population genetic structure with respect to the changing environmental factors in the EBS
- Variability in reproductive potential of EBS snow crab with respect to spawning stock demography and temperature

- Recruitment of larval and juvenile Tanner crab affected by predation from groundfish, biomass of mature female Tanner crab, and environmental variables
- Diet and reproductive status of snow crab in the northern Bering Sea prior to commercial removals
- Sperm reserves of EBS snow crab
- Affects of habitat, predator density and predator size on the cannibalistic predator functional response in red king crab
- Juvenile red king crab habitat choice and habitat specific survival and growth
- Affects of ocean acidification on juvenile red king crab, blue king crab and Tanner crab growth, survival and calcification
- Affects of ocean acidification on maternal condition and reproductive success and larval condition and survival of Tanner crab
- Affects of ocean acidification on red king crab embryology and larval condition and survival
- Affects of temperature on juvenile blue king crab growth and intermolt period
- Assessing discard mortality of Tanner crab in the Alaskan bottom trawl fishery
- Investigating the impact of cold temperatures on snow crab survival using reflex assessment model predictor in a simulated environment

#### Proposed crab ecosystem research

- Affects of ocean acidification on red and blue king crab larval development
- Determine the functional response of one year old red king crab predators using young of year red king crab and alternative prey
- Identify as well as assess spatial and temporal productivity trends which may impact crab stock recruitment
- Identify the spatial distribution of potential competitors/predators of Pribilof Island BKC
- Genetic identification of EBS Tanner crab diet

The following ecosystem indicators were selected for their relationship to variability in BSAI crab stock abundances in the eastern Bering Sea:

Changes in north Pacific climate effecting sea ice coverage in the EBS.

The north Pacific Climate is the primary driving force behind the extent and duration of sea ice coverage (Hunt, Jr. et al. 2010; Grebmeier et al. 2006). The extent of sea ice coverage is variable and related to the location of the Aleutian Low and Siberian High which typically produce northeast winds in the winter that freeze the seawater and push the ice southwestward (Stabeno et al. 2001). The extent and timing of the retreat of sea ice in the Bering Sea determines the strength and fate of the spring phytoplankton bloom and subsequent zooplankton production (Wang et al. 2008). When sea ice coverage over the southeast Bering Sea shelf occurs in March/April, a strong phytoplankton bloom occurs. In the absence of sea ice, the bloom does not occur until May/June and is typically weaker (Stabeno et al. 2001). Variability in the extent and timing of sea ice coverage in the EBS can have a major impact on the survival of larval crab and the whole food web structure (Hare et al. 2007).

The effects of variability in the north Pacific climate on BSAI crab stocks will be both direct and indirect due to changes in temperatures, winds, storm intensity, salinity, stratification, pH, and abundance of suitable physical habitat. There is, however, considerable uncertainty over the spatial and temporal distribution of the effects of changing climate on marine ecosystems (Brander 2010, Hoegh-Guldberg and Bruno 2010). When considering the effect of climate change on BSAI crab stocks, differing time scales will have different management implications (Brander 2010). On a time scale of 5 to 25 years, spanning several generations of crab, changes in climate affect the basic productivity of the marine ecosystem (King 2005). Long-term changes in sea ice cover may affect benthic communities because much of the production from retreating ice edge spring blooms sink to the bottom, but if these blooms do not occur there may not be sufficient phytoplankton falling to the benthos to support abundant communities (Lovvorn et al. 2005).

Summer bottom water temperatures impacting distribution of benthic crab, competitors and predators.

As a response to changing water temperatures, the ecosystem in the Bering Sea is shifting northward (Overland and Stabeno 2004). Changes in the location of the cold pool alter the composition of the arctic and subarctic marine communities, but the response among taxa is variable and difficult to predict (Aydin and Mueter 2007). Increased water temperatures in the mid-1980s resulted in a shift of mature female snow crab to the northwest EBS shelf (Zheng et al. 2001) while the more recent temperature decrease in the last decade did not result in a return of mature

females to their historical distribution (Orensanz et al. 2004). Other planktivorous feeders and potential crab competitors, such as juvenile sockeye salmon and age-0 pollock, increased in abundance and were widely distributed throughout the EBS during the warm years of 2002-2005. In the cold years of 2006-2008, juvenile sockeye salmon were primarily found in the inner Bristol Bay waters and age-0 pollock were restricted to the middle domain of the EBS with abundance decreasing for both species (Farley et al. 2008).

Major groundfish predators are intolerant of the low temperatures of ice-associated bottom water so a natural refugia for crabs is formed (Mueter and Litzow 2008). The distribution of Pacific cod in the EBS has been associated with areas outside of the cold pool and in water temperatures warmer than 0°C (Ciannelli and Bailey 2005; Lauth *in review*). Temperature has been shown to have opposing effects upon snow crab and their main predator, Atlantic cod (*G. morhua*). Snow crab abundance was negatively correlated with temperature while cod and temperature were positively correlated (Boudreau et al. 2011).

#### Changes in the abundance of Pleuronectidae and Gadidae biomass in the EBS

Groundfish predators have been shown to have a major impact on crab stocks (Livingston 1989, Aydin et al. 2007). Changes in the abundance of these predators would likely affect the variability of crab stocks, specifically at the larval and juvenile stages as adult crab are relatively invulnerable to predation except after molting when they are in a soft shell state (Blau 1986, Livingston 1989, Loher et al. 1998).

For king crab, numerous planktivorous fishes prey on Paralithodid larvae (Livingston et al. 1993; Wespestad et al. 1994). The size of Paralithodid prey in yellowfin sole and walleye pollock stomachs indicates they feed on larval and very early juvenile king crab (Livingston et al. 1993). Juvenile king crab may also fall prey to other flatfish species (Livingston and Goiney 1983), but crab begin to exceed the mouth gape of many of these predators as they grow. Suitably lagged models of predator abundance such as Pacific cod and yellowfin sole, could be used to predict future king crab abundance although the relationships need further analysis (Zheng and Kruse 2000, 2006).

A high number of early juvenile Tanner and snow crab age 0 to age 1 are consumed by Pacific cod in the eastern Bering Sea (Lang et al. 2005). It was estimated that Pacific cod removed up to 94% of age 1 Tanner crab and up to 57% of snow crab in the Bering Sea in a single year (Livingston 1989). A seasonal study in the Gulf of Alaska showed the primary prey item of Pacific cod were early juvenile Tanner crab ( $\leq 45$  mm CW), both by weight and number (Urban 2010).

## **Ecosystem-based Management Indicators**

### Purpose

This section of the CECI provides early signals of direct human effects on BSAI crab ecosystem components via directed fishery effects on the ecosystem and summarizes current management actions such as; management efforts in response to directed fishery effects on BSAI habitat, and spatial and temporal removals of the target catch affecting other biological predators. In this section, we also review potential fishery effects on crab life history stages such as removal of legal sized males, age at maturity and reproduction.

### Fishery-Specific Impacts on the Physical Environment

#### *Effects of Crab Fishing Gear on Seafloor Habitat*

In the BSAI crab fisheries Final Environmental Impact Statement (EIS), the impact of pot gear on benthic EBS species is discussed (NMFS 2004). Benthic species examined included fish, gastropods, coral, echinoderms (sea stars and sea urchins), non-target crab, and invertebrates (sponges, octopuses, anemones, tunicates, bryozoans, and hydroids). It is likely that habitat is affected during both setting and retrieval of pots, but little research has been done. Physical damage to the habitat by pot gear depends on habitat type. Sand and soft sediments where the majority of EBS crab pot fishing occurs are less likely to be impacted, whereas coral, sponge, and gorgonian habitats are more likely to be damaged by commercial crab pots in the AI GKC fishery (Quandt 1999, NMFS 2004). The total portion of the EBS impacted by commercial pot fishing may be less than 1% of the shelf area (NMFS 2004). The report concludes that BSAI crab fisheries have an insignificant effect on benthic habitat.

#### *Management Enacted Efforts*

Habitat protection areas, prohibited species caps (PSC) and crab bycatch limits are in place to protect important benthic habitat for crab and other resources and reduce crab bycatch in the trawl and fixed gear fisheries. Beginning in 1995, the Pribilof Islands Conservation Area was closed to all trawling and dredging year-round to protect BKC habitat (NPFMC 1994). Also beginning in 1995, the Red King Crab Savings Area was established as a year-round bottom trawl and dredge closure area (NPFMC 1995). This area was known to have high densities of adult red king crab, and closure of the area greatly reduced bycatch of this species. The Red King Crab Savings Subarea is a portion of the Red King Crab Savings Area between 56° 00' and 56° 10' N lat. Within this Subarea, non-pelagic trawl gear may be used if GHs were established for a Bristol Bay RKC fishery the previous year. The RKC bycatch limit is established by NMFS after consultation with the Council and the limit does not exceed an amount equivalent to 25 percent of the RKC PSC allowance (Federal Register 679.21 Prohibited Species Bycatch Management). To protect juvenile RKC and critical rearing habitat (stalked ascidians and other living substrate), another year-round closure to all trawling was implemented in 1996 for the nearshore waters of Bristol Bay. Specifically, the area east of 162° W (i.e., all of Bristol Bay) is closed to trawling and dredging, with the exception of an area



bounded by 159° to 160° W and 58° to 58°43' N that remains open to trawling during the period April 1 to June 15 each year (NPFMC 2008, Fig. 14).

The Bering Sea Habitat Conservation Area, Northern Bering Sea Research Area, Nunivak Island, Etolin Strait, and Kuskokwim Bay Habitat Conservation Area, St. Lawrence Island Habitat Conservation Area, and St. Matthew Island Habitat Conservation Area were closed to non-pelagic gear in 2008. These areas include BKC habitat, locations that have not been fished with non-pelagic gear, nearshore bottom habitat that support subsistence marine resources and a research area (Federal Register Vol. 73, No 144, July 25, 2008, Rules and Regulations). A scientific research plan is currently being developed for the Northern Bering Sea Research Area and will be reviewed by the North Pacific Fishery Management Council in 2011. The major objectives of the plan are to study the effects of bottom trawling on benthic species and habitat with the goal of providing information to assist in the development of future protection measures for crab and other species as well as subsistence needs of western Alaska communities (Fig. 15).

PSC limits are in place for RKC, Tanner and snow crab. If PSC limits are reached in predetermined bottom trawl fisheries executed in specific areas (Fig. 14), those fisheries are closed. Snow crab taken within the "Snow Crab Bycatch Limitation Zone" (COBLZ) accrue towards the PSC limits established for individual trawl fisheries. Upon attainment of a snow crab PSC limit apportioned to a particular trawl target fishery, that fishery is prohibited from fishing within the COBLZ. A recent review of the PSC limits for commercial crab species in groundfish fisheries is detailed in *Crab Bycatch in the Bering Sea/Aleutian Island Fisheries* (NPFMC 2010). Annual crab bycatch limits (CBLs) are specified for RKC, Tanner and snow crab in the scallop fishery in the Bering Sea, Registration Area Q, and are calculated as a percentage of the most recent abundance estimate of RKC, Tanner and snow crab in Registration Area Q.

#### *Effects of groundfish Fishing Gear on Seafloor Habitat*

McConnaughey et al. (2000) examined the impact of trawl gear on the EBS seafloor by comparing an area closed to trawling adjacent to an area that has experienced intensive fishing for yellowfin sole. There were significantly detectable differences in macrofaunal populations between the two areas, with greater diversity and niche breadth of sedentary macrofauna in the unfished area. The biomass of stalked, attached and encrusted epifaunal organisms (sponges, anemones, soft corals, and tunicates) was greater in the unfished area. These organisms provide substrate complexity and are vulnerable to bottom trawl gear. A larger number of marine snail and bivalve shells also added to the complexity of the substrate in the unfished area. Overall, the complexity of the benthic substrate as well as the epifaunal diversity is affected by bottom trawl gear and reduces the heterogeneity of the benthic communities (McConnaughey et al. 2000). Recent research by Rose et al. (2010) examined the adaptation of rubber cookie discs and different lengths of bottom trawl bridle cables to improve fishing efficiency of flatfish as well as reduce the impact of these bottom trawls to the seafloor.

The CPT presented a discussion paper to the NPFMC in March 2011 evaluating the effects of groundfish fishing on essential fish habitat for RKC. The discussion paper

highlighted the interaction between trawl fishing and ovigerous female RKC in the southwest area of Bristol Bay, an area with potentially higher survival rates for larval and juvenile RKC. The NPFMC requested further analysis on the effectiveness of the RKC Savings Area and the Nearshore Bristol Bay Trawl Closure with respect to the impact of fishing gear on seafloor habitat (Fig. 14).

### Fishery-Specific Impacts on Biological Environment

#### *Directed Fishery Contribution to Competitor and Predator Mortality*

The EBS crab fisheries catch a small amount of other species as bycatch. A limited number of groundfish, such as Pacific cod, Pacific halibut, yellowfin sole, and sculpin (*Myoxocephalus* spp.), are caught in the directed pot fishery (Barnard and Burt 2007; Barnard and Burt 2008; Gaeuman 2010). The invertebrate component of bycatch includes echinoderms (stars and sea urchin), snails, non-FMP crab (hermit crabs and lyre crabs), and other invertebrates (sponges, octopus, anemone, and jellyfish). Typically, low levels of bycatch of these species do not impact their abundance (NMFS 2004).

Mortality to fish and non-target invertebrates from ghost fishing of lost crab and groundfish pots in the EBS has not been evaluated. The term ghost fishing describes continued fishing by lost or derelict gear. Crab caught in lost pots may die of starvation; however, the impact of ghost fishing on crab stocks remains unknown. To reduce starvation mortality in lost pots, crab pots have been required to be fitted with degradable escape mechanisms such as cotton thread or twine since 1977. Pots without escape mechanisms could continue to catch and kill crab for many years. High and Worlund (1979) estimated an effective fishing life of 15 years for king crab pots. The ADFG requires the use of a biodegradable twine panel in each crab pot intended to disable ghost fishing in lost pots after approximately 30 days. Recent work indicates that even biodegradable twine may remain intact for up to 89 days in lost pots (Barnard 2008), or 3 times the length of time (30 days) found to cause irreversible starvation in crab (Paul et al. 1994). Testimony from crabbers and pot manufacturers indicate that all pots currently fished in Bering Sea crab fisheries contain escape mechanisms (NPFMC 2007).

NMFS conducted Endangered Species Act (ESA) Section 7 Consultations-Biological Assessments on the impact of the Bering Sea and Aleutian Island FMP crab fisheries on marine mammals (NMFS 2000) and on seabirds (NMFS 2002). As noted in the Endangered Species Act EIS report, crab fisheries do not adversely affect ESA listed species, destroy or modify their habitat, or comprise a measurable portion of their diet (NMFS 2004). Although the possibility of strikes of listed seabirds with crab fishing vessels does exist (NMFS 2000), NMFS concluded that available evidence is not sufficient to suggest that these interactions occur in today's fisheries or limit the recovery of seabirds. Of non-listed marine mammals, bearded seals (*Erignathus barbatus*) are the only marine mammal potentially impacted by crab fisheries insofar as crab are a measurable portion of their diet (Lowry et al. 1980; NMFS 2004). For non-listed seabirds, the Alaska Groundfish Fisheries Final Programmatic SEIS (NMFS 2004) provides life history, population biology and foraging ecology for marine birds. The SEIS

concluded that crab stocks under the NPFMC fishery management plan (NPFMC 1998) have very limited interaction with non-listed seabirds.

#### *Directed Fishery Contribution to Discards and Offal Production*

The EIS for the BSAI crab fisheries summarizes some of the effects of discards and offal production (NMFS 2004). Returning discards, process waste, and the contents of used bait containers to the sea provides energy to scavenging birds and animals that may not otherwise have access to those energy resources. The total offal and discard production as a percentage of the unused detritus already going to the bottom has not been estimated.

#### *Groundfish and Scallop Fisheries By-Catch of Commercial Crab*

RKC, Tanner and snow crab, regardless of sex or size, are considered prohibited species in the groundfish and scallop fisheries with an estimated handling mortality of 50% in fixed gear, 80% in trawl gear and 40% dredge gear fisheries. Bottom trawl fisheries in specific areas are closed when PSC limits of RKC, Tanner and snow crab are reached (see *Management Enacted Efforts* section).

Bycatch data of commercial crab species caught in the groundfish fisheries is provided by NMFS, Alaska Regional Office from 1991 through 2010 and incorporated into the individual species stock assessments when appropriate to their tier level.

The scallop fishery in the Bering Sea (Registration Area Q,) is executed from July 1<sup>st</sup> through the end of February and closes if harvest guidelines or CBLs are reached. Since 1993, 100% observer coverage has been required on all vessels participating in the scallop fishery. Scallop observers collect biological data from the targeted catch as well as bycatch species. The Bering Sea fishery within Area Q targets scallop beds in 90 to 106 m of water in a small area (13 nmi<sup>2</sup>) north of Unimak Island (Rosenkranz 2010). Scallop fishery closures in Area Q resulting from CBLs have decreased in recent years mainly due to lower crab abundances in the EBS (Barnhart and Rosenkranz 2003, Table 2).

### Fishery-Specific Impacts on Crab Biology

#### *Directed Fishery Effects of the Target Catch Relative to Predators*

The spatial and temporal removal of the target catch, legal sized male crab (Table 1), is dependent on the size of the vessel quota, weather conditions, advancing ice edge, processor demand, and Community Development Quotas (CDQ) deliveries distributed between St. Paul Island and Dutch Harbor, Alaska. Historically, Bristol Bay RKC is fished from late October through early December, and EBS Tanner and snow crab January through April. The St. Matthew Island BKC fishery opened in November of 2009 after a ten year rebuilding plan, although this fishery was historically executed in September and October just prior to the red king fishery. The Norton Sound RKC and Aleutian Islands GKC fisheries are conducted in the summer and fall.

