The Western Arctic Shelf–Basin Interactions (SBI) project, volume II: An overview

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\textbf{A B S T R A C T}

The Western Arctic Shelf–Basin Interactions (SBI) project is a 10-year Arctic environmental change program. A major field campaign occurred in the spring, summer and fall seasons between 2002 and 2004. The SBI program was developed to investigate the production, transformation and fate of carbon on shelf and slope regions of the Chukchi and Beaufort seas and shelf–basin interactions with the Arctic Basin. This 2nd special issue documents many of the key findings, ranging from sea ice and hydrographic changes to water column and sediment dynamics and trophic level interactions during the core Phase II field program. The integration of these results with ongoing synthesis and modeling activities within the SBI program are illustrating the critical importance of this continental shelf environment to understand shelf–basin interactions and the ongoing changes being observed and forecasted in the marine Amerasian Arctic.

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1. Introduction

The Arctic Ocean continental margins are the key transformation zone between the shelf and deep-basin regions, acting as a dynamic boundary for cross-slope exchange of salt, nutrients, and multiple forms of carbon. The margins play a major role in the ventilation of the deep basins by transporting dense, brine-enriched shelf waters and associated organic and inorganic carbon to abyssal depths and into the North Atlantic. From the pan-Arctic perspective, the margins are the main avenues for boundary current transport and the overall large-scale ocean mechanism that transports heat, salt, fresh water, biogeochemical properties, and sediments around the Arctic Ocean. The accelerated melt of sea-ice cover observed during the last decade suggests the importance of oceanic forcing and shelf–basin exchange downstream of heat pathways from the sub-Arctic marginal seas into the basin, in addition to the atmospheric effects. Changes in the sea-ice cover have significant ramifications to the entire Arctic system and beyond, including the ocean thermohaline circulation and heat budget, climate and ecosystems, native communities, the use of the region for natural resource exploration and commercial transportation.

The Western Arctic Shelf–Basin Interactions (SBI) program was developed to investigate the production, transformation and fate of carbon on the shelf and slope regions of the Chukchi and Beaufort Sea. A central hypothesis was that sea-ice extent and duration is a major driving force for ecosystem processes in the region. The SBI program, funded by the National Science Foundation and Office of Naval Research, occurred during a changing sea-ice period, with sea-ice retreat more extensive in 2004 than 2002. The overall goals and history of the SBI program are outlined in the Introductory chapter of the first DSR special issue on the SBI program (Grebmeier and Harvey, 2005); here we provide a brief background and introduction to continued efforts to understand this system.

The SBI project was developed to consist of three phases extending over a 10-year period. Phase I (1999–2001) used analyses of historical data, opportunistic field sampling and modeling to evaluate key processes occurring in the Chukchi and Beaufort Seas relevant to the SBI goals. Phase II (2002–2006) encompassed the core field program which had three goals: (1) to evaluate the physical modifications of Pacific and other waters flowing over the Chukchi shelf and slope and into the Arctic Basin, (2) to evaluate the biogeochemical modifications of these waters by water-column and sediment processes in the Chukchi and Beaufort shelf and slope regions, with an emphasis on carbon and nutrient signatures, and key biological trophic-level organisms, and (3) comparative studies between the wide Chukchi and narrow Beaufort shelves and slopes to evaluate the dominant processes and allow model development to extrapolate results from the SBI region to the pan-Arctic scale. The focal point of the final SBI Phase III project following this field effort are to evaluate and synthesize key processes and simulate scenarios of the potential impacts of climate warming on shelf–basin interactions.
in the Arctic. Results and progress from Phase I and II are presented in this second of the two special issues which have documented the SBI core field season from 2002 to 2004.

The field program encompassed a suite of moorings in Bering Strait, and the Chukchi and Beaufort shelf and slope regions, together with multiple cruises over 3 years, which spanned shelf-to-basin domains (Fig. 1). Five key transect lines were occupied in spring, summer, and fall: the Herald Valley (HV) line, the West Hanna Shoal (WHS) line, the East Hanna Shoal (EHS) line, the Barrow Canyon (BC) line, and the East Barrow (EB) line. With publication of the first SBI DSR special issue in 2005, we note that 2004 was the highest ice retreat on record. However, the western Amerasian Arctic has been experiencing rapid ice retreat, with 2007 now being the highest sea-ice retreat in the satellite record in the Arctic (Serreze et al., 2007), 2008 coming in a close second (NSIDC website, see Fig. 2). Heavy sea-ice cover in the SBI area occurred during both spring cruises in 2002 and 2004, with moderate sea-ice cover during summer of 2002, and light to no sea ice during summer of 2004.