There are few species identified as predators of legal sized male crab and specific information is limited due to the difficulty of identifying prey items to the species level with only partial carapace or dactyl pieces. Based on food habits data collected in the summer months during the annual EBS bottom trawl survey, Pacific cod, Pacific halibut and skates are the primary predators of large or legal size crab although legal sized crab are a minimal component of these predators diets.

#### *Directed Fishery Effects on Target Crab, Age-At-Maturity and Reproduction*

In the BSAI, minimum size limits for male crab are established based upon the estimated average size-at-maturity with the intent of allowing males to mate at least once before becoming harvestable. Females are not harvested and fishing seasons are timed to protect the crab when they are molting and mating (NPFMC 2008). It is possible that male-only fisheries with minimum size limits reduce the abundance of large crab; however this has not been examined for Bering Sea crab stocks. In Glacier Bay National Park and Preserve, located at the northern end of the southeastern Alaska panhandle, the number and size of legal-sized male Dungeness crab increased significantly after the closure of the park to commercial fishing. Females and sub-legal males were not targeted by the commercial fishery and these crab did not increase in size or abundance following the closure of the fishery (Taggart et al. 2004). Commercial fishing in Glacier Bay National Park and Preserve appeared to have altered the size structure of male Dungeness crab which may also be occurring within EBS crab stocks.

Over time, size-at-maturity may be reduced due to fishing-induced mating selection in male-only fisheries (Zheng 2008). A significant decline in size at 50% maturity of male Bristol Bay Tanner crab may be the result of genetic responses to the fishery. Fast-growing males may not have an opportunity to mate prior to being harvested in the fishery, whereas slow-growing males may undergo their terminal molt to maturity before reaching the legal size limit and therefore mate (Zheng 2008). Recent analysis of the economic and biological impact of reducing the legal size of Tanner crab in the EBS concluded that a reduction would result in decreased handling mortality in the directed fishery of the terminally molted sublegal males due to the increased CPUE from the smaller legal males but handling mortality would not be reduced in other fisheries (Bechtol et al. 2010). A reduction in the size of legal caught Tanner crab may also reduce potential risk of genetic effects from removing only the larger males (Zheng and Pengilly 2011).

A reduction in the abundance of large males may result in the mating of less fecund males, reduced female mate choice and an increased chance of sperm limitation (Smith and Jamieson 1991; Sato et al. 2005a; Sato et al. 2006; Sato and Goshima 2006; Sainte-Marie et al. 2008). Male size and mating frequency affects reproductive success of many crab species. In general larger males are more successful at mating (production of a fertilized egg clutch) and can successfully mate with multiple females (Paul and Paul 1990; Paul and Paul 1997; Sato et al. 2005b; Sato and Goshima 2006). Based upon manipulation population studies of *Hapalogaster dentate*, a decrease in male size and sex ratio would result in sperm limitation (Sato and Goshima 2006). Laboratory research and field studies in eastern Hokkaido, Japan suggest that sperm limitation could occur in fished populations of *Paralithodes brevipes* (Sato et al. 2005b). Large male snow crab

from heavily harvested stocks in the Gulf of St. Lawrence, Canada have small amounts of spermatophores in their vas deferens which is in contrast to higher levels observed in lightly or not fished stocks (Conan and Comeau 1986; Sainte-Marie et al. 1995). In heavily exploited snow crab stocks, a high percentage of males may be harvested upon reaching morphometric maturity resulting in an inability of mature males to accumulate a sufficient number of spermatophores necessary to successful mate (Conan and Comeau 1986; Sainte-Marie et al. 1995). In the EBS, female snow crab sperm reserves increase with female size and appear to generally be lower than other snow crab stocks (Slater et al. 2010). Limited sperm reserve data from EBS snow and Tanner crab suggest that in 2005 less than one half of primiparous females sampled had sufficient sperm reserves to fertilize a full second clutch of eggs (Gravel and Pengilly 2007). Alternately, in northern California, nearly all molting female Dungeness crab mate regardless of size despite intense fishing on males (Hankin et al. 1997). The short and long term effects of removing large male crab from a population is not well understood and may vary by species and population.

## Literature Cited

- Abrunhosa, F.A. and J.K. Kittaka. 1997. Functional morphology of mouthparts and foregut of the last zoea, glaucothoe and first juvenile of the king crabs *Paralithodes camtschaticus*, *P. brevipes* and *P. platypus*. Fisheries Science 63(6):923-930.
- Acuna, E. and R.R. Lauth. 2008. Results of the 2007 eastern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-181, 195 pp.
- Armstrong, D.A., J.L. Armstrong, R. Palacios, G. Jensen, and G. Williams. 1985. Early life history of juvenile blue king crab, *Paralithodes platypus*, around the Pribilof Islands. pp. 211-229 *In*: Proceedings of the International King Crab Symposium, Alaska Sea Grant Report No 85-12, University of Alaska, Fairbanks.
- Arnold, K. E., H. S. Findlay, J. I. Spicer, C. L. Daniels, and D. Boothroyd. 2009. Effect of CO<sub>2</sub>-related acidification on aspects of the larval development of the European lobster, *Homarus gammarus* (L.). Biogeosciences 6:1747-1754.
- Aydin, K., and F. Mueter. 2007. The Bering Sea – A dynamic food web perspective. Deep-Sea Research II 57:2501-2525.
- Aydin, K., S. Gaichas, I. Ortiz, D. Kinzey, and N. Friday. 2007. A comparison of the Bering Sea, Gulf of Alaska, and Aleutian Islands large marine ecosystems through food web modeling. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-178, 298p.
- Barange, M. and R. I. Perry. 2009. Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. *In* K. Cochrane, C. De. Young, D. Soto, and T. Bahri (eds.), Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FOA Fisheries and Aquaculture technical paper. No. 530. Rome, FAO. pp 7-106.
- Barnard, D. R. 2008. Biodegradable twine report to the Alaska Board of Fisheries. Alaska Department of Fish and Game, Fishery Data Series No. 08-05, Anchorage.
- Barnard, D.R. and R. Burt. 2007. Alaska Department of Fish and Game summary of the 2005/2006 mandatory shellfish observer program database for the rationalized crab fisheries. Alaska Department of Fish and Game, Fishery Data Series No. 07-02, Anchorage.
- Barnard, D.R. and R. Burt. 2008. Alaska Department of Fish and Game summary of the 2006/2007 mandatory shellfish observer program database for the rationalized crab fisheries. Alaska Department of Fish and Game, Fishery Data Series No. 08-17, Anchorage.
- Barnhart, J. P. and G. E. Rosenkranz. 2003. Summary and analysis of onboard observer-collected data from the 1999/2000 through 2001/2002 statewide commercial weathervane scallop fishery. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 4K03-09, Kodiak.

- Bechtol, W.R., G. H. Kruse, J. Greenberg, and H. Geier. 2010. Analysis of the Minimum Size Limit for Eastern Bering Sea Tanner Crab Fisheries: A Preliminary Report. North Pacific Fishery Management Council, Anchorage, AK.
- Beverton, R.J.H., and S.J Holt. 1957. On the dynamics of exploited fish populations Fishery Investigation, Series 2, vol. 19. UK Ministry of Agriculture and Fisheries, London, p. 533.
- Beamish, R.J. and C. Mahnken. 1999. Taking the next step in fisheries management. Ecosystem approaches for fisheries management. Alaska Sea Grant College Program. AK-SG-99-01.
- Blau, S.F. 1986. Recent declines of red king crab (*Paralithodes camtschatica*) populations and reproductive conditions around the Kodiak Archipelago, Alaska, pp 360-369. In G. S. Jamieson and N. Bourne (eds.), North Pacific Workshop on stock assessment and management of invertebrates. Canadian Special Publication of Fisheries and Aquatic Sciences 92.
- Blau, S.F. 1990. Size at maturity of female red king crabs in the Adak management area, Alaska, p. 105-116. In Proceedings of the international symposium on king and Tanner crabs, University of Alaska Sea Grant Report 90-04, Anchorage, AK.
- Bond, N. and J. Overland. 2009. North Pacific climate overview, p. 29. In J. Boldt and S. Zador (eds.), Appendix C: Ecosystem Considerations for 2009. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- Bond, N. and L.Guy. 2010. North Pacific climate overview, p. 90. In S. Zador and S. Gaichas (eds.), Appendix C: Ecosystem Considerations for 2011. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- Boudreau, S.A., S.C Anderson, B. Worm. 2011. Top-down interactions and temperature control of snow crab abundance in the northwest Atlantic Ocean. Mar. Ecol. Prog. Ser. 429:169-183.
- Bower, S.M., S.E. McGladdery, I.M. Price. 1994. Synopsis of infectious diseases and parasites of commercially exploited shellfish. Annual Review of Fishery Diseases 4:1-199.
- Brander, K.M. 2007. Global fish production and climate change. 2007. Proceedings of National Academy of Sciences 104:19709-19714.
- Brander, K. M. 2010. Impacts of climate change on fisheries. Journal of Marine Systems 79:389-402.
- Bright, D. B. 1967. Life histories of the king crab, *Paralithodes camtschatica*, and the "Tanner" crab, *Chionoecetes bairdi*, in Cook Inlet, Alaska. Ph.D. Thesis, University of Southern California, CA.
- Caldeira, K., and M. E. Wickett. 2003. Anthropogenic carbon and ocean pH. Nature 425:365-365.
- Cameron, M. and P. Boveng. 2009. Habitat use and seasonal movements of adult and subadult bearded seals. AFSC quarterly research report Oct-Nov-Dec 2009.

- Cameron, M., J. London, and P. Boveng. 2009. Telemetry of Ice Seals Captured During a Research Cruise Aboard the *McArthur II* in the Eastern Bering Sea. AFSC quarterly research report April-May-June 2009.
- Charmantier, G. and M. Charmantier-Daures. 1995. Osmoregulation and salinity tolerance in zoeae and juveniles of the snow crab *Chionoecetes opilio*. *Living Resources* 8:171-179.
- Chilton, E.A, R.J. Foy, and C.E. Armistead. 2010. Temperature effects on assessment of red king crab in Bristol Bay, Alaska. In: G.H. Kruse, G.L. Eckert, R.J. Foy, R.N. Lipcius, B. Sainte-Marie, D.L. Stram, and D. Woodby (eds.), *Biology and management of exploited crab populations under climate change*. Alaska Sea Grant, University of Alaska Fairbanks.
- Ciannelli, L. and K. M. Bailey. 2005. Landscape dynamics and resulting species interactions: the cod-capelin system in the southeastern Bering Sea. *Marine Ecology Progress Series* 291: 227-236.
- Cigliano M, M.C. Gambi, R. Rodolfo-Metalpa, F.P. Patti, and J.M. Hall-Spencer. 2010. Effects of ocean acidification on invertebrate settlement at volcanic CO<sub>2</sub> vents. *Marine Biology* 157:2489-2502.
- Clarke, W.G. and S. R. Hare. 2008. Assessment of the Pacific halibut stock at the end of 2007. *International Pacific Halibut Commission Assessment Report*, p. 27.
- Comeau S, G. Gorsky, S. Alliouane, and J.P. Gattuso. 2010a. Larvae of the pteropod *Cavolinia inflexa* exposed to aragonite undersaturation are viable but shell-less. *Marine Biology* 157:2341-2345
- Comeau S, R. Jeffree, J.L. Teysse, and J.P. Gattuso. 2010b. Response of the arctic pteropod *Limacina helicina* to projected future environmental conditions. *PLoS One* 5:7
- Conan, G.Y. and M. Comeau. 1986. Functional maturity and terminal molt of male snow crab, *chionoecetes opilio*. *Canadian Journal of Fisheries and Aquatic Sciences* 43:1710-1719.
- Coyle, K.O., B. Konar, A. Blanchard, R.C. Highsmith, J. Carroll, M. Carroll, S.G. Denisenko, and B.I. Sirenko. 2007. Potential effects of temperature on the benthic infaunal community on the southeastern Bering Sea shelf: possible impacts of climate change. *Deep-Sea Research Part II: Topical Studies in Oceanography*. 54: 2885-2905.
- Dew, C.B., 1990. Behavioral ecology of podding red king crab, *Paralithodes camtschatica*. *Canadian Journal of Fisheries and Aquatic Sciences* 47, 1944-1958.
- Dionne, M., B. Sainte-Marie, E. Bourget, and D. Gilbert. 2003. Distribution and habitat selection of early benthic stages of snow crab *Chionoecetes opilio*. *Marine Ecology-Progress Series* 259:117-128.
- Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas. 2009. Ocean Acidification: The Other CO<sub>2</sub> Problem. *Annual Review of Marine Science* 1:169-192
- Dupont S, J. Havenhand, W. Thorndyke, L. Peck, and M. Thorndyke. 2008. Near-future level of CO<sub>2</sub>-driven ocean acidification radically affects larval survival and development in the brittlestar *Ophiothrix fragilis*. *Marine Ecology-Progress Series* 373:285-294.
- Egilsdottir H., J.I. Spicer, and S.D Rundle. 2009. The effect of CO<sub>2</sub> acidified sea water and reduced salinity on aspects of the embryonic development of the amphipod *Echinogammarus marinus* (Leach). *Marine Pollution Bulletin* 58:1187-1191



- Ellis, R.P., J. Bersey, S.D. Rundle, J.M. Hall-Spencer, and J.I. Spicer. 2009. Subtle but significant effects of CO<sub>2</sub> acidified seawater on embryos of the intertidal snail, *Littorina obtusata*. *Aquatic Biology* 5:41-48.
- Epelbaum, A.B., R.R. Borisov, and N.P. Kovatcheva. 2006. Early development of the red king crab *Paralithodes camtschaticus* from the Barents Sea reared under laboratory conditions: morphology and behavior. *Journal of the Marine Biological Association of the United Kingdom* 86:317-333.
- Fabry, V. J., J. B. McClintock, J. T. Mathis, and J. M. Grebmeier. 2009. Ocean acidification at high latitudes: The bellwether. *Oceanography* 22:160-171.
- Farley, E., J. Moss, J. Murphy, and L. Eisner. 2008. Variations in juvenile salmon, age-0 pollock, and age-0 Pacific cod catch per unit effort and distributions during fall 2002-2007 in the eastern Bering Sea-BASIS. In J. Boldt (ed.) Appendix C: Ecosystem Considerations for 2008. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- Feder, H., K. McCumby and A.J. Paul. 1980. The Food of Post-larval King Crab, *Paralithodes camtschatica*, in Kachemak Bay, Alaska (Decapoda, Lithodidae). *Crustaceana* 39(3): 315-318.
- Feder, H.M. and S.C. Jewett. 1981. Feeding interactions in the eastern Bering Sea with emphasis on the benthos p. 1229-1261. In D.W. Hood and J.A. Calder (eds.), *The eastern Bering Sea shelf: oceanography and resources*. Vol. 2. U.S. Dep. Commer., NOAA, University of Washington Wash. Press, Seattle, WA.
- Feely, R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero. 2004. Impact of anthropogenic CO<sub>2</sub> on the CaCO<sub>3</sub> system in the oceans. *Science* 305:362-366.
- Feely, R. A., S. C. Doney, and S. R. Cooley. 2009. Ocean acidification: present conditions and future changes in a high-CO<sub>2</sub> world. *Oceanography* 22:36-47.
- Findlay, H. S., M. A. Kendall, J. I. Spicer, and S. Widdicombe. 2009. Future high CO<sub>2</sub> in the intertidal may compromise adult barnacle *Semibalanus balanoides* survival and embryonic development rate. *Marine Ecology-Progress Series* 389:193-202.
- Gaeuman, W. B. 2010. Summary of the 2008/2009 mandatory shellfish observer program database for the rationalized crab fisheries. Alaska Department of Fish and Game, Fishery Data Series No. 10-01, Anchorage.
- Gaichas, S. and J. Bolt. 2009. Time trends in non-target species catch, pp.124-126. In J. Boldt and S. Zador (eds.) Appendix C: Ecosystem Considerations for 2009. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- Gao K, Z. Ruan, V. Villafane, J. Gattuso, and E. Helbling. 2009. Ocean acidification exacerbates the effect of UV radiation on the calcifying phytoplankter *Emiliania huxleyi*. *Limnology and Oceanography* 54:1855-1862.
- Gazeau F, J.P. Gattuso, C. Dawber, A.E. Pronker, F. Peene, J. Peene, C.H.R. Heip, and J.J. Middelburg. 2010. Effect of ocean acidification on the early life stages of the blue mussel *Mytilus edulis*. *Biogeosciences* 7:2051-2060.