This special issue documents many of the key findings by investigators in their continuing efforts; here we provide only brief summaries of findings of papers reported by investigators in each chapter. We follow with a general discussion of key synthesis activities being undertaken in the current SBI Phase III program, concluding with a suggested list of activities that require further scientific efforts.

2. Hydrography and ice conditions

Sea-ice conditions were at a minimum in 2004 of the SBI program. Codispoti et al. (2009) present a summary of the hydrographic regime during the spring and summer 2004 process cruises and compares their observations to the 2002 spring and
summer cruises. Both similarities and differences were found in their analysis, including: (1) dissolved inorganic nitrogen limited phytoplankton growth in both years, suggesting that the fixed-N transport through Bering Strait is a major control on biological productivity; (2) the head of Barrow Canyon was a region of enhanced biological production; (3) a common observation of plume-like nutrient maxima and N** minima (a signal of sedimentary denitrification) extending from the shelf into the interior; (4) oxygen super-saturations were common in or just above the shallow nitratcline; and (5) surface waters at the deepest stations in the Arctic Basin were already depleted in nitrate, ammonium, and urea during the spring period. Major differences between the 2 years included: (1) the greater influence of warm, relatively low-nutrient Alaska Coastal Water (ACW) during 2004 entering the region via Bering Strait, (2) differences in water temperature and nutrients were most pronounced in the upper ~100 db, and (3) the increased influence of warm water in 2004 relative to 2002 was most evident in the East Barrow (EB) section in the western Beaufort Sea where surface layers were up to five degrees warmer in 2004.

While the stronger inflow of ACW in 2004 may have reduced the autotrophic nutrient supply, observed rates of primary production, bacterial production, and particulate organic carbon export were higher in 2004 than 2002. The authors suggest that a difference in the availability of light was the primary cause. Although springtime ice thicknesses were greater in 2004 than in 2002, snow cover was significantly less in 2004 and may have compensated for the modest differences in ice thickness influencing light penetration. In addition, there was a rapid and extensive retreat of the ice cover in summer 2004 that may have allowed phytoplankton to increase utilization of nutrients in the shallow, high-nutrient layer. More light combined with warmer temperatures in 2004 could enhance that fraction of primary production supported by nutrient recycling. Enhanced subsurface primary production during summer 2004 is suggested by the results of incubation experiments as well as more extreme dissolved oxygen super-saturations in the vicinity of the nitratcline. Although there were differences in the timing of the seasonal occupation, there is little doubt that biological conditions at the ensemble of hydrographic stations occupied in 2004 during the SBI process differed significantly from those at the stations occupied in 2002.

Nikolopoulos et al. (2009) investigated the structure, variability, and transport of the western Arctic boundary current using a high-resolution mooring array of profiling equipment at 152 W in the Beaufort Sea maintained across the western Arctic boundary current in the Beaufort Sea north of Alaska from 2002 to 2004. The array tracked the mean flow of incoming Pacific water to the Arctic, which transits to the east, and was trapped along the shelf break near 100 m in a narrow, 10–15 km jet that varied seasonally. During summer this water becomes a surface-intensiﬁed jet as it advects buoyant, fresh Alaskan Coastal Water. In fall and winter, the current often reverses (flows westward) under upwelling-favorable winds. Between the storms, as the eastward flow re-establishes, the current develops a deep extension to depths exceeding 700 m. In spring the bottom-trapped flow advects winter-transformed Paciﬁc water from the Chukchi Sea. The year-long mean volume transport of Paciﬁc Water is 0.13 ± 0.08 Sv to the east, which is less than 20% of the long-term mean Bering Strait inflow.