- Gish, R. K. 2006. The 2005 Pribilof District king crab survey. Alaska Department of Fish and Game, Fishery Management Report. No. 06-60, Anchorage.
- Grant, T.G., J.N. Ianelli, and R.R. Lauth. 2009. Assessment of the Pacific cod Stock in the Bering Sea and Aleutian Islands. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands region. North Pacific Fishery Management Council, Anchorage, AK.
- Gravel, K. A., and D. Pengilly. 2007. Investigations on reproductive potential of snow and Tanner crab females from the eastern Bering Sea in 2005. Alaska Department of Fish and Game, Fishery Data Series No. 07-23, Anchorage.
- Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E.V., Carmack, E.C., Cooper, L.W., Frey, K.E., Helle, J.H., McLaughlin, F.A., McNutt, S.L. 2006. A major ecosystem shift in the northern Bering Sea. *Science* 311:1461-1464.
- Haflinger, K. 1981. A survey of benthic infaunal communities of the Southeastern Bering Sea shelf, p. 1091-1104. *In* D.W. Hood and J.A. Calder (eds.), *The eastern Bering Sea Shelf: Oceanography and Resources*, Vol. 2. U.S. Dept. Commer. NOAA. University of Washington Wash. Press, Seattle, WA.
- Hankin, D. G., T. H. Butler, P. W. Wild, and Q. L. Xue. 1997. Does intense fishing on males impair mating success of female Dungeness crabs? *Canadian Journal of Fisheries and Aquatic Sciences* 54:655-669.
- Hare, S. R. 2010. Assessment of the Pacific halibut stock at the end of 2010. nt. Pac. Halibut Comm. Report of Assessment and Research Activities in 2010. 91 pp.
- Hare, S.R., and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* 47:103-145.
- Hare, C.E., K. Leblanc, G.R. DiTullio, R.M. Kudela, Y. Zhang, P.A. Lee, S. Riseman, and D.A. Hutchins. 2007. Consequences of increased temperature and CO<sub>2</sub> for phytoplankton community structure in the Bering Sea. *Marine Ecology-Progress Series* 352:9-16.
- Hamazaki, T., Fair, L.F., Ward, L., Brenann E.L. 2005. Analyses of Bering Sea bottom-trawl surveys in Norton Sound: absence of regime shift effect on epifauna and demersal fish. *ICES Journal of Marine Science*. 62(8): 1597-1602.
- Hawkes, C.R., T.R. Meyers, and T.C. Shirley. 1985. Larval biology of *Briarosaccus callosus* Boschma (Cirripedia: Rhizocephala). *Proc. Biol. Soc. Washington*, Washington D.C. 98: 935-944.
- High, W.L., and Worlund, D.D. 1979. Escape of king crab, *Paralithodes camtschatica*, from derelict pots. NOAA Tech. Rep. No. NMFS SSRF-734.
- Hoegh-Guldberg, O. and J. F. Bruno. 2010. The Impact of Climate Change on the World's Marine Ecosystems. *Science* 328:1523-1528.
- Holladay, B. A., and B. L. Norcross. 1995. Diet diversity as a mechanism for partitioning nursery grounds of pleuronectids, pp 177-203. *In* International Symposium on North Pacific Flatfish. Alaska Sea Grant Coll. Program, Anchorage, AK

- Hunt Jr., G. L., C. Baduini, and J. Jahncke. 2002. Diets of short-tailed shearwaters in the southeastern Bering Sea. *Deep Sea Research Part II: Topical Studies in Oceanography* 49:6147-6156.
- Hunt, G.L., Jr., Allen, B.M., Angliss, R.P., Baker, T., Bond, N., Buck, G., Byrd, G.V., Coyle, K.O., Devol, A., Eggers, D.M., Eisner, L., Feely, R., Fitzgerald, S., Fritz, L.W., Gritsay, E.V., Ladd, C., Lewis, W., Mathis, J., Mordy, C.W., Mueter, F., Napp, J. Sherr, E., Shull, D., Stabeno, P., Stepanenko, M.A., Strom, S., Whitledge, T.E., 2010. Status and trends of the Bering Sea region, 2003-2008, pp. 196-267 In S.M. McKinnell and M.J. Dagg [Eds.] *Marine Ecosystems of the North Pacific Ocean, 2003-2008*. PICES Special Publication 4, 393 p.
- Hunt Jr., G.L., K.L. Coyle, L.B. Eisner, E.V. Farley, R.A. Heintz, F. Mueter, J.M. Napp, J.E. Overland, P.H. Ressler, S. Salo, P. Stabeno. 2011. Climate impacts on eastern Bering Sea foodwebs: a synthesis of new data and an assessment of the Oscillating Control Hypothesis. *ICES Journal of Marine Science* 68(5):2-15.
- Ianelli, J. S. Barbeaux, and T. Honkalehto. 2009. Assessment of the walleye pollock stock in the eastern Bering Sea. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands region. North Pacific Fishery Management Council, Anchorage, AK.
- Jensen, P.C., K. Califf, V.C. Lowe, L. Hauser, and J. F. Morado. 2010. Molecular detection of *Hematodinium* sp. in Northeast Pacific *Chionoecetes* spp. and evidence of two species in the Northern Hemisphere. *Diseases of Aquatic Organisms* 89:155-166.
- Jewett, S. C., and H. M. Feder. 1983. Food of the Tanner Crab *Chionoecetes bairdi* near Kodiak Island, Alaska. *Journal of Crustacean Biology* 3(2):196-207.
- Jewett, S.C., and C.P. Onuf. 1988. Habitat suitability index models: red king crab. U.S. Fish and Wildlife Service, Biological Report 82(10): 34 p.
- Johnson, T. 2003. The Bering Sea and Aleutian Islands: regions of wonder. Alaska Sea Grant College Program, University of Alaska Fairbanks, Alaska. 191 p.
- King, J. R. 2005. Report of the Study Group on fisheries and ecosystem responses to recent regime shifts. PICES Scientific Report vol. 28. 162 pp.
- Kinney, J. C., W. Maslowski, and S. Okkonen. 2009. On the processes controlling shelf-basin exchange and outer shelf dynamics in the Bering Sea. *Deep-Sea Research Part II-Topical Studies in Oceanography* 56:1351-1362.
- Krieger, K. J. and B. L. Wing. 2002. Megafauna associations with deepwater corals (*Primnoa* spp.) in the Gulf of Alaska. *Hydrobiologia* 471:83-90.
- Kroeker K.J., R.L. Kordas, R.N. Crim, and G.G. Singh. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology Letters* 13:1419-1434.
- Kruse, G.H., Livingston, P., Overland, J.E., Jamieson, G.S., McKinnell, S. and Perry, R.I. (eds.) 2006, Report of the PICES/NPRB Workshop on Integration of Ecological Indicators of the North Pacific with Emphasis on the Bering Sea. PICES Sci. Rep. No. 33, 109 pp.

- Kurihara, H., S. Shimode, and Y. Shirayama. 2004a. Effects of raised CO<sub>2</sub> concentration on the egg production rate and early development of two marine copepods (*Acartia steueri* and *Acartia erythraea*). *Marine Pollution Bulletin* 49:721-727.
- Kurihara, H., S. Shimode, and Y. Shirayama. 2004b. Sub-lethal effects of elevated concentration of CO<sub>2</sub> on planktonic copepods and sea urchins. *Journal of Oceanography* 60:743-750.
- Kuris, A.M., S.F. Blau, A.J. Paul, J.D. Shields, and D.E. Wickham. 1991. Infestation by brood symbionts and their impact on egg mortality of the red king crab, *Paralithodes camtschatica*, in Alaska: Geographic and temporal variation. *Canadian Journal of Fisheries and Aquatic Sciences* 48:559-568.
- Ladd, C., G. L. Hunt, C. W. Mordy, S. A. Salo, and P. J. Stabeno. 2005. Marine environment of the eastern and central Aleutian Islands. *Fisheries Oceanography* 14:22-38.
- Lang, G.M., C.W. Derrh, and P.A. Livingston. 2003. Groundfish food habits and predation on commercially important prey species in the eastern Bering Sea from 1993 to 1996. U.S. Dep. Commer., NOAA AFSC Processed Rep. 2003-04, 351 p. Alaska Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA, Seattle WA 98115.
- Lang, G.M., P.A. Livingston, and K.A. Dodd. 2005. Groundfish food habits and predation on commercially important prey species in the eastern Bering Sea from 1997 through 2001. U.S. Dep. Commer., NOAA Tech. Memo., NMFS-AFSC-158, 230 p.
- Lauth, R.R. 2009. Forage fish, eastern Bering Sea species, p. 69. *In* J. Boldt and S. Zador (eds.) Appendix C: Ecosystem Considerations for 2009. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- Lauth, R.R. 2010. Results of the 2009 eastern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo., NMFS-AFSC-204, 228 p.
- Lauth, R.R. *In Review*. Results of the 2010 eastern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo., NMFS-AFSC.
- Lauth, R.R. and E. Acuna. 2009. Results of the 2008 eastern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo., NMFS-AFSC-195, 229 p.
- Livingston, P.A. 1989. Interannual trends in Pacific cod, *Gadus macrocephalus*, predation on three commercially important crab species in the eastern Bering Sea. *Fishery Bulletin* 87: 807-827.
- Livingston, P.A., and B. J. Goiney, JR. 1983. Food habits literature of North Pacific marine fishes: a review and selected bibliography. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-54, 81 p.
- Livingston, P.A., A. Ward, G.M. Lang, and M.-S. Yang. 1993. Groundfish food habits and predation on commercially important prey species in the eastern Bering Sea from 1987 to 1989. NOAA Tech. Memo., NMFS-AFSC-11, 192 pp.

- Loher, T. and D.A. Armstrong. 2005. Historical changes in the abundance and distribution of ovigerous red king crabs (*Paralithodes camtschaticus*) in Bristol Bay (Alaska), and potential relationship with bottom temperature. *Fisheries Oceanography* 14:292-306.
- Loher, T. and D.A. Armstrong. 2000. Effects of habitat complexity and relative larval supply on the establishment of early benthic phase red king crab (*Paralithodes camtschaticus* Tilesius, 1815) populations in Auke Bay, Alaska. *Journal of Experimental Marine Biology and Ecology* 245:83-109.
- Loher, T., P.S. Hill, G. Harrington, and E. Cassano. 1998. "Management of Bristol Bay red king crab: a critical intersections approach to fisheries management." *Reviews in Fisheries Science* 6(3):169-251.
- Lovrich, G. A. and B. Sainte-Marie. 1997. Cannibalism in the snow crab, *Chionoecetes opilio* (O. Fabricius) (Brachyura: Majidae), and its potential importance to recruitment. *Journal of Experimental Marine Biology and Ecology* 211:225-245.
- Lovvorn, J.R. 2010. Predicting snow crab growth and size with climate warming in the northern Bering Sea. North Pacific Research Board Final Report 713, 24 p.
- Lovvorn, J.R., L.W. Cooper, M.L. Brooks, C.C. De Ruyck, J.K. Bump, and J.M. Grebmeier. 2005. Organic matter pathways to zooplankton and benthos under pack ice in late winter and open water in late summer in the north-central Bering Sea. *Marine Ecology-Progress Series* 291:135-150.
- Lowry, L. F., K. H. Frost, and J. J. Burns. 1980. Feeding of bearded seals in the Bering and Chukchi seas and trophic interaction with Pacific walruses. *Arctic* 33:330-342.
- Martin, M. 2010. Water temperature data collections - Aleutian Islands trawl surveys, p. 104. In S. Zador and S. Gaichas (eds.), Appendix C: Ecosystem Considerations for 2011. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- Maslowski, W., R. Roman, and J. C. Kinney. 2008. Effects of mesoscale eddies on the flow of the Alaskan Stream. *Journal of Geophysical Research-Oceans* 113.
- McConnaughey, R. A., K.L. Mier, and C.B. Dew. 2000. An examination of chronic trawling effects on soft-bottom benthos of the eastern Bering Sea. *ICES Journal of Marine Sciences* 57(5):1377-1388.
- McConnaughey, R. A., and K. R. Smith. 2000. Associations between flatfish abundance and surficial sediments in the eastern Bering Sea. *Canadian Journal of Fisheries and Aquatic Sciences* 57:2410-2419.
- Meyers, T. R., B. Eaton, S. Short, C. Botelho, T. Koeneman, A. Sparks, and F. Morado. 1990. Bitter crab dinoflagellate disease: overview of the causative agent and its importance and distribution in the Alaskan Tanner crab (*Chionoecetes bairdi*, *C. opilio*) fisheries, p. 405. In *Proceedings of the International Symposium on King and Tanner Crabs*. Lowell Wakefield Fisheries Symposium Series., Alaska Sea Grant Report, 90-04, University of Alaska Fairbanks, AK.
- Meyers, T.R., J.F. Morado, A.K. Sparks, G. Bishop, T. Pearson, J.D. Urban, and D. Jackson. 1996. The distribution of bitter crab syndrome in Tanner crabs (*Chionoecetes bairdi*, *C.*

- opilio*) from the Gulf of Alaska and the Bering Sea. *Disease of Aquatic Organisms* 26: 221-227.
- Mizobata, K., and S. Saitoh. 2004. Variability of Bering Sea eddies and primary productivity along the shelf edge during 1998-2000 using satellite multisensor remote sensing. *Journal of Marine Systems* 50:101-111.
- Morado, J.F., T.R. Meyers, and R.S. Otto. 2000. Distribution and prevalence of bitter crab syndrome in snow (*Chionoecetes opilio*) and Tanner (*Chionoecetes bairdi*) crabs of the Bering Sea. *Journal of Shellfish Research* 19: 646-647.
- Morado, J.F. 2010. Protistan diseases of commercially important crabs. *Journal of Invertebrate Pathology* (Spec. Issue). In press.
- Mueter, F.J. and M.A. Litzow. 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications* 18:309–320.
- Napp, J., and A. Yamaguchi. 2008. Bering Sea zooplankton, p. 66. *In* J. Boldt (ed) Appendix C: Ecosystem Considerations for 2008. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- National Marine Fisheries Service (NMFS). 2000. Endanger Species Act, Section 7 Consultations-Biological Assessments for Marine Mammal. National Marine Fisheries Service, Alaska Region.
- National Marine Fisheries Service (NMFS). 2002. Endanger Species Act, Section 7 Consultations-Biological Assessments for Seabirds. National Marine Fisheries Service, Alaska Region.
- National Marine Fisheries Service (NMFS). 2004. Final Environmental Impact Statement for Bering Sea and Aleutian Islands Crab Fisheries. National Marine Fisheries Service, Alaska Region.
- North Pacific Fishery Management Council (NPFMC). 1994. Environmental Assessment/Regulatory Impact Review for Amendment 21a to the Bering Sea/Aleutian Islands Groundfish Fishery Management Plan. North Pacific Fishery Management Council, Anchorage, AK.
- North Pacific Fishery Management Council (NPFMC). 1995. Environmental Assessment/Regulatory Impact Review for Amendment 37 to the Bering Sea/Aleutian Islands Groundfish Fishery Management Plan. North Pacific Fishery Management Council, Anchorage, AK.
- North Pacific Fishery Management Council (NPFMC). 1998. Fishery Management Plan for the Bering Sea/Aleutian Islands king and Tanner crabs. North Pacific Fishery Management Council, Anchorage, AK.
- North Pacific Fishery Management Council (NPFMC). 2003. Environmental Assessment for Amendment 17 to the Fishery Management Plan for the king and Tanner crab fisheries in the Bering Sea/Aleutian Islands: A rebuilding plan for the Pribilof Islands blue king crab stock. North Pacific Fishery Management Council, Anchorage, AK.

- North Pacific Fishery Management Council (NPFMC). 2007. Environmental Assessment for Amendment 24. Overfishing definitions for Bering Sea and Aleutian Islands King and Tanner crab stocks. North Pacific Fishery Management Council, Anchorage, AK.
- North Pacific Fishery Management Council (NPFMC). 2008. Fishery Management Plan for Bering Sea/Aleutian Islands King and Tanner Crabs. North Pacific Fishery Management Council, Anchorage, AK.
- North Pacific Fishery Management Council (NPFMC). 2010. Crab bycatch in the Bering Sea/Aleutian Islands Fisheries. North Pacific Fishery Management Council, Anchorage, AK.
- Okkonen, S. R. 1996. The influence of an Alaskan Stream eddy on flow through Amchitka Pass. *Journal of Geophysical Research-Oceans* 101:8839-8851.
- Orensanz, J. M., B. Ernst, D. A. Armstrong, P. Stabeno, and P. Livingston. 2004. Contraction of the geographic range of distribution of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea- an environmental ratchet? *California Cooperative Oceanic Fisheries Investigations (CALCOFI) Reports* 45: 65-79.
- Orensanz, J. M., B. Ernst, and D. A. Armstrong. 2007. Variation of female size and stage at maturity in snow crab (*Chionoecetes opilio*) (Brachyura : Majidae) from the eastern Bering sea. *Journal of Crustacean Biology* 27:576-591.
- Orlov 1998. The diets and feeding habits of some deep-water skates (*Rajidae*) in the Pacific waters off the Northern Kuril Islands and Southeastern Kamchatka. *Alaska Fishery Research Bulletin*. 5(1): 1-17.
- Ormseth, O., B. Matta, and J. Hoff. 2010. Bering Sea and Aleutian Islands skates. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands region. North Pacific Fishery Management Council, Anchorage, AK.
- Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R. M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R. G. Najjar, G. K. Plattner, K. B. Rodgers, C. L. Sabine, J. L. Sarmiento, R. Schlitzer, R. D. Slater, I. J. Totterdell, M. F. Weirig, Y. Yamanaka, and A. Yool. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* 437:681-686.
- Otto, R. S., and P. A. Cummiskey. 1985. Observation on the reproductive biology of golden king crab (*Lithodes aequispina*) in the Bering Sea and the Aleutian Islands, pp 123-135. *In* B. Melteff (*ed.*) *Proceedings of the International King Crab Symposium*. Alaska Sea Grant College Program Report No. 85-12, University of Alaska Fairbanks, AK.
- Otto R.S., R.A. MacIntosh, and P.A. Cummiskey. 1990. Fecundity and other reproductive parameters of female red king crab (*Paralithodes camtschatica*) in Bristol Bay and Norton Sound, Alaska, p. 65-90 *In* B. Melteff (*ed.*) *Proceedings of the International Symposium on King and Tanner crabs*. Alaska Sea Grant College Program Report No. 90-04, University of Alaska Fairbanks, AK.
- Overland, J.E., J.M. Adams, and N.A. Bond. 1999. Decadal variability of the Aleutian Low and its relation to high-latitude circulation. *Journal of Climate* 12:1542-1548.