Measurements of sea-ice thickness are reported by Shirasawa et al. (2009) using an ice-based electromagnetic induction instrument (IEM) together with a ship-based instrument during the early melt season in the southern Chukchi Sea in 2002 and 2004, and in late summer 2003 at the time of minimum ice extent in the northern Chukchi Sea. Ice-thickness modes in the probability density functions (PDFs) derived from drill-hole and IEM measurements agreed well, with modes at 1.5–1.6 and 1.8–1.9 m for all data from level ice. In 2002 and 2004, a significant fraction (between one-third and one-half) of level ice was found to consist of rafted ice segments. Snow depth varied significantly between years, with 2004 data showing more than half the snow cover on level ice to be at or below 0.05 m depth in late spring. Ice-growth simulations and examination of ice drift and deformation history indicate that impacts of atmospheric and oceanic warming on level ice thickness in the region over the past few decades are masked to a large extent by variability in snow depth and the contribution of deformation processes. In comparison with submarine sonar ice-thickness data from previous decades, a reduction in ice thickness of about 0.5–1 m was seen, and can be explained in part by the replacement of multi-year with first-year ice over the Chukchi and Beaufort shelves.

3. Planktonic life and water-column processes

Sea-ice and water samples were collected on the shelves and slope regions of the Chukchi and Beaufort Seas during the spring 2002 expedition (Gradinger, 2009). Algal pigment content, particulate organic carbon and nitrogen and primary productivity were estimated for both habitats based on ice cores, brine collection and water samples from 5 m depth. The pigment content and primary productivity of the sea-ice algae significantly exceeded water-column parameters, making sea ice the habitat with the highest food availability for herbivores in early spring in the Chukchi and Beaufort Seas. Stable isotope signatures for ice and water samples did not differ significantly for δ15N, but did for δ13C (ice: -25.1% to -14.2%; water: -26.1% to -22.4%). The analysis of nutrient concentrations and the fluorescence signal of ice algae and phytoplankton indicate that nutrients were the prime limiting factor for sea-ice algal productivity. Estimated spring primary production was about 1–2 g C m⁻² of sea-ice algae on the shelves, an estimate that would require substantial nutrient input from the water column. Mathis et al. (2009) assess the magnitude, distribution and fate of net community production (NCP) in the Chukchi Sea, dissolved inorganic carbon (DIC), dissolved organic carbon and nitrogen (DOC and DON), and particulate organic carbon and nitrogen (POC and PON) during the spring and summer of 2004, and compare these observations to similar observations taken in 2002. Distinctive differences in hydrographic conditions were observed between these 2 years, which allowed them to consider several factors that could impact NCP and carbon cycling in both the Chukchi shelf and the adjacent Canada Basin. Between the spring and summer cruises high rates of phytoplankton production over the Chukchi shelf resulted in a significant drawdown of DIC in the mixed layer and the associated production of DOC/N and POC/N. Similarities between 2004 and 2002 indicated that the highest rates of NCP occurred over the northeastern part of the Chukchi shelf near the head of Barrow Canyon, which has historically been a hotspot for biological activity in the region. However, in 2004, rates of NCP over most of the northeastern shelf were similar and in some cases higher than rates observed in 2002. This was unexpected in light of the greater influence of low-nutrient waters from the Alaskan Coastal Current in 2004, which should have suppressed NCP rates compared to 2002. Between spring and summer of 2004 normalized concentrations of DIC in the mixed layer decreased by as much as 280 μmol kg⁻¹, while DOC and DON increased by ~16 and 9 μmol kg⁻¹, respectively. Given the decreased availability of inorganic nutrients in 2004, rates of NCP could be attributed to increased light penetration, which may have allowed phytoplankton to increase utilization of nutrients.
deeper in the water column. In addition, there was a rapid and extensive retreat of the ice cover in summer 2004, with warmer temperatures in the mixed layer that could have enhanced NCP. Estimates of NCP near the head of Barrow Canyon in 2004 were ~1500 mg carbon (C)m⁻² d⁻¹, which was ~400 mg C m⁻² d⁻¹ higher than the same location in 2002. Estimates of NCP over the shelf break and deep Canada Basin were low in both years, confirming that there is little primary production in the interior of the western Arctic Ocean.

Sukhanova et al. (2009) evaluated the phytoplankton species composition in the Chukchi and Beaufort seas during the spring and summer SBI process cruises in 2002 to detail community structure and seasonal changes. In May and June, when ice cover was >80% with no vertical stratification in the water column, the observed succession of phytoplankton corresponded to the end of the winter biological season. During this period phytoplankton abundance varied from a few tens to a few thousands of cells per liter, while biomass ranged from 0.1 to 3.0 mg C m⁻³. Only small regions in the southeastern Chukchi Sea and off Pt. Barrow had high algal numbers (0.13–1.3 x 10⁶ cells L⁻¹) and biomass (22–536 mg C m⁻³), including a high abundance of early spring diatoms in the upper water column that indicated the beginning of the spring bloom. During the summer period phytoplankton abundance and biomass were an order of magnitude higher than in spring over the Chukchi shelf and shelf/continental slope of the Beaufort Sea. Algal taxonomic diversity increased in the summer due to enhanced types of diatoms, dinoflagellates, and coccolithophorids. Seasonal differences in phytoplankton species composition were lowest over the Chukchi Sea slope and in the deep-water area. Notably high phytoplankton concentrations occurred in the lower layers of the euphotic zone. In both the spring and summer 2002 cruises, phytoplankton reached a maximum abundance on: (1) the shelf northwestern of Point Barrow, (2) in the southern part of the Chukchi Sea southwest of Point Hope, (3) in the northern part of the Chukchi shelf between the 50- and 100-m isobaths, and (4) on the continental slope of the Beaufort Sea.

Kirkman et al. (2009) studied the standing stocks and production rates for phytoplankton and heterotrophic bacteria during spring and summer cruise in 2002 and 2004. Rates of primary and bacterial production were higher in the summer than in spring and higher in shelf waters than in the basin for both years. Primary production was three-fold higher in 2004 than in 2002, with ice-corrected rates being 1581 and 458 mg C m⁻² d⁻¹, respectively, for the entire region. The authors concluded that the difference between years was mainly due to low ice coverance in the summer of 2004. The spatial and temporal variation in primary production led to comparable variation in bacterial production. Although temperature explained as much variability in bacterial production as did primary production or phytoplankton biomass, there was no relationship between temperature and bacterial growth rates above about 0 °C. Bacteria accounted for a highly variable fraction of total respiration, from 3% to over 60%, with a mean of 25%. Likewise, the fraction of primary production consumed by bacterial respiration varied greatly over time and space.

Arctic microbial communities respond to a variety of natural organic matter substrates and Dyda et al. (2009) evaluated bacterial growth and production rates in response to additions of terrestrial peat, ice algae and ice-rafted debris. Intact phospholipids and fatty acids were used to evaluate the relationship between lipids and bacterial community structure and the impact of varied organic substrates on microbial lipid synthesis. Ice algae supported both higher bacterial growth and production than terrestrial-derived peat examined during shipboard experiments. In spite of disparate growth kinetics, the bacterial community composition examined by several molecular methods, including automated ribosomal intergenic spacer analysis (ARISA), remained similar in all amended incubations. Gammaproteobacteria dominated the initial incubations, whereas extended incubations with terrestrial peat found Alphaproteobacteria, in particular Sulfitobacter phytoplotype closely related (>99%) to an Arctic sea-ice associated member of the Roseobacter clade, became the dominant bacteria. Arctic bacterioplankton preferentially synthesized two phospholipids, phosphatidylethanolamine and phosphatidylglycerol, when grown on all substrates. Overall, results show that the source of organic matter plays an important role in structuring bacterioplankton community composition, with similar phospholipids and fatty acid lipid distributions observed among phylogenetically distinct bacteria.