- Overland, J.E. and P.J. Stabeno. 2004. Is the climate of the Bering Sea warming and affecting the ecosystem? EOS 85:309-316.
- Overland, J.E., S. Rodionov, S. Minobe, N. Bond. 2008. North Pacific regime shifts: Definitions, issues and recent transitions. Progress in Oceanography 77:92-102.
- Overland, J.E. 2008. Ice cover index data reported on the NOAA Bering Climate web page: [//www/beringclimate.noaa.gov/data/BCresult.php](http://www/beringclimate.noaa.gov/data/BCresult.php)
- Overland, J.E., P.J. Stabeno, M.Y. Wang, C. Ladd, N.A. Bond, and S. Salo. 2009 Eastern Bering Sea climate, FOIC, pp. 47-52. In J. Boldt and S. Zador (eds.) Appendix C: Ecosystem Considerations for 2009. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- Palacios, R., D. A. Armstrong, J. L. Armstrong, and G. Williams. 1985. Community analysis applied to characterization of blue king crab habitat around the Pribilof Islands, pp 193-209. In Proceedings of the international king crab symposium. Alaska Sea Grant Program Report No. 85-12, University of Alaska Fairbanks, AK.
- Parada, C., D.A. Armstrong, B. Ernst, S. Hinckley, and J.M. Orensanz. 2010. Spatial dynamics of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea, putting together the pieces of the puzzle. Bulletin of Marine Science, 86(2):413-437.
- Parker, L. M., P. M. Ross, and W. A. O'Connor. 2009. The effect of ocean acidification and temperature on the fertilization and embryonic development of the Sydney rock oyster *Saccostrea glomerata* (Gould 1850). Global Change Biology 15:2123-2136.
- Parker, L. M., P. M. Ross, and W. A. O'Connor. 2010. Comparing the effect of elevated pCO<sub>2</sub> and temperature on the fertilization and early development of two species of oysters. Marine Biology 157:2435-2452.
- Paul, J. M., and A. J. Paul. 1990. Breeding success of sublegal size male red king crab *Paralithodes camtschatica* (Tilesius, 1815) (Decapoda, Lithodidae). Journal of Shellfish Research 9:29-32.
- Paul, A. J., and J. M. Paul. 1996. Male Tanner crab carapace widths at previous intermolt estimated from laboratory growth, Kachemak Bay, Alaska. Alaska Fishery Research Bulletin 3(2):132-135.
- Paul, A. J., and J. M. Paul. 1997. Breeding success of large male red king crab *Paralithodes camtschaticus* with multiparous mates. Journal of Shellfish Research 16:379-381.
- Paul, A. J., and J. M. Paul. 2001a. Effects of temperature on length of intermolt periods in juvenile male *Chionoecetes bairdi*. Alaska Fishery Research Bulletin 8(2):132-134.
- Paul, A. J., and J. M. Paul. 2001b. Growth of juvenile golden king crabs *Lithodes aequispinus* in the laboratory. Alaska Fishery Research Bulletin 8(2):135-138.
- Paul, J.M., A.J. Paul, and A. Kimker. 1994. Compensatory feeding capacity of 2 brachyuran crabs, Tanner and Dungeness, after starvation periods like those encountered in pots. Alaska Fishery Research Bulletin 1:184-187.



- Paul, A.J., J.M. Paul, P.A. Shoemaker, and H.M. Feder. 1979. Prey concentrations and feeding response in laboratory-reared stage-one zoeae of king crab, snow crab, and pink shrimp. *Transactions of American Fisheries Society* 108: 440-443.
- Paul, J. M. 1982. Distribution of Juvenile *Chionoecetes Bairdi* in Cook Inlet. *In Proceedings of the international symposium on the Genus Chionoecetes*. Alaska Sea Grant Program Report No. 82-10, University of Alaska Fairbanks, AK.
- Pirtle, J.L. and A.W. Stoner. 2010. Red king crab (*Paralithodes camtschaticus*) early post-settlement habitat choice: Structure, food, and ontogeny. *Journal of Experimental Marine Biology and Ecology* 393:130-137.
- Quandt, A. 1999. Assessment of fish trap damage on coral reefs around St. Thomas, USVI. Independent Project Report, University of Virginia Institute, Virginia. 9 p.
- Raven. J., K. Caldeira, H. Elderfield, O. Hoegh-Guldberg, P. Liss, U. Riebesell, J. Shepherd, C. Turley, and A. Watson. 2006. Ocean acidification due to increasing atmospheric carbon dioxide. The Royal Society Policy Document 12 5.
- Renner, M., G.L. Hunt, J.F. Piatt, G.V. Byrd. 2008. Seasonal and distributional patterns of seabirds along the Aleutian Archipelago. *Marine Ecology-Progress Series* 357:301-311.
- Rho, T.K., T. E. Whitley, and J.J. Goering. 2005. Interannual variations of nutrients and primary production over the southeastern Bering Sea shelf during the spring of 1997, 1998, and 1999. *Oceanology*, 45(3):376-390.
- Ricker, W.R. 1954. Stock and recruitment. *Journal of the Fisheries Research Board of Canada* 11, 559–623.
- Ries, J.B., A.L. Cohen, and D.C. McCorkle. 2009. Marine calcifiers exhibit mixed responses to CO<sub>2</sub>-induced ocean acidification. *Geology* 37:1131-1134.
- Rodin, V. E. 1989. Population Biology of the King Crab *Paralithodes camtschatica* Tilesius in the North Pacific Ocean. *In: Kruse et al, (eds.)*, Proceedings of the International Symposium on King and Tanner Crabs, Alaska Sea Grant Report No 90-04, University of Alaska, Fairbanks.
- Rodolfo-Metalpa R., C. Lombardi, S. Cocito, J.M. Hall-Spencer, and M.C. Gambi. 2010a. Effects of ocean acidification and high temperatures on the bryozoan *Myriapora truncata* at natural CO<sub>2</sub> vents. *Mar Ecol-Evol Persp* 31:447-456.
- Rodolfo-Metalpa R., S. Martin, C. Ferrier-Pages, and J.P. Gattuso. 2010b. Response of the temperate coral *Cladocora caespitosa* to mid- and long-term exposure to pCO<sub>2</sub> and temperature levels projected for the year 2100 AD. *Biogeosciences* 7:289-300.
- Rose, C.S., J.R. Gauvin, and C.F. Hammond. 2010. Effective herding of flatfish by cables with minimal seafloor contact. *Fishery Bulletin* 108:136-144.
- Rosenkranz, G.E. and M. Spafard. 2010. Summary of observer data collected during the 2008/2009 Alaska weathervane scallop fishery. Alaska Department of Fish and Game, Fishery Data Series No. 10-97, Anchorage.
- Rosenkranz, G.E. 2010. Summary of observer data collected during the 2007/2008 Alaska weathervane scallop fishery. Alaska Department of Fish and Game, Fishery Data Series No. 10-36, Anchorage.

- Rosenkranz, G.E., A.V. Tyler, and G.H. Kruse. 2001. Effects of water temperature and wind on year-class success of Tanner crabs in Bristol Bay, Alaska. *Fisheries Oceanography* 10:1-12.
- Rosenkranz, G.E., A.V. Tyler, G.H. Kruse, and H.J. Niebauer. 1998. Relationship between wind and year class strength of Tanner crabs in the southeastern Bering Sea. *Alaska Fishery Research Bulletin* 5:18-24.
- Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K. Lee, J.L. Bullister, R. Wanninkhof, C.S. Wong, D.W.R. Wallace, B. Tilbrook, F.J. Millero, T.H. Peng, A. Kozyr, T. Ono, and A.F. Rios. 2004. The ocean sink for anthropogenic CO<sub>2</sub>. *Science* 305:367-371.
- Sadorus, L.L. and Lauth, R. 2009. Cruise report for the 2009 NMFS Bering Sea trawl survey. Int. Pac. Halibut Comm. Report of Assessment and Research Activities in 2010. 91 pp.
- Sainte-Marie, B., T. Gosselin, J.M. Seigny, and N. Urbani. 2008. The snow crab mating system: Opportunity for natural and unnatural selection in a changing environment. *Bulletin of Marine Science* 83:131-161.
- Sainte-Marie, B., S. Raymond, and J.C. Brethes. 1995. Growth and maturation of the benthic stages of male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). *Canadian Journal of Fisheries and Aquatic Sciences* 52:903-924.
- Sato, T., M. Ashidate, and S. Goshima. 2005a. Negative effects of delayed mating on the reproductive success of female spiny king crab, *Paralithodes brevipes*. *Journal of Crustacean Biology* 25:105-109.
- Sato, T., M. Ashidate, S. Wada, and S. Goshima. 2005b. Effects of male mating frequency and male size on ejaculate size and reproductive success of female spiny king crab *Paralithodes brevipes*. *Marine Ecology-Progress Series* 296:251-262.
- Sato, T., M. Ashidate, T. Jinbo, and S. Goshima. 2006. Variation of sperm allocation with male size and recovery rate of sperm numbers in spiny king crab *Paralithodes brevipes*. *Marine Ecology-Progress Series* 312:189-199.
- Sato, T., and S. Goshima. 2006. Impacts of male-only fishing and sperm limitation in manipulated populations of an unfished crab, *Hapalogaster dentata*. *Marine Ecology-Progress Series* 313:193-204.
- Schumacher, J.D., N.A. Bond, R.D. Brodeur, P.A. Livingston, J.M. Napp, and P.J. Stabeno. 2003. Climate change in the southeastern Bering Sea and some consequences for biota, p. 17-40. *In* G. Hempel and K. Sherman (eds.) *Large Marine Ecosystems of the World-Trends in Exploitation, Protection and Research*. Elsevier Science, Amsterdam.
- Shepherd, J.G., J.G. Pope, and R.D. Cousens. 1984. Variations in fish stocks and hypotheses concerning their links with climate. *Rapports P.-v Reunions Conseil international pour L'Exploration de la Mer* 185, 255-267.
- Shimek, R.L. 1984. The diets of Alaskan *Neptunea*. *Veliger* 26:274-281.
- Shirley, T.C. 2006. Cultivation potential of golden king crab, pp. 47-54. *In* B. Stevens (ed.) *Alaska crab stock enhancement and rehabilitation*, Alaska Sea Grant Report No 06-04, University of Alaska, Fairbanks

- Shirley, T.C. and S. M. Shirley. 1989. Temperature and salinity tolerances and preferences of red king crab larvae. *Marine and Freshwater Behavior and Physiology* 16:19-30.
- Shirley, T.C., and S. Zhou. 1997. Lecithotrophic development of the golden king crab *Lithodes aequispinus* (Anomura: Lithodidae). *Journal of Crustacean Biology* 17:207–216.
- Siddeek, S.M.S., J. Zheng, J.F. Morado, G. Kruse, and W. Bechtol. 2010. Rebuilding analysis of the eastern Bering Sea Tanner crab stock: Consideration of new overfishing definitions and bitter crab disease. *ICES Journal of Marine Science* 67:000-000.
- Simenstad, C.A., J.S. Isakson, and R.E. Nakatani. 1977. Marine fish communities of Amchitka Island, AK, pp. 451-492. *In* M. L. Merritt and R. G. Fuller (eds.), *The Environment of Amchitka Island, Alaska*. U.S. ERDA, TID-26712.
- Slater, L. M., K. A. MacTavish, and D. Pengilly. 2010. Preliminary analysis of spermathecal load of primiparous snow crabs (*Chionoecetes opilio*) from the eastern Bering Sea, 2005-2008. *In*: G.H. Kruse, G.L. Eckert, R.J. Foy, R.N. Lipcius, B. Sainte-Marie, D.L. Stram, and D. Woodby (eds.), *Biology and management of exploited crab populations under climate change*. Alaska Sea Grant, University of Alaska Fairbanks.
- Slizkin, A. G. 1989. Tanner Crabs (*Chionoecetes opilio*, *C. bairdi*) of the Northwest Pacific: Distribution, Biological Peculiarities, and Population Structure. *In*: Kruse et al, (eds.), *Proceedings of the International Symposium on King and Tanner Crabs*, Alaska Sea Grant Report No 90-04, University of Alaska, Fairbanks
- Smith, B. D., and G. S. Jamieson. 1991. Possible consequences of intensive fishing for males on the mating opportunities of Dungeness crabs. *Transactions of the American Fisheries Society* 120:650-653.
- Smith, K.R., and R.A. McConnaughey. 1999. Surficial sediments of the eastern Bering Sea continental shelf: EBSSSED database documentation. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-104, 41 p.
- Smith, K.R. and C.E. Armistead. *In review*. *Neptunea* species on the eastern Bering Sea shelf. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-xx, 45p.
- Somerton, D.A., and R.A. MacIntosh. 1985. Reproductive biology of the female blue king crab *Paralithodes platypus* near the Pribilof Islands, Alaska. *Journal of Crustacean Biology* 5 (3): 365-376.
- Somerton, D.A., and R.S. Otto. 1986. Distribution and reproductive biology of the golden king crab, *Lithodes aequispina*, in the eastern Bering Sea. *Fishery Bulletin* 84:571-584.
- Somerton, D.A. and W. Donaldson. 1998. Parasitism of the golden king crab, *Lithodes aequispinus*, by two species of snailfish, genus *Careproctus*. *Fishery Bulletin* 96:871-884.
- Soong, J. 2008. Analysis of red king crab data from the 2008 Alaska Department of Fish and Game trawl survey of Norton Sound. *Fishery Data Series No. 08-58*, Nome.
- Sparks, A.K., and J. Hibbits. 1979. Black mat syndrome, an invasive mycotic disease of the Tanner crab, *Chionoecetes bairdi*. *Journal of Invertebrate Pathology* 34:184-191.
- Sparks, A.K. and J.F. Morado. 1986a. A herpes-like virus disease in the blue king crab, *Paralithodes platypus*. *Diseases of Aquatic Organisms* 1: 115-122.

- Sparks, A.K. and J.F. Morado. 1986b. Observations on the histopathology and host response in lithodid crabs parasitized by *Briarosaccus callosus*. *Diseases of Aquatic Organisms* 2: 31-38
- Squires, H.J., and E.G. Dawe. 2003. Stomach contents of snow crab (*Chionoecetes opilio*, Decapoda, Brachyura) from the Northeast Newfoundland Shelf. *Journal of Northwest Atlantic Fishery Science* 32:27-38.
- Stabeno, P.J., N.A. Bond, N.B. Kachel, S.A. Salo, and J.D. Schumacher. 2001. On the temporal variability of the physical environment over the south-eastern Bering Sea. *Fisheries Oceanography* 10:81-98.
- Stabeno, P. J., N. Kachel, C. Mordy, D. Righi, and S. Salo. 2008. An examination of the physical variability around the Pribilof Islands in 2004. *Deep-Sea Research Part II-Topical Studies in Oceanography* 55:1701-1716.
- Stevens, B.G. and K.M. Swiney. 2005. Post-settlement effects of habitat type and predator size on cannibalism of glaucothoe and juveniles of red king crab *Paralithodes camtschaticus*. *Journal of Experimental Marine Biology and Ecology* 321(1): 1-11.
- Stevenson, D. 2004. Identification of skates, sculpins, and smelts by observers in north Pacific groundfish fisheries (2002-2003), U.S. Dep. Commer. Tech. Memo. NMFS-AFSC-142. 67 p.
- Stevenson, D. and G. Hoff. 2009. Species Identification Confidence in the Eastern Bering Sea Shelf Survey (1982-2008). U.S. Dep. Commer. Processed Report. NMFS-AFSC-2009-04. 56 p.
- Stone, R.P. 2006. Coral habitat in the Aleutian Islands: depth distribution, fine-scale species associations, and fisheries interactions. *Coral Reefs* 25(2): 229-238.
- Stoner, A.W., M.L. Ottmar, and S.A. Haines. 2010. Temperature and habitat complexity mediate cannibalism in red king crab: Observations on activity, feeding, and prey defense mechanisms. *Journal of Shellfish Research* 29, 1-8.
- Taggart, S.J., T.C. Shirley, C.E. O'Clair, and J. Mondragon. 2004. Dramatic increase in the relative abundance of large male Dungeness crabs *Cancer magister* following closure of commercial fishing in Glacier Bay, Alaska. *American Fisheries Society Symposium* 42: 243-253.
- Talmage S.C., and C.J. Gobler. 2009. The effects of elevated carbon dioxide concentrations on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*). *Limnology and Oceanography* 54:2072-2080.
- Taylor, D.M., and R.A. Khan. 1995. Observations on the occurrence of *Hematodinium* sp. (Dinoflagellata: *Syndinidae*), the causative agent of bitter crab disease in Newfoundland snow crab (*Chionoecetes opilio*). *Journal of Invertebrate Pathology* 65:283-288.
- Thompson, G.G. J. N. Ianelli, and R.R. Lauth. 2009. Assessment of the Pacific Cod Stock in the Eastern Bering Sea and Aleutian Islands Area. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands region. North Pacific Fishery Management Council, Anchorage, AK.

- Tyler, A.V. and G.H. Kruse. 1996. Conceptual modeling of brood strength of red king crabs in the Bristol Bay region of the Bering Sea, p. 511-543. *In* High Latitude Crabs: Biology, Management, and Economics. Alaska Sea Grant College Program Report No. 96-02, University of Alaska, Fairbanks, AK.
- Urban, J.D. 2010. Pacific cod predation on Tanner crab in Marmot Bay, Alaska. In: G.H. Kruse, G.L. Eckert, R.J. Foy, R.N. Lipcius, B. Sainte-Marie, D.L. Stram, and D. Woodby (eds.), Biology and management of exploited crab populations under climate change. Alaska Sea Grant, University of Alaska Fairbanks.
- Walther, K., K. Anger, and H. O. Pörtner. 2010. Effects of ocean acidification and warming on the larval development of the spider crab *Hyas araneus* from different latitudes (54° vs. 79°N). *Mar Ecol Prog Ser* 417:159-170
- Wang, M., C. Ladd, J. Overland, P. Stabeno, N. Bond, and S. Salo. 2008 Eastern Bering Sea Climate- FOCI. 2008, p. 106-113. *In* J. Boldt (ed) Appendix C: Ecosystem Considerations for 2008. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- Wang, M.Y., J.E. Overland, and N. A. Bond. 2010. Climate projections for selected large marine ecosystems. *Journal of Marine Systems* 79:258-266.
- Watson S., P. Southgate, P. Tyler, and L. Peck. 2009. Early larval development of the sydney rock oyster *Saccostrea glomerata* under near-future predictions of CO<sub>2</sub>-driven ocean acidification. *Journal of Shellfish Research* 28:431-437.
- Webb, J. and D. Woodby. 2008. Long-term Alaska crab research priorities preliminary draft update, 2008. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 5J08-04, Juneau.
- Wespestad, V.G., Livingston, P.A. and Reeves, J.E. 1994. Juvenile sockeye salmon (*Oncorhynchus nerka*) predation on Bering Sea red king crab (*Paralithodes camtschaticus*) larvae as a cause of recruitment variation. ICEC C.M. 1994/R:10, Copenhagen, 10 pp.
- Wilderbuer, T.K., D.G. Nichol, and J. Ianelli. 2009. Yellowfin Sole. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands region. North Pacific Fishery Management Council, Anchorage, AK.
- Wood H.L., J.I. Spicer, and S. Widdicombe. 2008. Ocean acidification may increase calcification rates, but at a cost. *Proceedings of the Royal Society B-Biological Sciences* 275:1767-1773.
- Yang, M.S. 2003. Food habits of the important groundfishes in the Aleutian Islands in 1994 and 1997. U.S. Dep. Commer., NOAA AFSC Processed Rep. 2003-07, 231 p. Alaska Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA, Seattle WA 98115.
- Yang, M.S. 2007. Food habits and diet overlap of seven skate species in the Aleutian Islands. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-177, 57 p.
- Yeung, C., and R.A. McConnaughey. 2006. Community structure of eastern Bering Sea epibenthic invertebrates from summer bottom-trawl surveys 1982 to 2002. *Marine Ecology-Progress Series* 318:47-62.

- Yeung, A., M.S. Yang, R. A. McConnaughey. 2010. Polychaete assemblages in the south-eastern Bering Sea: linkages with groundfish distribution and diet. *Journal of the Marine Biology Association of the United Kingdom* 90(5):903-917.
- Zador, S. and S. Gaichas (*eds.*). 2010. Appendix C: Ecosystem Considerations for 2011. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, North Pacific Fishery Management Council, Anchorage, AK.
- Zheng, J. 2008. Temporal changes in size at maturity and their implications for fisheries management for eastern Bering Sea Tanner crab. *Journal of Northwest Atlantic Fishery Science* 41:137-149.
- Zheng, J., and G.H. Kruse. 2000. Recruitment patterns of Alaskan crabs and relationships to decadal shifts in climate and physical oceanography. *ICES Journal of Marine Science* 57:438-451.
- Zheng, J., and G.H. Kruse. 2003. Stock-recruitment relationships for three major Alaskan crab stocks. *Fisheries Research* 65: 103-121.
- Zheng, J., and G.H. Kruse. 2006. Recruitment variation of eastern Bering Sea crabs: climate-forcing or top-down effects? *Progress in Oceanography* 68: 184-204.
- Zheng, J., G. H. Kruse, and D. R. Ackley. 2001. Spatial distribution and recruitment patterns of snow crabs in the eastern Bering Sea. Pages 233–255 *in* G. H. Kruse, N. Bez, A. Booth, M.W. Dorn, S. Hills, R. N. Lipcius, D. Pelletier, C. Roy, S. J. Smith, and D. Witherell, eds. *Spatial processes and management of marine populations*. Alaska Sea Grant College Program, Report No. AK-SG-01–02. Fairbanks, Alaska.
- Zheng, J., M.C. Murphy, and G.H. Kruse. 1997. Application of a catch-survey analysis to blue king crab stocks near Pribilof and St. Matthew Islands. *Alaska Fishery Research Bulletin* 4(1): 62-74.
- Zheng, J., and D. Pengilly, 2011. Overview of proposed harvest strategy and minimum size limits for Bering Sea District Tanner crab. Alaska Department of Fish and Game, Special Publication No. 11-02, Anchorage.
- Zhou, S. and T. C. Shirley. 1998. A submersible study of red king crab and Tanner crab distribution by habitat and depth. *Journal of Shellfish Research* 17(5):1477-1479.

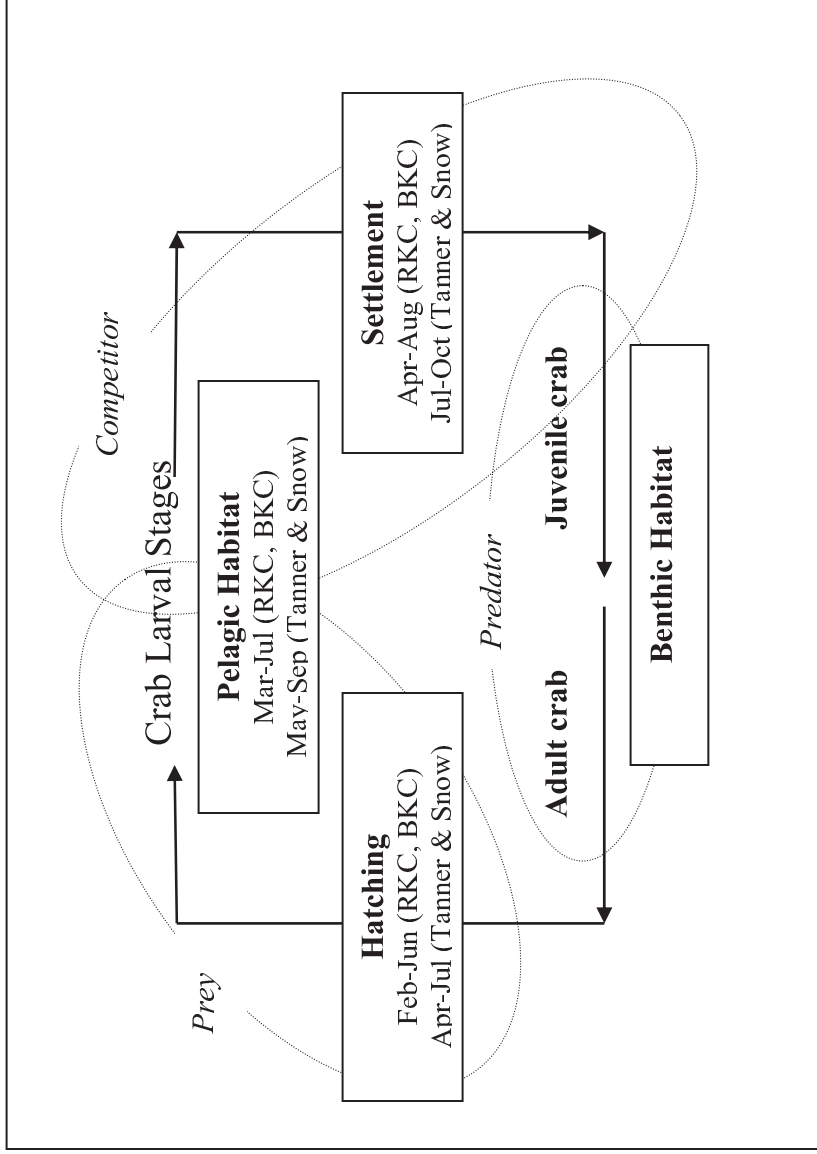


Figure 1. Seasonal timing and duration of crab life history stages in relation to the physical and biological components of the Bering Sea/Aleutian Island ecosystem, red king crab (RKC) and blue king crab (BKC).

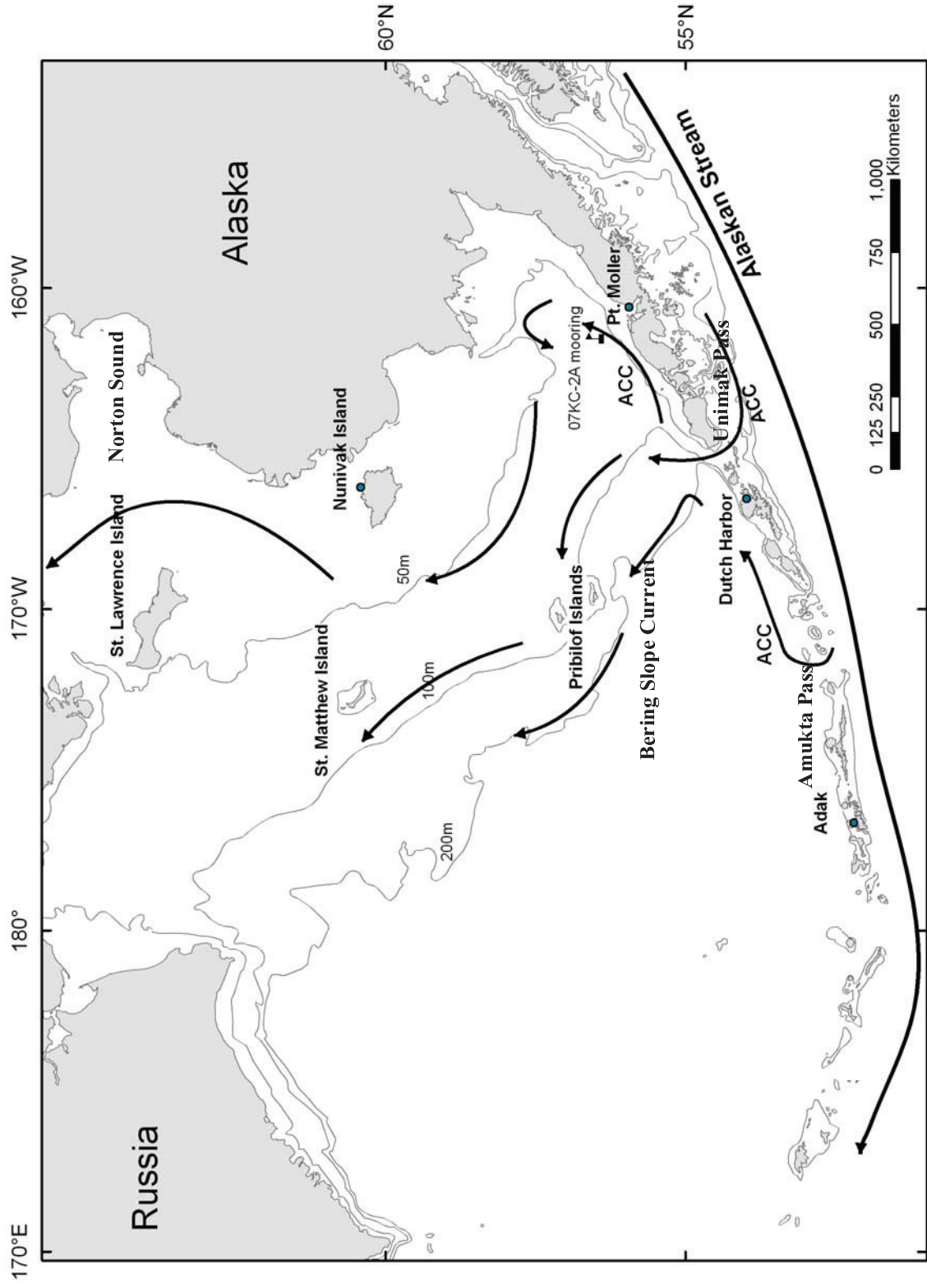


Figure 2. Inner, Middle, and Outer domains on the eastern Bering Sea shelf with King Crab mooring 2A (KC-2A) and major current flow depicted, including the Alaska Coastal Current (ACC) entering through Unimak Pass (Current flow from Stabeno et al. 2001).



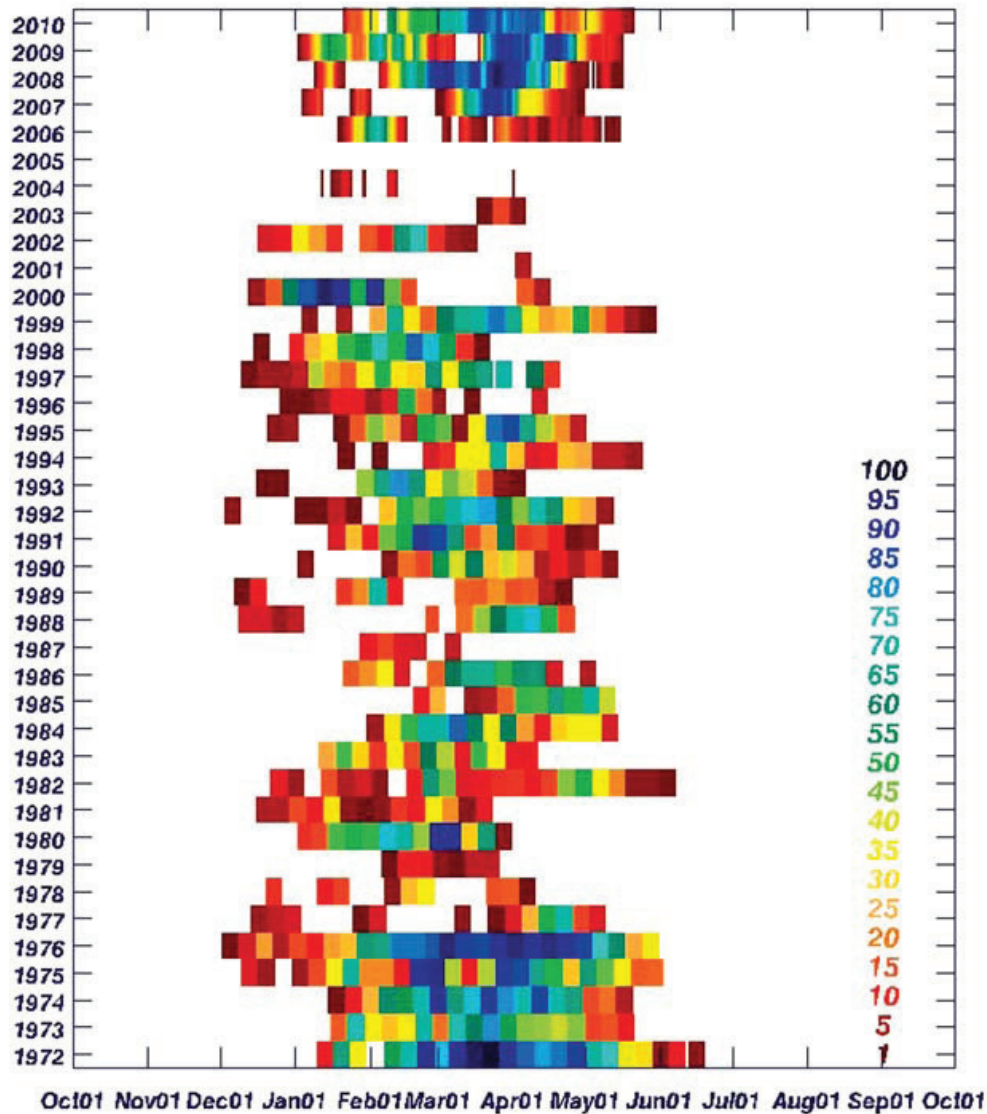


Figure 3. The percentage of sea ice coverage in the eastern Bering Sea as the average ice concentration in a  $2^{\circ} \times 2^{\circ}$  box at  $56\text{-}58^{\circ}\text{N}$ ,  $163\text{-}165^{\circ}\text{W}$  from 1972-2010. The numeric color scale on the right corresponds with the percentage of ice coverage (Source: Hunt et al. 2011).

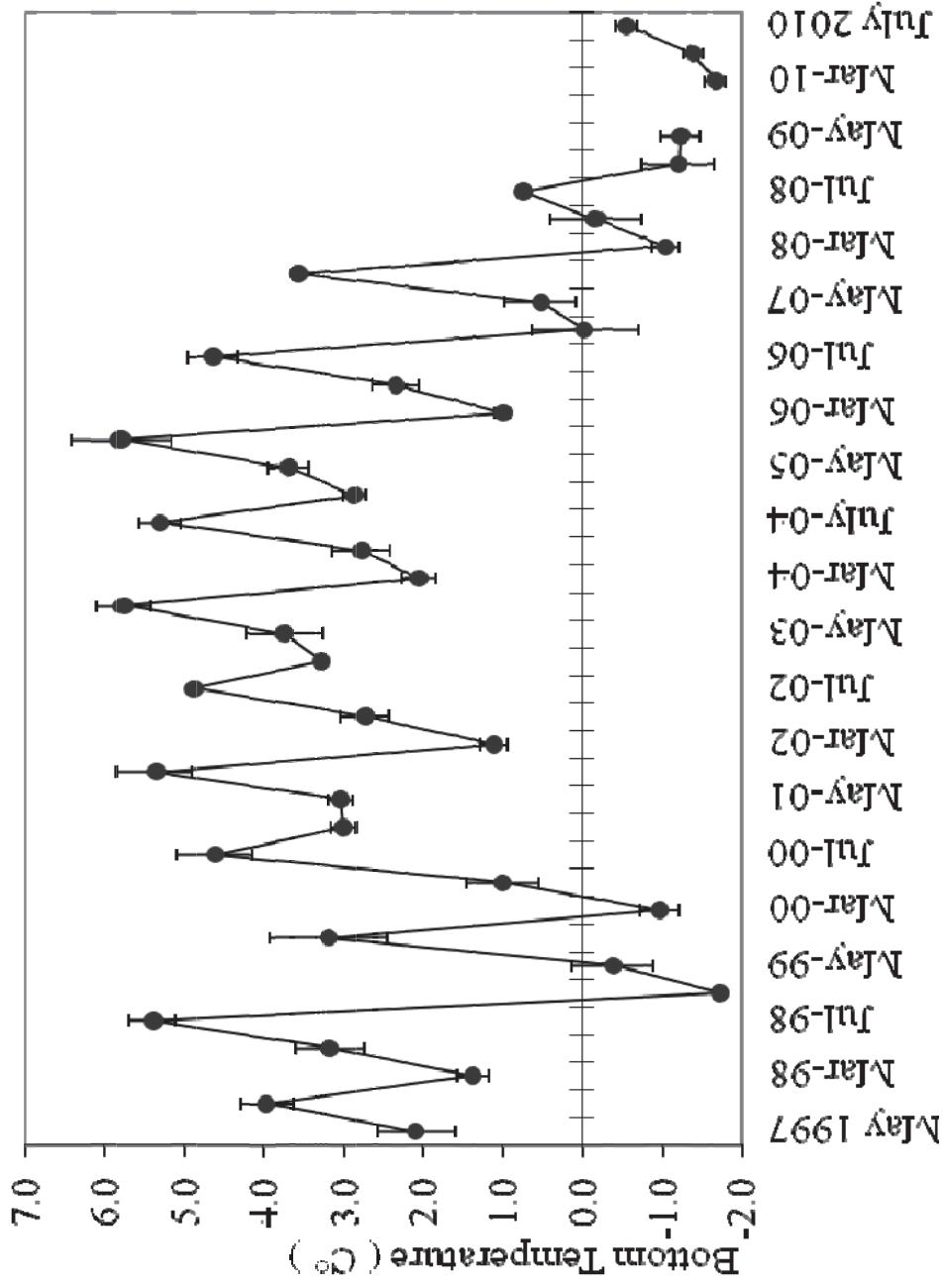


Figure 4. Monthly averaged water temperatures ( $^{\circ}\text{C} \pm \text{SD}$ ) at the Bristol Bay mooring M2 in eastern Bering Sea from May 1997 to July 2010. Data in July 2009 was not available.