Microzooplankton grazing impact on phytoplankton was assessed by Sherr et al. (2009) using a dilution technique during spring and summer 2002 and 2004 SBI cruises over the productive shelf regions of the Chukchi Sea, slope regions of the Beaufort Sea, and oligotrophic deep-water sites in the Canada Basin. Heavy sea-ice cover occurred during both spring cruises in 2002 and 2004, with moderate sea-ice cover during summer of 2002, and light to no sea ice during summer of 2004. There was a corresponding range of trophic conditions from low chlorophyll a (chl a) (<0.5 µg L⁻¹) during heavy ice cover in spring and in the open basin, to late spring and summer shelf and slope open-water diatom blooms with chl a >5 µg L⁻¹. The microzooplankton community was dominated by large naked ciliates and heterotrophic gymnodinoid dinoflagellates. Significant, but low, rates of microzooplankton herbivory were found in half of the experiments. Phytoplankton intrinsic growth rates varied from highest values of about 0.4 d⁻¹ to an average lower value of 0.16 d⁻¹. Light limitation in spring and post-bloom senescence during summer was suggested as the likely explanations of observed low phytoplankton growth rates. Microzooplankton grazing averaged 22% of phytoplankton daily growth, with grazing and growth rates found in this study being low compared to rates reported in the Barents Sea in the Arctic and other major geographic regions of the world ocean.

Moving up the trophic food web, Campbell et al. (2009) evaluated the role of mesozooplankton as consumers and transformers of primary and secondary production in the Beaufort and Chukchi Seas during four cruises in spring and summer of both 2002 and 2004 as part of the SBI program. Mesozooplankton biomass was dominated by life stages of four copepod taxa: Calanus glacialis, C. hyperboreus, Metridia longa, and Pseudocalanus spp. Significant interannual, seasonal, regional, between species, and even within species differences in grazing rates were observed. Overall, the dominant zooplankton exhibited typical feeding behavior in response to chlorophyll concentration. Microzooplankton were preferred prey at almost all times, with the strength of the preference positively related to the proportion of microzooplankton prey availability. Average mesozooplankton grazing impacts on both chlorophyll standing stock (0.6 ± 0.5% d⁻¹ in spring, 5.1 ± 6.3% d⁻¹ in summer) and primary production (12.8 ± 11.8% d⁻¹ in spring, 27.6 ± 24.5% d⁻¹ in summer) were quite low and also varied between shelf, slope, and basin. Coincident microzooplankton grazing experiments (Sherr et al., 2009) were conducted at most stations. Together, microzooplankton–mesozooplankton grazing consumed an estimated 44% of the total water-column primary production, leaving >50% directly available for local export to the benthos or for offshore transport into the adjacent basin.

In an opportunistic study, Linas et al. (2009) undertook a survey of a Pacific-origin cold-core eddy on the continental slope north of the Chukchi Shelf in the Canada Basin, western Arctic, centered at ~160 m depth using high-horizontal-resolution
physical and chemical sampling and lower-horizontal-resolution biological sampling. Water-mass characteristics and the presence of copepods from the North Pacific Ocean (Neocalanus flemingeri and Metridia pacifica) demonstrated that the core contained water of Pacific origin. Most zooplankton taxa in the eddy core were elevated compared with those in similar density water in the surrounding Arctic Basin. Based on tracer-age estimates and previous observations of eddy formation, the eddy likely formed during the previous spring/summer from the Chukchi shelf break jet. Notably, the eddy also contained elevated abundances of Arctic-origin copepods (M. longa and C. glacialis). Analysis of a shelf–basin transect occupied in August 2004 showed that these species were present in high abundances in relatively shallow water (50 m) inshore of the shelf break due to upwelling of deeper basin water and copepods being brought onto the shelf in response to easterly winds. If the formation of the observed eddy occurred during, or shortly after, a period of such winds, upwelled Arctic-origin copepods on the shelf might have been entrained into the feature. These authors suggest that formation and subsequent migration of such eddies may provide a mechanism for transporting zooplankton from the productive Chukchi Shelf into the less productive interior of the Canada Basin, thus affecting deep-basin Arctic foodwebs.

Lepore et al. (2009) used Pb-210 isotopes (22 yr half-life) collected from seawater and particulate matter as a tracer for shelf–basin transport and as an indicator of sediment focusing on the Chukchi Sea shelf-slope region. Samples were collected along three shelf–basin transects identified as West Hanna Shoal, East Hanna Shoal, and Barrow Canyon. Distributions of 210Pb and suspended particulate matter indicate efficient removal of 210Pb over the shelf, with low 210Pb activities measured throughout the halocline of the Canada Basin being attributed to shelf scavenging and subsequent advective transport into the interior basin. Additionally, 210Pb inventories were used to construct a water-column sediment budget of 210Pb and determine regions of particle export and deposition on the continental shelf and slope. Sediment focusing calculated with this 210Pb budget was observed throughout the shelf-slope region, particularly in shallow (<100 m) shelf waters at Barrow Canyon. Despite elevated concentrations of suspended particulate matter in Barrow Canyon, the 210Pb budget does not indicate that sediment transport occurred from the West and East Hanna Shoals into Barrow Canyon.