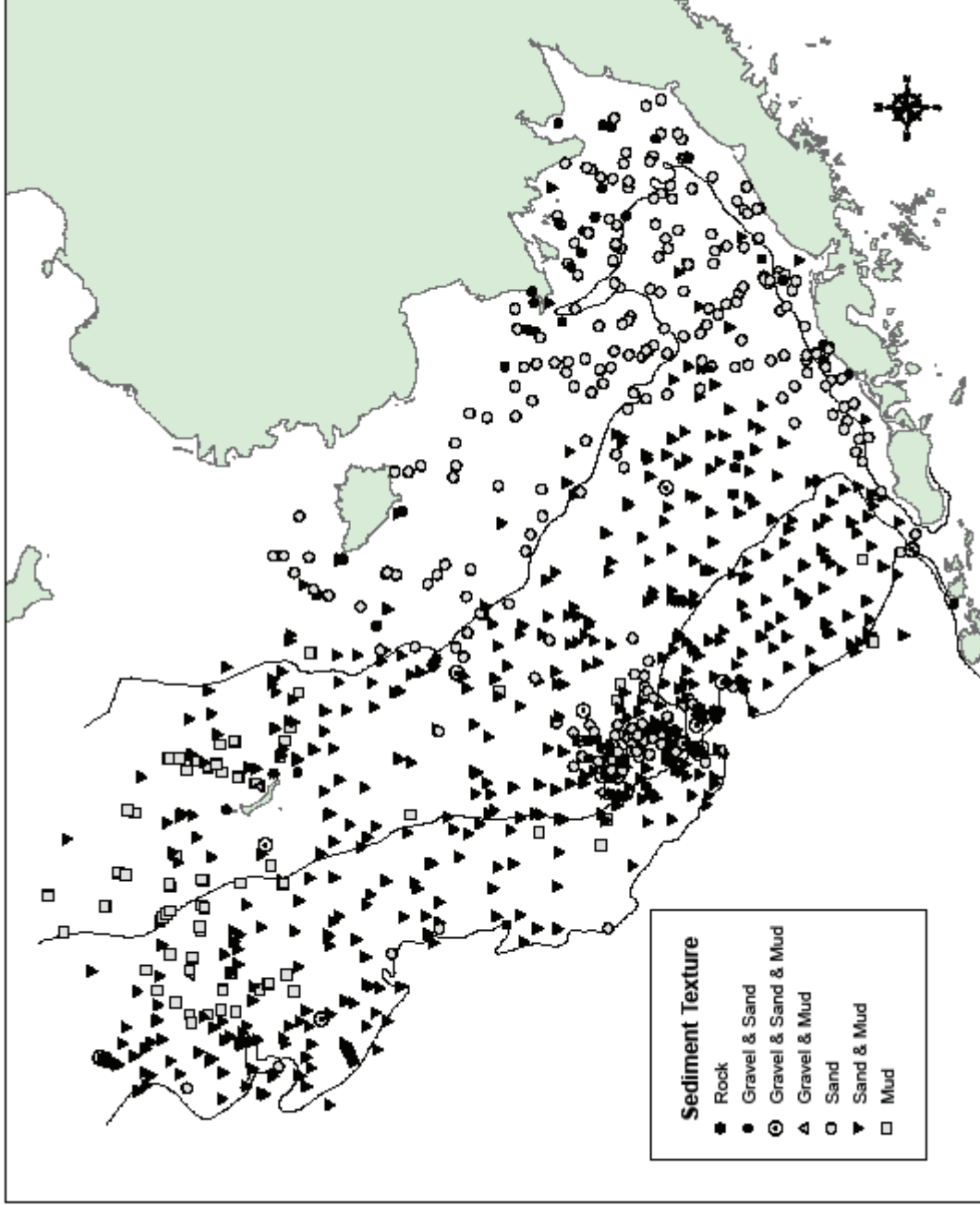


Figure 5. Distribution of benthic sediment types in the eastern Bering Sea (Source: Smith and McConnaughey 1999).

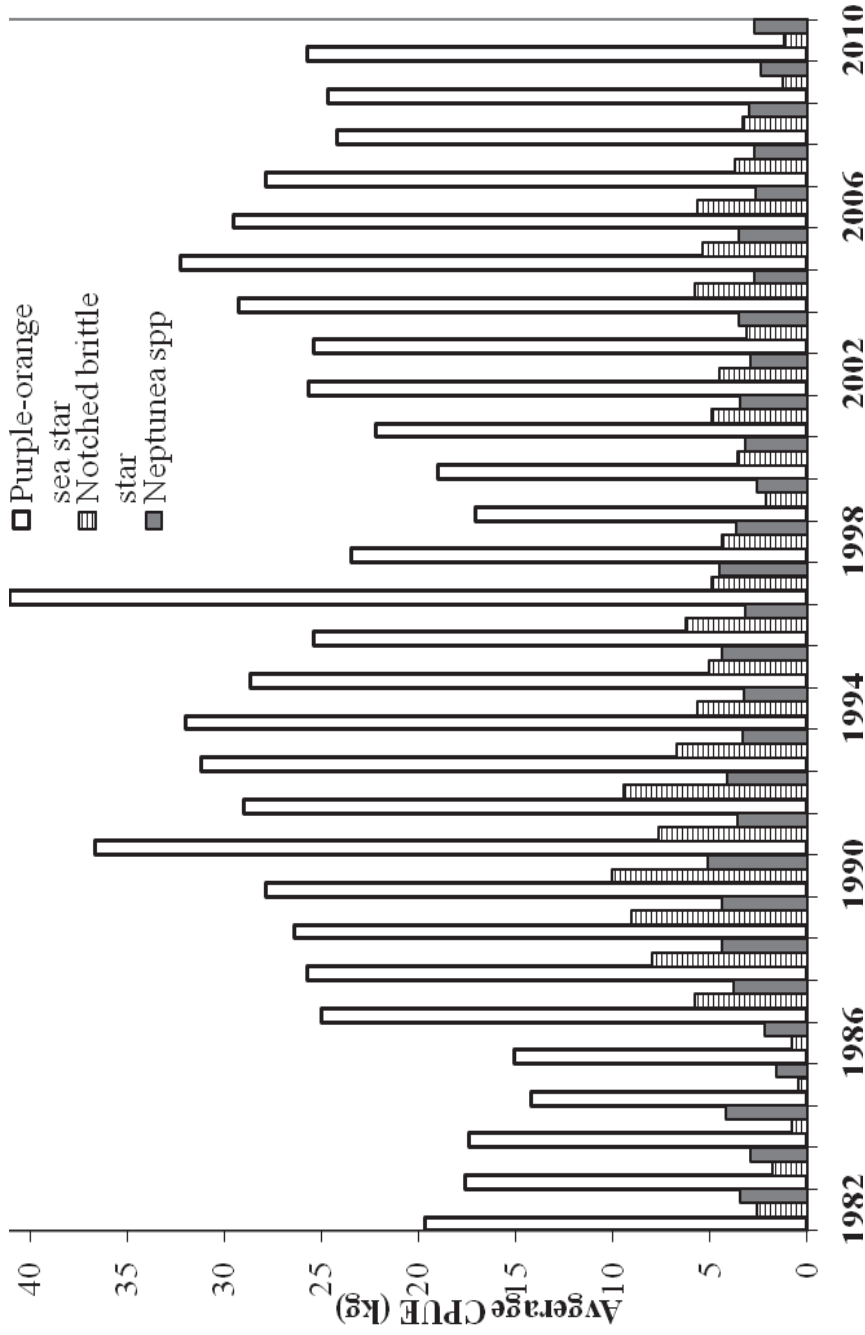


Figure 6. Average Catch Per Unit Effort (CPUE) by weight (kg) of the most prevalent benthic invertebrates caught on the eastern Bering Sea bottom trawl survey from 1982-2010.

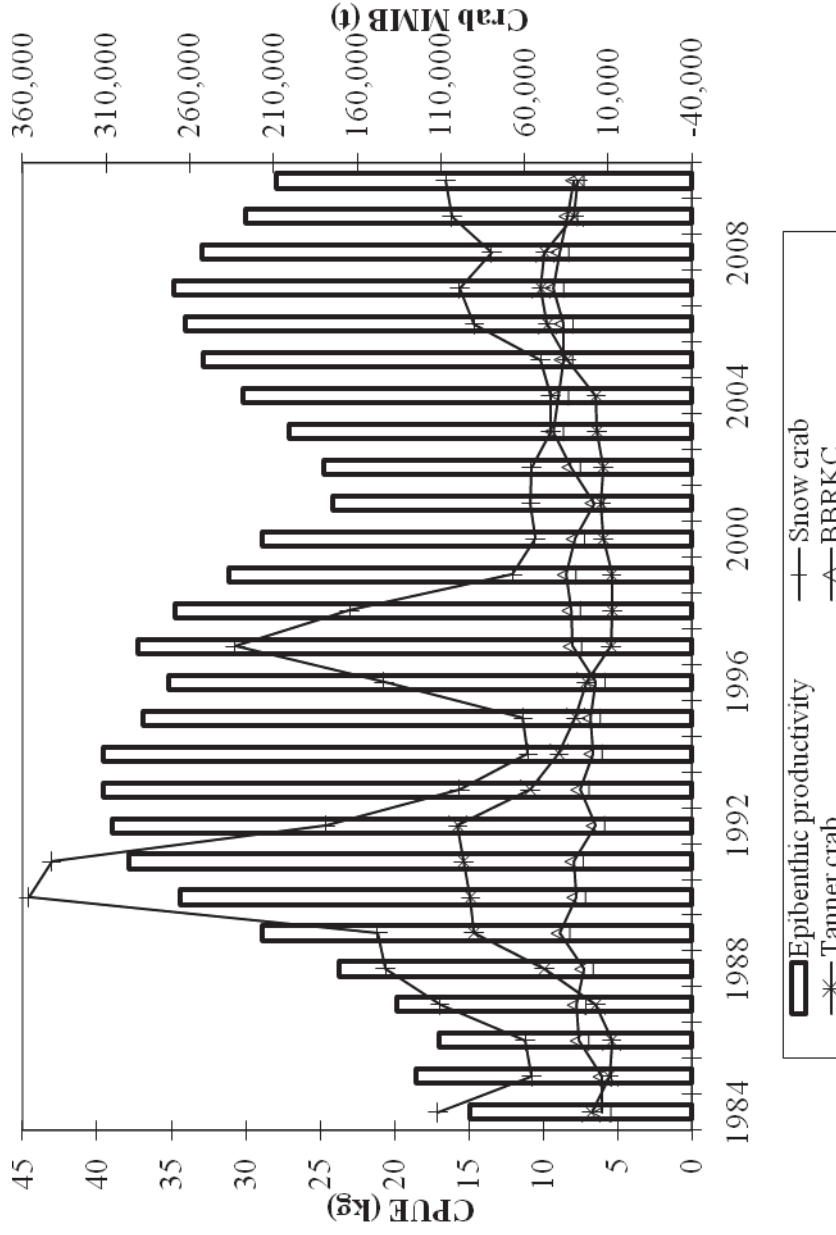


Figure 7. Epibenthic productivity (four year average of the most prevalent benthic invertebrates CPUE from the eastern Bering Sea bottom trawl survey) and mature male biomass of three commercial crab stocks in the eastern Bering Sea from 1984-2010 (BBRKC = Bristol Bay red king crab).

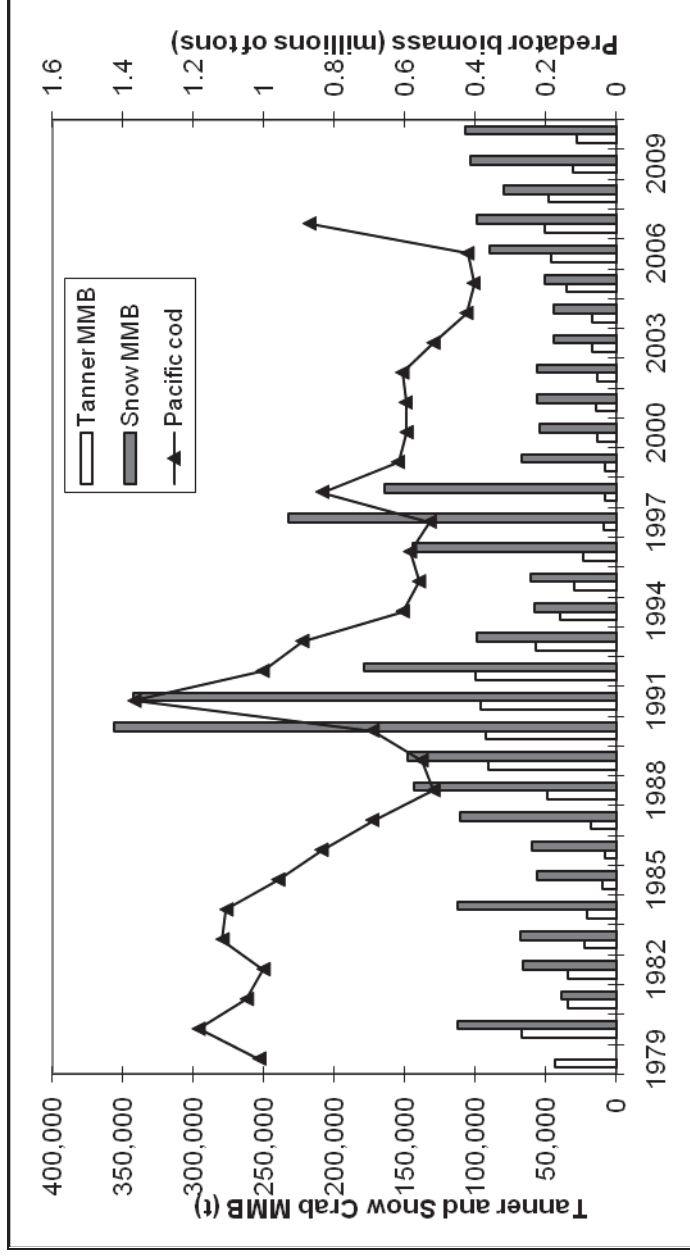


Figure 8. Trends in mature male biomass of Tanner and snow crab from the National Marine Fisheries Service annual eastern Being Sea bottom trawl survey, 1979 to 2010, in contrast to Pacific Cod biomass (time lag of three years).

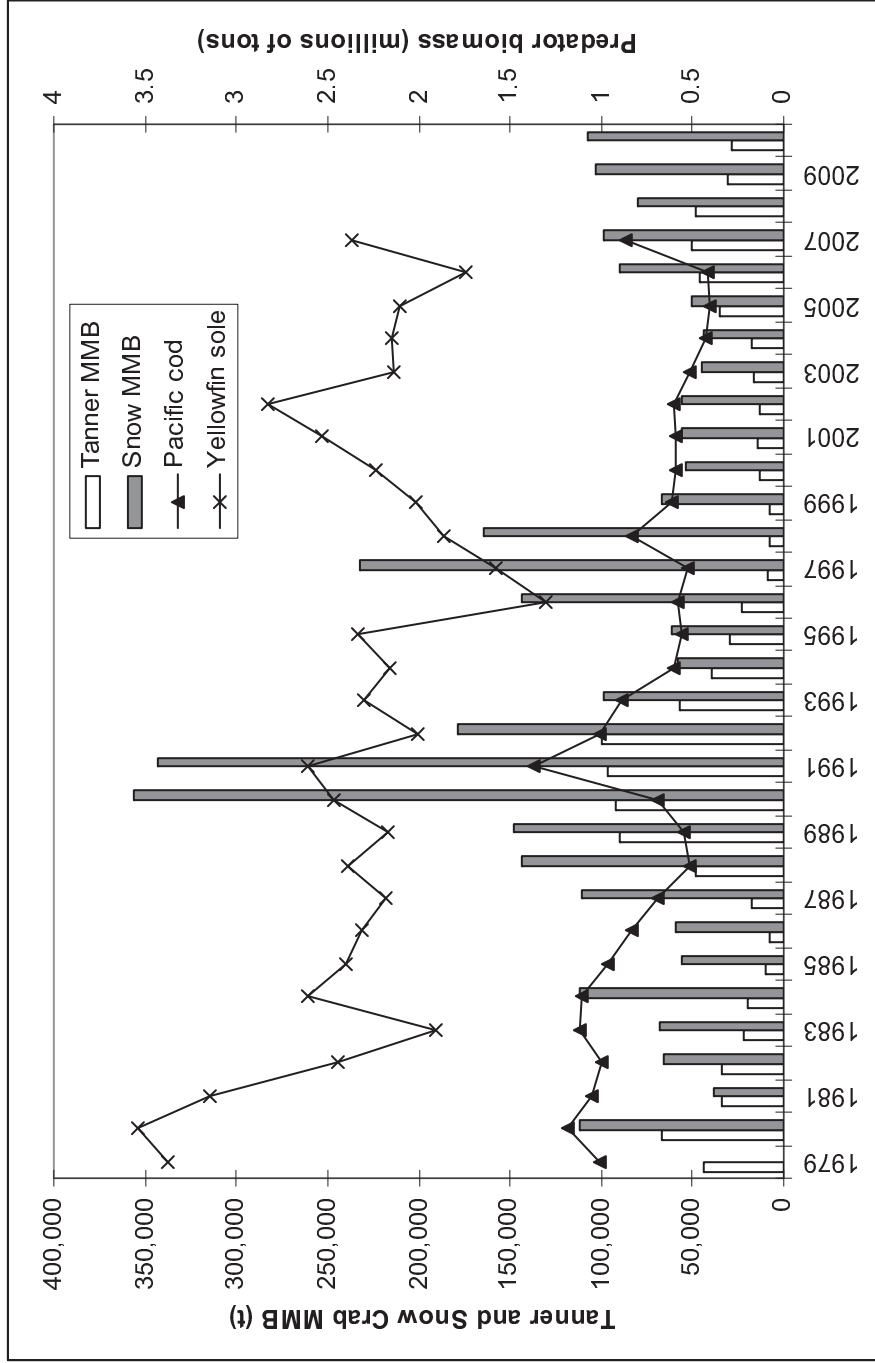


Figure 9. Trends in mature male biomass of Tanner and snow crab from the National Marine Fisheries Service annual eastern Being Sea bottom trawl survey in contrast to Pacific cod and yellowfin sole biomass (time lag of three years).

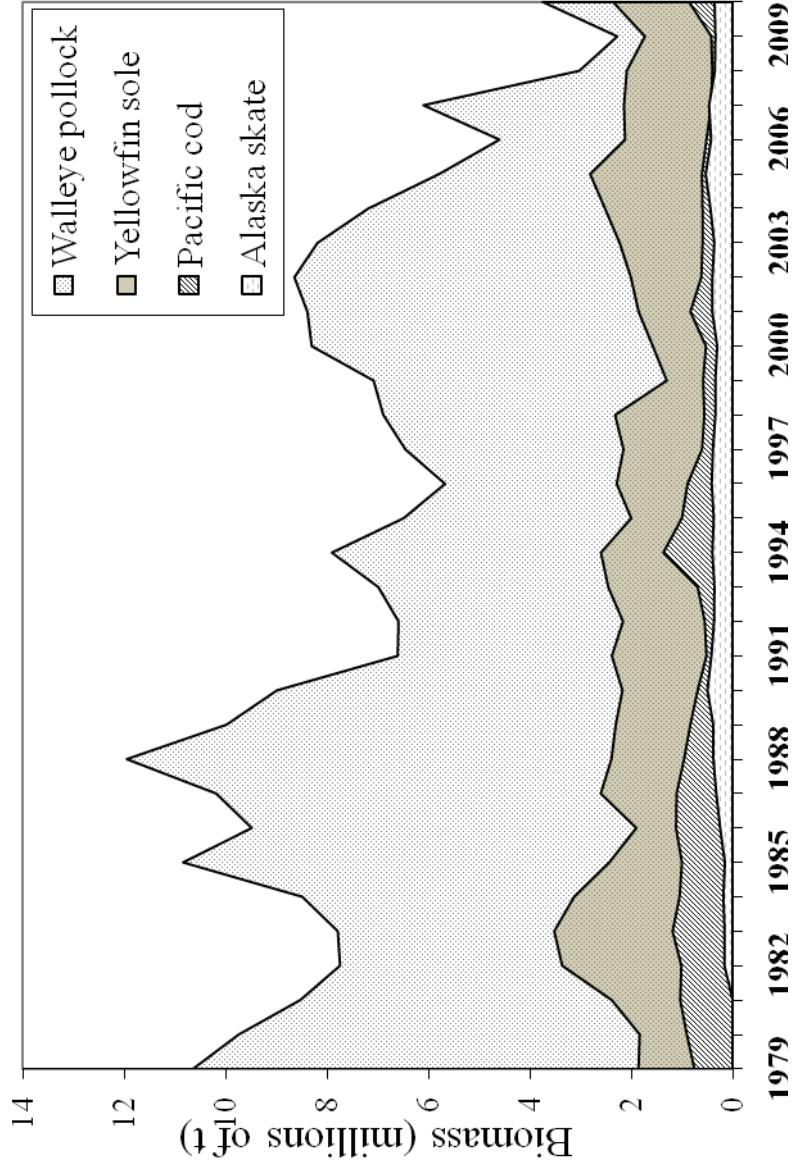


Figure 10. Trends in total biomass estimates of four major crab predators derived from the National Marine Fisheries Service eastern Bering Sea bottom trawl survey, 1979 to 2010.



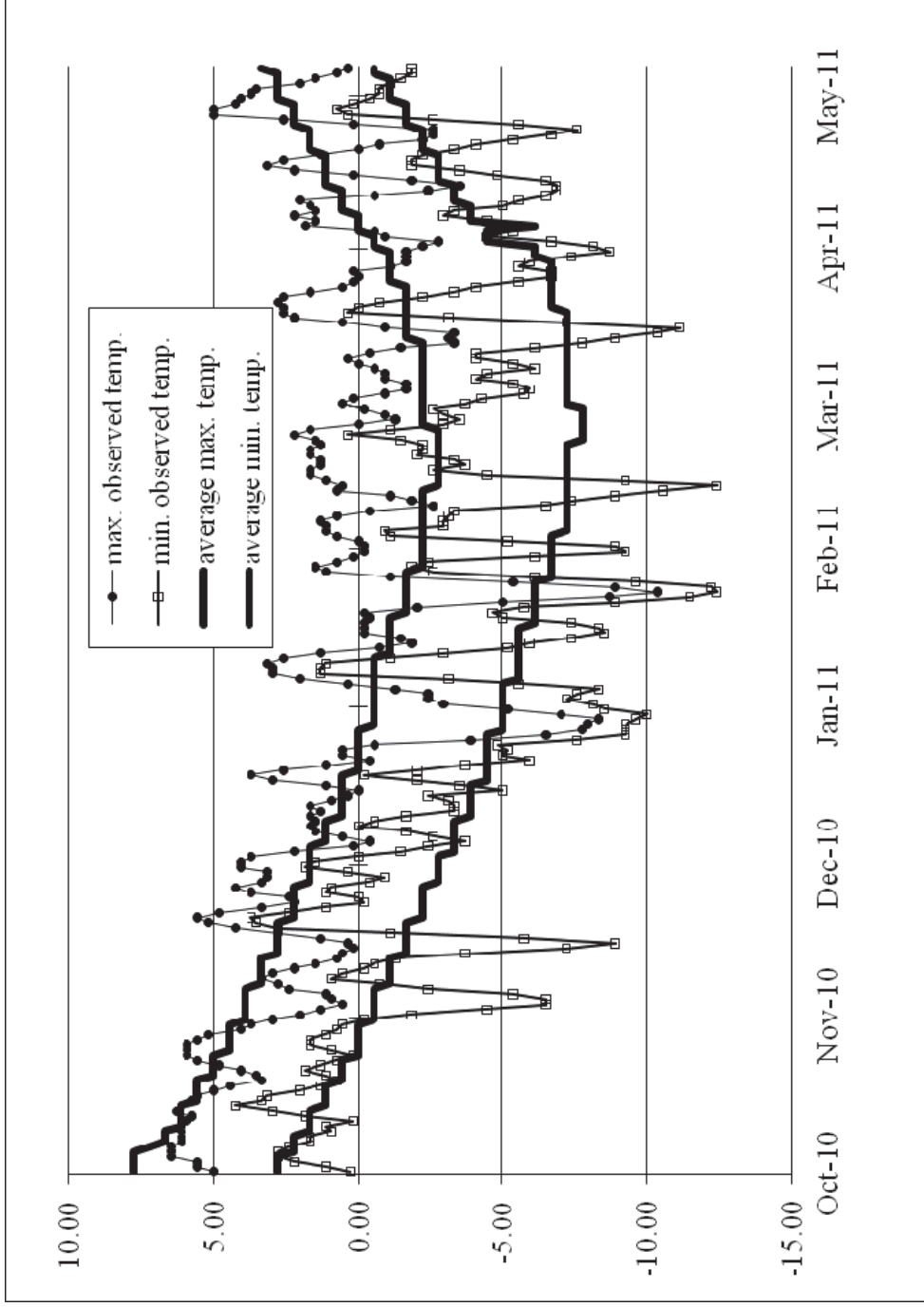


Figure 11. Three day running average of maximum and minimum temperatures (°C) from the St. Paul, Alaska weather station along with the long-term average maximum and minimum daily temperatures (1947-2011).

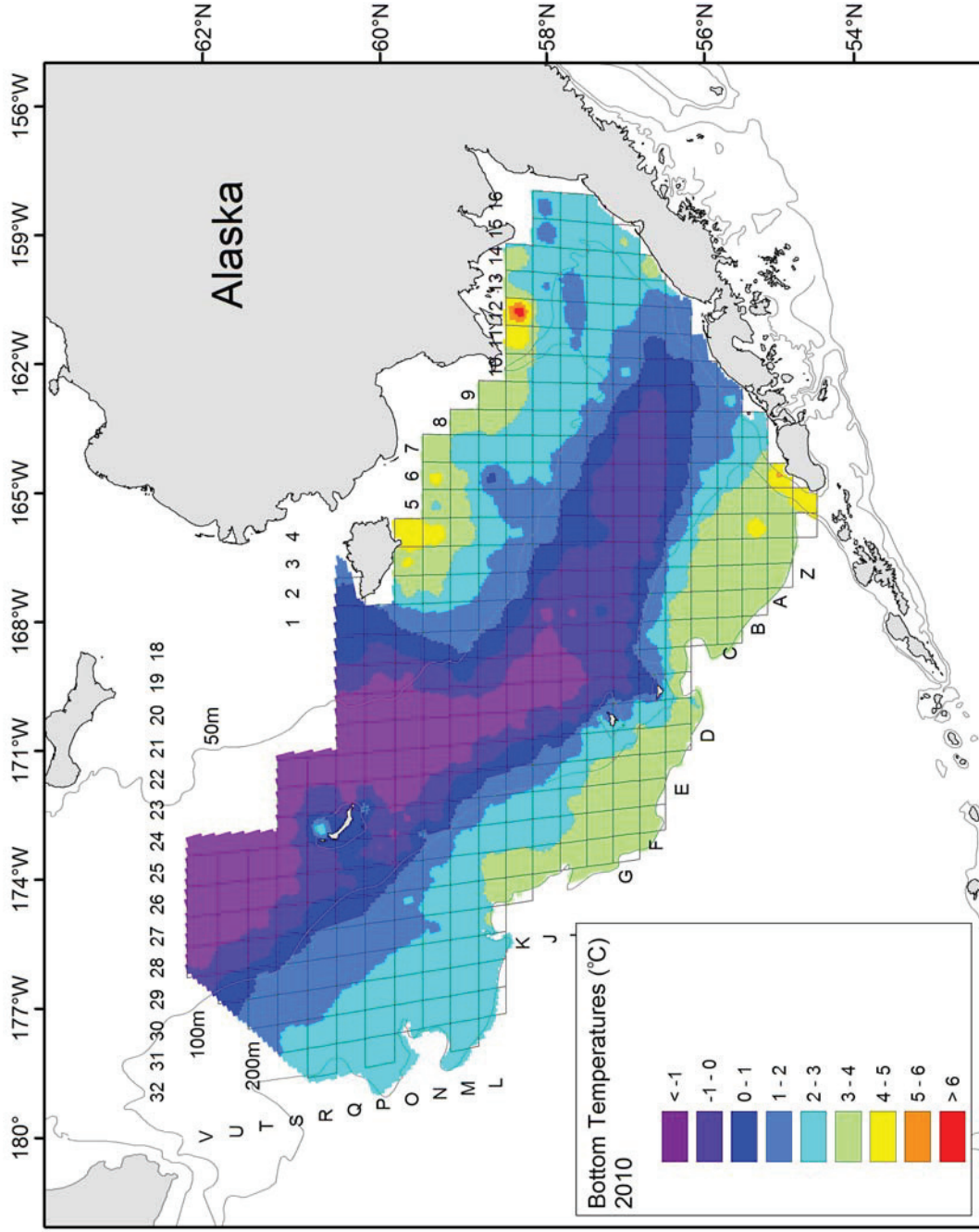


Figure 12a. Mean bottom temperatures (°C) measured at stations from the National Marine Fisheries Service eastern Bering Sea bottom trawl survey, beginning 7 June 2010 in Bristol Bay and ending on 4 August 2010 at station V27.

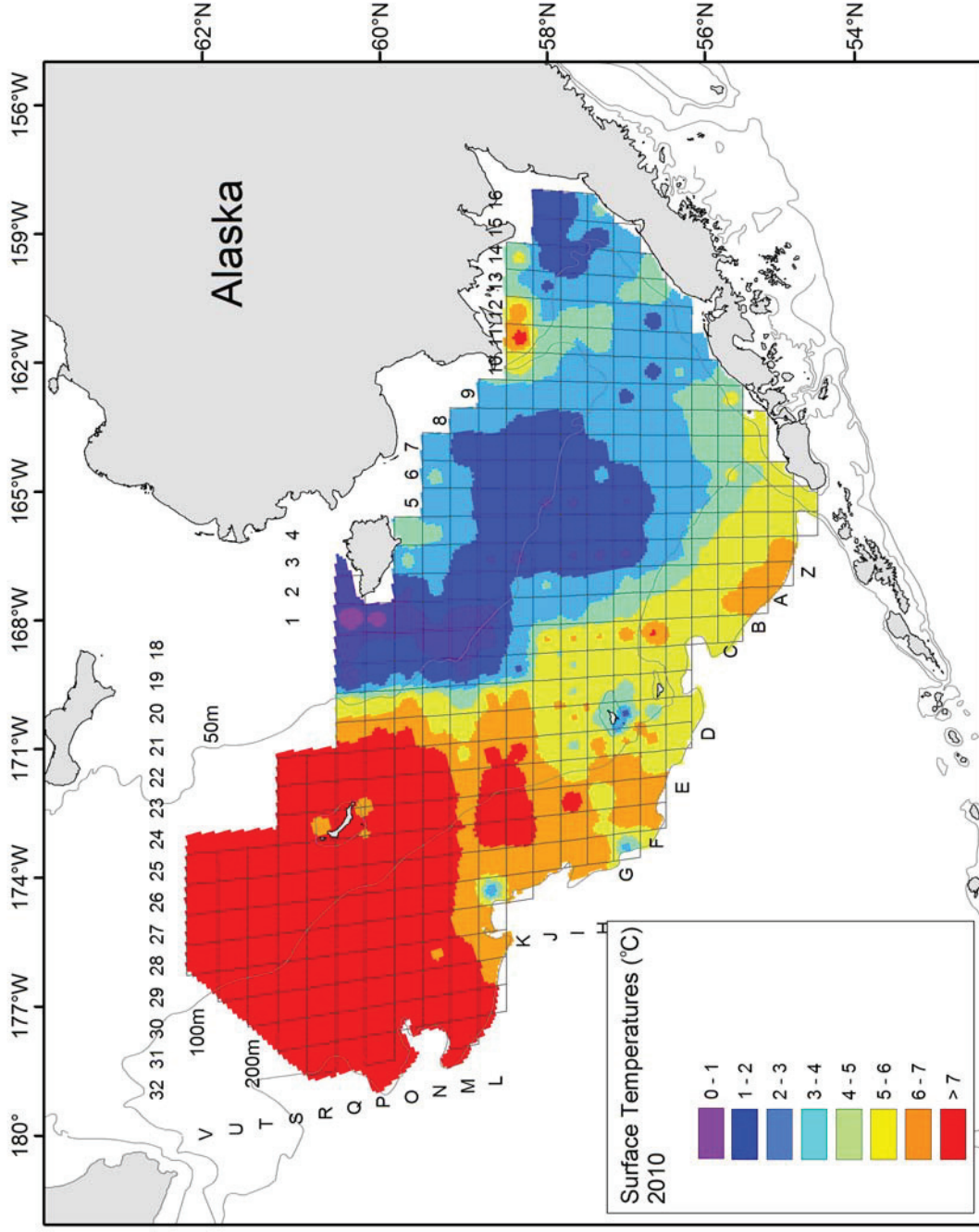


Figure 12b. Mean sea surface temperatures (°C) measured at stations from the National Marine Fisheries Service eastern Bering Sea bottom trawl survey, beginning 7 June 2010 in Bristol Bay and ending on 4 August 2010 at station V27.