4. Sediment processes and recycling

The sediments on the shallow continental shelves and slope region of the Chukchi and Beaufort seas provide a contemporary and sometimes long-term record of overlying water-column processes. Cooper et al. (2009) present data on the quality and quantity of particulate organic material deposited to the benthos in the Chukchi Sea. Using current and past stable and radiocarbon isotopic measurements of organic carbon, C/N ratio of particulate matter in the water and sediment, and inventories of chlorophyll a present in surface sediments, they suggest that sedimentation processes in the regional Bering Strait ecosystem may have shifted in the past decade. Surface sediments collected in 2004 adjacent to the Russian coastline in the Chukchi Sea were less refractory based on carbon isotope ratios and C/N ratios than were observed for surface sediments at similar locations in 1995 and 1988. Using 8Be and chlorophyll a inventories, they determined that short-term sedimentation on the shelf occurs immediately north of Bering Strait as well as within and downstream of Barrow and Herald Canyons. Only small seasonal differences (i.e. ice-covered versus open-water conditions) in the quality of particulate organic carbon reaching the benthos occurred in the most productive waters, such as Barrow Canyon. However, seasonal variations were found in less productive waters using C/N ratios and δ13C tracers, with the δ13C values in the organic fractions of the sediments being less negative than observed in settling material in the water column, indicative of biological processing within the sediments.

Another contemporary sediment tracer study used chlorophyll a and total organic carbon content (TOC) in surface sediment to evaluate the persistence of algal pigments in Arctic sediments measurements in sediment cores collected from the shelf, slope, and basin of the Bering, Chukchi, and Beaufort Seas during the high ice-covered May–June period and July–August (largely ice-free period) in 2004 (Pirtle-Levy et al., 2009). Surface sediment chl a was found to decrease with increasing water depth, with significant positive correlations found between chl a and TOC and chl a and C/N ratios in the basin (>2000 m). By comparison, significant negative correlations were found between chl a and C/N ratios on the shelf (<200 m). The chl a values generally declined in down-core profiles, but measurable inventories of subsurface chl a were present at depth in deeper slope and basin sediment cores. Some of these subsurface peaks were consistent with Cs137 peaks in the 1960s bomb fallout period. The depth of penetration of 137Cs in some continental slope sediments, together with detectable chl a, suggests that chl a has the potential to be buried in some of these deeper-water sediments under cold conditions for decadal periods in the absence of deposit feeders. Because organic deposition from the water column is episodic at high latitudes and concentrated following the spring bloom, these buried sources of organic materials may ultimately be important for benthic invertebrates that could utilize this food source during times of the year when primary production flux from the overlying water column is reduced.

The study by Chang and Devol (2009) evaluated the sedimentary nitrogen budget of the SBI study using seasonal and spatial patterns of sedimentary denitrification from the downward diffusive flux of nitrate in the shelf and slope sediments as well as whole-core measurements in the Chukchi Sea during two SBI cruises in the summer and spring of 2002 and 2004, respectively. Recent global nitrogen budget estimates suggest that at least half of the ocean’s fixed nitrogen is lost by sedimentary denitrification in continental shelves, and the Arctic has the potential to be a substantial contributor to the overall global sedimentary denitrification budget. Denitrification rates generally decreased with increasing water depth, although rates showed little variation between the two seasons. However, rates were found to correspond with differences in annual overlying primary productivities and particulate organic carbon export fluxes. In the context of the global nitrogen budget, these authors estimate that the Arctic continental shelves provide about 4–13% of the total sink of fixed nitrogen in the ocean.