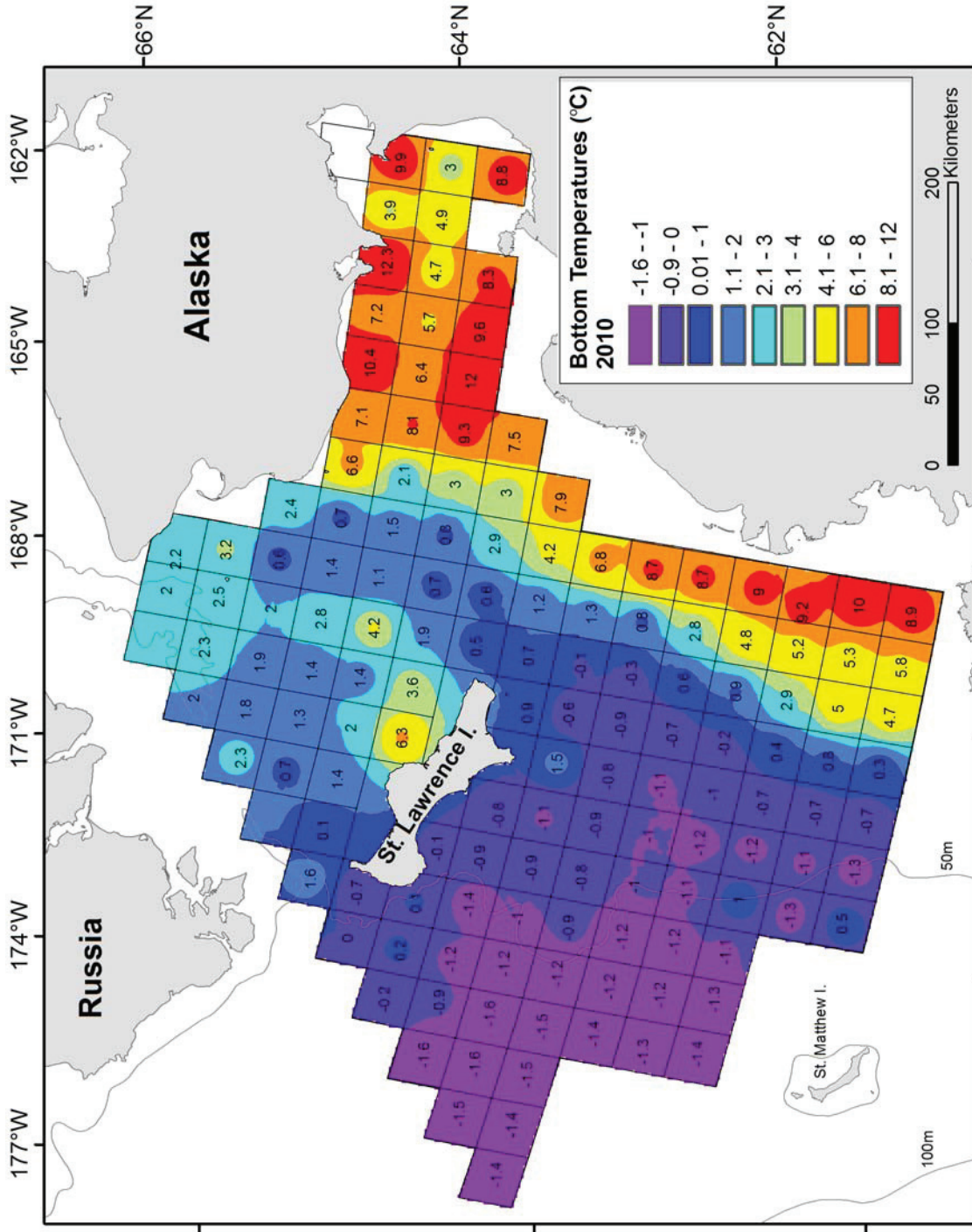


Figure 13a. Mean bottom temperatures (°C) measured at stations on the northern extension of the 2010 National Marine Fisheries Service eastern Bering Sea bottom trawl survey, conducted from 23 July to 9 August 2010.

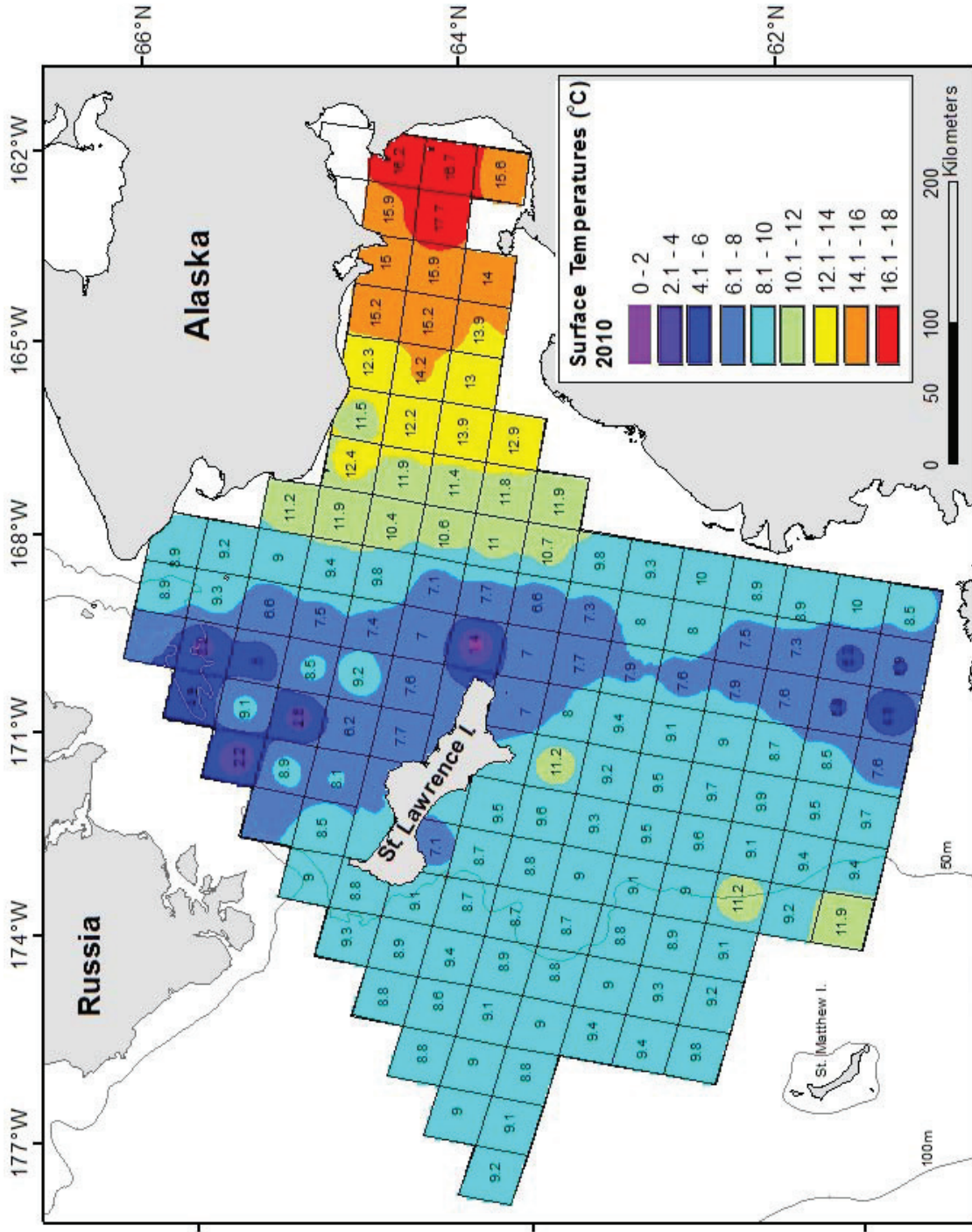


Figure 13b. Mean sea surface temperatures (°C) measured at stations on the northern extension of the 2010 National Marine Fisheries Service eastern Bering Sea bottom trawl survey, conducted from 23 July to 9 August 2010.

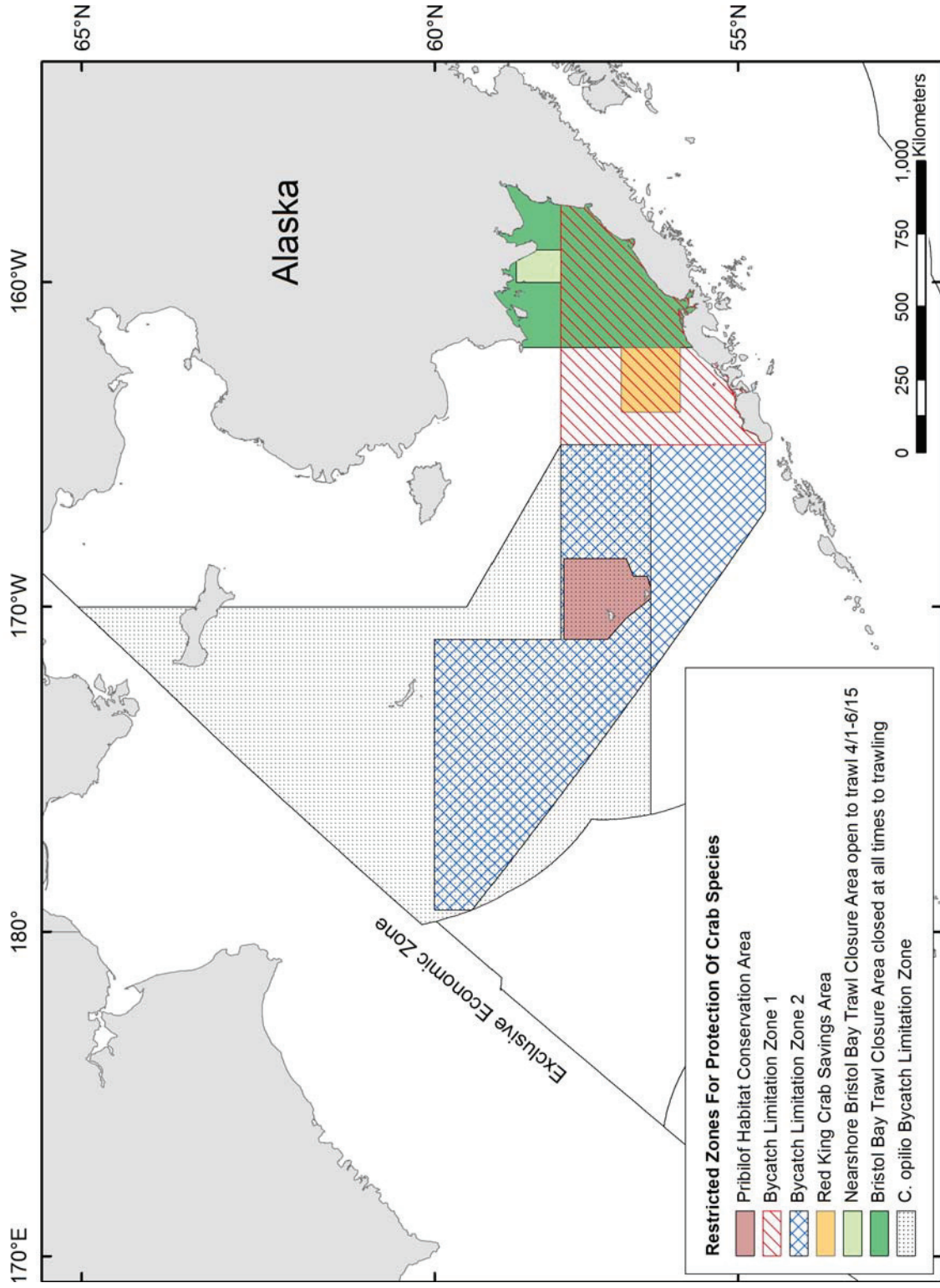


Figure 14. Restricted areas in the eastern Bering Sea enacted as protective management for commercial crab species.

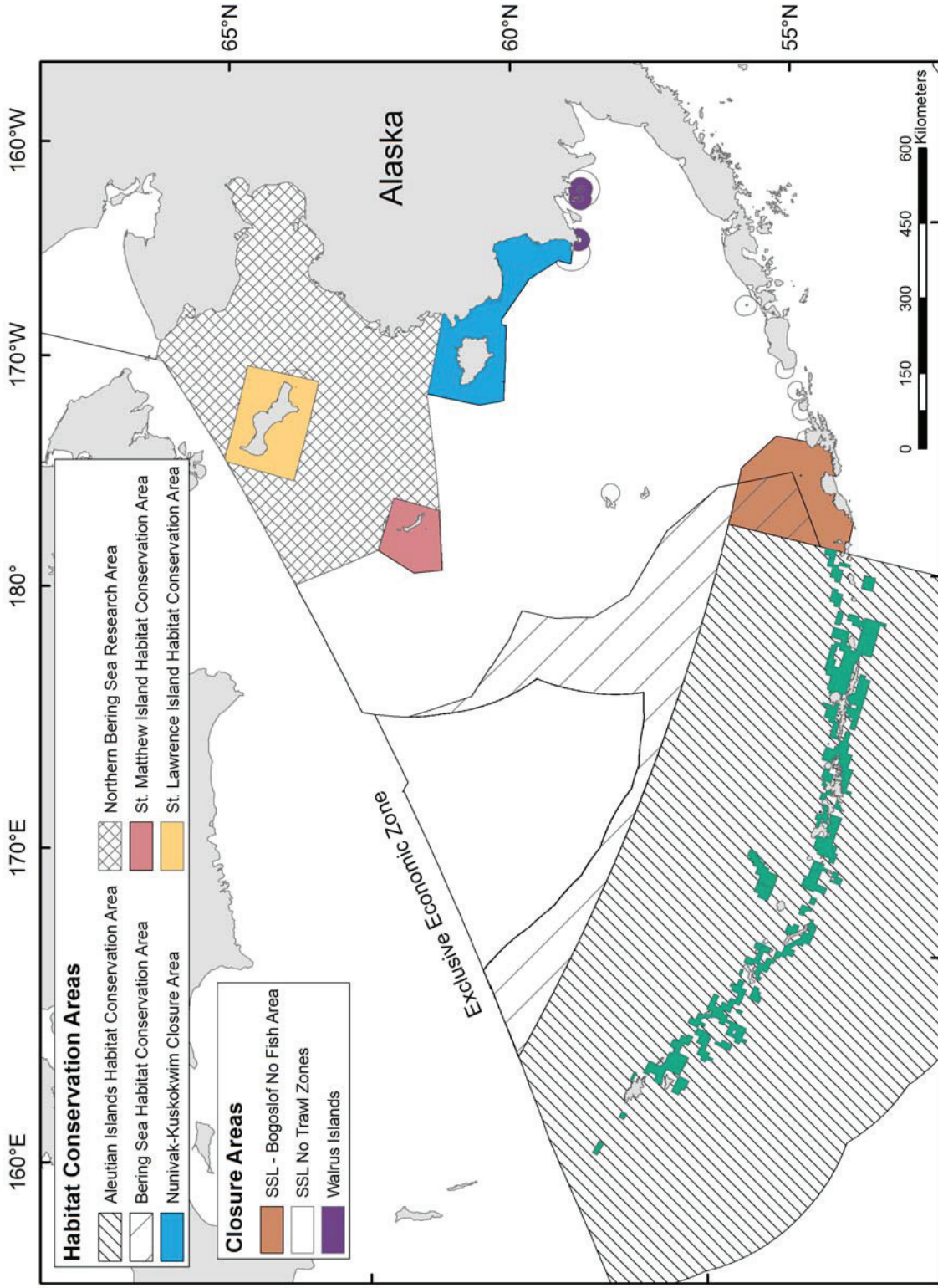


Figure 15. Habitat conservation areas and other locations closed to bottom trawling in the eastern Bering Sea and Aleutian Islands.

Table 1. Summary of ten commercial stocks managed under the Bering Sea and Aleutian Island (BSAI) king and Tanner crab Fishery Management Plan. Species listed in bold represents 2010/2011 commercial fisheries. TAC (Total Allowable Catch), GHL (Guideline Harvest Level), RKC (red king crab), BKC (blue king crab), GKC (golden king crab), CL (carapace length), CW (carapace width).

BSAI Crab Stock	TAC or GHL	Status of Fishery	Fishing season	Legal male size	Mean size retained males in 2009/2010
<b>Bristol Bay RKC</b>	14.84 million pounds legal males	Open in 2010	October 15, 2010-January 15, 2011	$\geq 135$ mm CL	153.2 mm CL
Pribilof Islands RKC		Closed in 1998			
<b>Norton Sound RKC</b>	0.40 million pounds legal males	Open in 2010	June through following August	$\geq 121$ mm CW	116 mm CW
Aleutian Islands (Adak) RKC		Closed in 2004			
<b>Aleutian Islands GKC</b>	5.985 million pounds legal males	Open in 2010	August through following spring	$\geq 135$ mm CL	151.6 mm CL east of 174°W, 151.2 mm CL west of 174°W
<b>Pribilof Islands GKC</b>	0.15 million pounds of legal males	Few vessels registered for 2009-2010	August through following spring	$\geq 140$ mm CW	No vessels registered 2006-2009
Pribilof Islands BKC		Closed in 2002			
<b>St. Matthew Island BKC</b>	1.60 million pounds legal males	Open 2009 after 10 yr rebuilding plan	October 15, 2010 to February 1, 2011	$\geq 120$ mm CL	N/A
EBS Tanner crab		Closed in 2010	October to March or April	$\geq 138$ mm CW	150 mm CW east of 166° W
<b>EBS snow crab</b>	54.28 million pounds of legal males	Open in 2010/2011	October 15, 2010 to May 2011	$\geq 78$ mm CW legal, $\geq 102$ mm CW preferred	110 mm CW



Table 2. Historical bycatch statistics from the Bering Sea (Registration Area Q) scallop fishery. Fishing was not opened during the 1995/96 season (Source: Rosenkranz and Spafard 2010).

Season	Crab bycatch limits			Estimated bycatch (number animals)				Lbs meat per	
	Tanner	King (red)	Snow	Tanner	King (red)	Snow	Halibut	Tanner/snow*	Tanner/snow*
1993/94	260,000	17,000	NA	290,913	207	15,000	165	<1	<1
1994/95	260,000	17,000	NA	220,710	22	34,867	3,513	2	2
1996/97	257,000	500	275,000	16,642	0	106,935	124	1	1
1997/98	238,000	500	172,000	28,446	0	195,345	98	<1	<1
1998/99	215,000	500	130,000	39,363	146	232,911	98	<1	<1
1999/2000	65,000	500	300,000	62,268	2	159,656	106	<1	<1
2000/01	65,000	500	150,000	52,505	2	103,350	50	1	1
2001/02	65,000	500	300,000	48,718	2	68,458	76	1	1
2002/03	65,000	500	300,000	48,053	2	70,795	85	<1	<1
2003/04	65,000	500	150,000	31,316	0	16,206	61	<1	<1
2004/05	65,000	500	150,000	15,303	0	3,843	0	<1	<1
2005/06	65,000	500	150,000	15,529	2	5,211	53	1	1
2006/07	260,000	24	300,000	45,204	10	8,543	82	<1	<1
2007/08	260,000	500	300,000	35,288	1	19,367	11	<1	<1
2008/09	260,000	500	300,000	60,373	1	17,205	0	<1	<1
2009/10	260,000	500	300,000	27,430	1	36,786	4	<1	<1

\* Ratio of pounds scallop meat harvested for each incidentally caught Tanner crab or snow crab × Tanner crab hybrid.