5. Coupled biophysical modeling

A 9-km resolution pan-Arctic ice-ocean model was used to better describe the circulation and exchanges in the Bering Sea, particularly near the shelf break and upstream to the main SBI study area (Clement Kinney et al., 2009). The authors examined the relationship between the Bering Slope Current and exchange across the shelf break and resulting mass and property fluxes onto the shelf. The Bering Sea shelf break region is characterized by the northwestward-flowing Bering Slope Current. Previously, it was thought that once this current neared the Siberian coast, a portion
of it made a sharp turn northward and encircled the Gulf of Anadyr in an anticyclonic fashion. Model results instead indicate Pacific water from the deep basin is periodically moved northward onto the shelf by mesoscale processes along the shelf break. Canyons along the shelf break appear to be more prone to eddy activity and, therefore, are associated with higher rates of on-shelf transport, a result that was suggested as potentially important in the northern Chukchi shelf canyon systems as well.

6. Summary

Findings from the NSF-supported Shelf–Basin Interactions project in the Amerasian Arctic indicate that higher heat and freshwater fluxes have been passing through Bering Strait in recent years (Woodgate et al., 2006). The SBI studies in the first and this current special issue have also unequivocally identified seasonal and interannual variation of physical and biochemical mechanisms involved in cross-margin exchange, such as advection, eddy formation, upwelling and along-canyon transport, as well as nutrient flux and transformations that affect biological parameters (dominant species types, location, and interactions at the shelf break). The biogeochemical and biological studies undertaken during SBI indicate interannual patterns of organic carbon deposition and recycling driven by changes in carbon supply and temperature. Changes in physical conditions force the ecosystem response, especially in regions of extreme variability, i.e. along the pathways of warm Pacific and Atlantic water advected north across the marginal shelves into the Arctic basin.

One of the most critically affected ecosystems by the advection of warm, nutrient-rich, and biologically productive water include the Chukchi/Beaufort region, the focus of the SBI program. Sea-ice cover has recently and dramatically retreated northward in summer (Serreze et al., 2007) and in some cases in winter, which brings additional consequences of shifts in light limitation, ice-edge position, vertical mixing. Some of the highlights of this 2nd SBI special issue include:

1. The reduced snow cover and sea-ice extent in 2004 versus 2002, as well as sea-ice thickness between 2003 and 2004, were the dominant factors for enhanced primary production measurements in the region, supporting a developing hypothesis that extensive early season ice retreat will increase overall primary production in the shelf regions.

2. The seasonal formation and dissolution of water masses in the region and seasonal transport variability influence northward transport and shelf–basin exchange over an annual season. Changes in the forcing function of salt and nutrients through Bering Strait and in the Beaufort slope jet will have a seasonal influence on shelf exchange of salt, heat, particulate, and organic carbon as well as planktonic species.

3. The development of seasonal plumes of nutrient-enriched waters transported off the continental shelf at depths near the shelf break, together with the generation of eddies and their entrained carbon, are key driving mechanisms for shelf–basin exchange.

4. Rates of primary and bacterial production were higher in the summer than in spring and in shelf waters than in the basin for both 2002 and 2004, although primary production was higher in 2004 than 2002, coincident with reduced sea-ice extent.

5. Ice algae supported both higher bacterial growth and production than terrestrial-derived peat, indicating that the source of organic matter plays an important role in structuring bacterioplankton community composition. The hypothesized reduction in sea-ice extent and coincident ice algae, along with enhanced coastal erosion and peat import to the ocean, may change microbial carbon cycling in the region with climate warming.

6. Diatoms dominated the spring and early summer season, with dinoflagellates as the major group in mid-to late summer. Microzooplankton grazing on phytoplankton averaged 22% of phytoplankton daily growth, with grazing and growth rates found in this study being low.

7. Mesozooplankton biomass was dominated by life stages of four copepod taxa: C. glacialis, C. hyperboreus, M. longa, and Pseudocalanus spp. The dominant zooplankton exhibited typical feeding behavior in response to chlorophyll concentration. Microzooplankton were preferred prey at almost all times, with the strength of the preference positively related to the proportion of microzooplankton prey availability.

8. Microzooplankton–mesozooplankton grazing consumed only 44% of the total water-column primary production over spring and summer in the SBI region, leaving > 50% directly available for local export to the benthos or for offshore transport into the adjacent basin.

9. An important mechanism for on–off shelf to basin transport is the formation and transport of eddies at the slope that provide a method for transporting shelf water and entrained hydrographic characteristics and zooplankton populations from the productive Chukchi Shelf into the less productive interior of the Canada Basin, thus affecting deep-basin Arctic foodwebs.

10. Sediment tracers, such as 7Be and chlorophyll a inventories, indicate that short-term sedimentation on the shelf occurs immediately north of Bering Strait as well as within and downstream of Barrow and Herald Canyons. These areas also underlie the most productive water-column regions, suggesting high pelagic–benthic coupling occurs on a seasonal basis at “hot spot” regions in the SBI study area.

11. A high percentage of labile marine phytodetritus settles on the shelf, declining in importance on the continental slope and in the Arctic basin. Some areas observed subsurface peaks of viable chlorophyll, indicating a reservoir of material can remain at depth in sediments for multiple years. Due to the episodic, seasonal nature of primary production and deposition at high latitudes and its likely linkage to ice retreat, these buried sources of organic materials may be an important food source for benthic invertebrates during low-productivity seasons.

12. Based on Pb tracers, sediments are focused at the outer continental shelf-slope region, particularly in the shallow (~100 m) shelf waters at the head of Barrow Canyon, a region of measured high primary production. However, despite elevated concentrations of suspended particulate matter in Barrow Canyon, the 210Pb budget does not indicate that sediment transport occurred from the West and East Hanna Shoals into Barrow Canyon, leaving unanswered a source for this material.

13. Sedimentary denitrification, a dominant sediment cycling process in continental shelves, generally decreased with increasing water depth in the SBI region, with little variation between spring and summer seasons. However, rates did correspond to differences in annual overlying primary productivities and particulate organic carbon export fluxes.

14. Model results upstream of the SBI region in the northern Bering Sea indicate Pacific water from the deep basin is periodically moved northward onto the shelf by mesoscale processes along the shelf break. Canyons along the shelf break appear to be more prone to eddy activity and, therefore, are associated with higher rates of on-shelf transport, a result that may likely also occur in the northern Chukchi shelf canyon systems.
7. Future direction

The Shelf–Basin Interactions program is now in phase III, which is focused on integration and modeling efforts to evaluate slope physical and hydrographic conditions, zooplankton dynamics, and associated change with climate warming. An implicit emphasis in these studies is the relevance to pan-arctic and global models. Results of the SBI program have illustrated the critical importance of continental shelf environments to aid in understanding the dynamic environment of the Arctic and the ongoing changes observed and forecast for this region. Within these shelf environments, process studies have identified a number of important characteristics of this region driven by ice, and the need to capture the episodic inputs of materials that are advected from the shelves. The episodic input of organic material to the deep ocean has been observed in other Arctic regions (e.g., the western Barents Sea to the Norwegian Sea; Thomsen et al., 2001) and suggests that tracing the seasonal cycling and transfer of materials will be important for understanding elemental cycles across the entire Arctic region. Ultimately, these and ongoing synthesis activities will investigate global change consequences for the ecosystems of the Arctic shelves and basin.

Development of a Pan-Arctic model (including embedded regional submodels) suitable for exploring “what-if scenario” studies related to global change, would move our understanding of the Arctic system forward, particularly if it can incorporate retrospective and ongoing data collections being made during the current 2007–2009 International Polar Year.

New programs that link the Arctic Ocean to its Pacific and Atlantic gateways will also be an important component to understanding the polar oceans. For example, recent observations have shown that spring and summer productivity on the northern Bering Sea shelf can be linked to decadal scale atmospheric/sea ice/oceanographic processes, and reflect the regime-induced climate changes in the western Arctic (Overland and Stabeno, 2004; Grebmeier et al., 2006). New initiatives in the Bering Sea as part of the Bering Sea Ecosystem Project (BEST) and Bering Sea Integrated Ecosystem Research Program (BSIERP) are now underway to document the ecosystem changes impacted by the extent of sea ice in the Bering Sea, upstream of the core SBI study region. The shallow and dynamic Bering Strait region and adjacent seas have also been identified as a key location to monitor changes in the ecosystem identified by the SBI, SEARCH (Study of Environmental Arctic Change) and AON (Arctic Observing Network; National Research Council, 2006) programs (Grebmeier et al., 1998; SEARCH, 2005).

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