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BENTHIC PROCESSES IN THE NORTHERN BERING/CHUKCHI SEAS: STATUS AND GLOBAL CHANGE

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Introduction

The shallow Arctic waters have important pelagic and benthic foodwebs, with the benthos playing a much greater role in system production and turnover than at lower latitudes (Laevastu and Favorite, 1981; Grebmeier and Barry, 1992; Grebmeier *et al*., 1995). The Bering and Chukchi Seas contain some of the highest faunal biomass in the Arctic, as well as in the world ocean. High nutrient levels in the seawater are upwelled onto the shelf and influence the planktonic and benthic foodwebs as well as sediment community dynamics. In regions of high water column production there is a tight coupling between water column and benthic production. Both zooplankton grazing and the microbial loop have little influence on carbon utilization in waters that are extremely rich in phytoplankton, allowing more utilizable carbon to settle to the benthos to maintain a rich benthic food web. Regions of high benthic production in shallow Arctic seas, such as Lancaster Sound and the Bering, Chukchi, and Barents Seas support a large component of bottom-feeding fish, whales, seals, walruses, and seaducks (Hood and Calder, 1981; Welch *et al*., 1992; Joiris *et al*., 1996).

Benthic production is extremely important in the northern Bering and Chukchi Seas, with high organic carbon deposition occurring over the shallow shelves, resulting in enhanced benthic standing stock to support key higher trophic organisms, such as Pacific walrus, gray whales, and bearded seals (Grebmeier *et al*. 1995). Predation by demersal fish, invertebrates, and marine mammals is an important factor limiting benthic biomass in the southeast Bering Sea. By comparison, cold temperatures limit fish populations in the northern Bering Sea northward, where benthic-feeding marine mammals and seabirds provide relatively higher regional predation pressure (Grebmeier *et al*., 1995). On the shallow Bering Sea shelf, the benthic food web is influenced by endotherm predation on bivalves and amphipods. The prey base for both gray whales and walruses is apparently declining as these apex predators approach or exceed carrying capacity (Lowry *et al*., 1980; Highsmith and Coyle, 1992), so major environmental changes affecting prey communities are likely to have significant effects.

The Northern Bering and Chukchi Seas

The seasonally ice-covered Bering and Chukchi Sea shelves are some of the largest continental shelves in the world. Mean current flow of Pacific-derived water is northward over most of the year into the Arctic Ocean. Sea ice production, extent, and duration are critical for annual carbon production (both sea ice algae and open water phytoplankton), water mass formation, and hydrographic flow influencing subsequent carbon transport through the system, as well as resting sites for marine mammals. High primary production can occur regionally in the water column (up to 300 g C m^{-2} yr^{-1}; Springer and McRoy, 1993; Springer *et al*., 1996), with ice-edge production quantitatively more important in regions of limited open water production. In specific areas of these seas this production is not directly consumed by pelagic secondary consumers, but rather by a rich macrobenthic community (Highsmith and Coyle, 1992; Grebmeier, 1993; Grebmeier and Cooper, 1995). As a result, large populations of benthic-feeding marine mammals and birds serve as apex predators in the food chain (Fay *et al*., 1977; Grebmeier and Harrison, 1992; Highsmith and Coyle, 1992; Oliver and Slattery, 1985; Oliver *et al*., 1983; Hunt, 1991).

The benthos is a long-term integrator of overlying water column processes. The distribution of benthic standing stock (Figure 1) and sediment oxygen uptake (an indicator of carbon supply to the benthos; Figure 2) in the northern Bering and southern Chukchi Seas indicate a strong pelagic-benthic coupling of biological processes in the region (Grebmeier, 1993; Grebmeier *et al*., 1995). The highest benthic biomass regions occur in the northern Bering Sea southwest of St. Lawrence Island, in the central Gulf of Anadyr, north and south of Bering Strait, at a few offshore sites in the East Siberian Sea, and in the northeast sector of the Chukchi Sea (Figure 1). By comparison, sediment oxygen uptake patterns indicate enhanced carbon deposition to the benthos southwest of St. Lawrence Island, northern Bering Sea, and southern Chukchi Sea (Figure 2). The lower uptake rates nearshore in the East Siberian and Chukchi Seas and northeast sector of the Chukchi Sea indicate reduced carbon deposition. This decoupling between benthic biomass (long-term scale) and sediment oxygen uptake (short-term scale) in these areas is likely due to higher current flow and associated transport of carbon past the sites on variable time scales.

Stable carbon and nitrogen isotope ratios of primary and secondary consumers in the northern Bering/Chukchi Seas also reflect the strong coupling between the pelagic and benthic components. In the Chukchi Sea, Dunton *et al*. (1989) found low ^{13}C enrichment of secondary consumers relative to that of zooplankton and similar ^{15}N enrichments among a variety of secondary consumers relative to zooplankton. These data reflect the existence of shorter food chains (Figure 3), which in the Chukchi Sea is related to a more direct coupling of benthic consumers to the very high pelagic primary production on the shallow shelf, little of which is grazed before reaching the sea bed (Dunton *et al*., 1989). Stable isotopic analyses of sediment organic carbon also indicate a coupling between the water column and benthos, with less negative ^{13}C values occurring under the more productive regions of the northern Bering and Chukchi Seas (Naidu *et al*., in press).

Geographically, the benthos in the region south of St. Lawrence Island and into the Gulf of Anadyr in the northern Bering Sea and the southern Chukchi Sea is dominated by bivalves, amphipods, and polychaetes (Grebmeier 1993; Grebmeier and Cooper, 1994, 1995; Grebmeier *et al*., 1995). The area north of St. Lawrence Island to Bering Strait is dominated by amphipods and bivalves. As one moves northward to the Chukchi outer shelf the faunal are dominated by a mix of amphipods, bivalves, and polychaetes. Benthic faunal biomass declines northward in the Chukchi Sea, although there is an enrichment in benthic biomass near Barrow Canyon and the outer edge of the Chukchi continental shelf (Feder *et al*., 1994; Grebmeier, unpubl. data; Figure 2). A relatively rich region of benthic fauna also occurs just to the east in the Beaufort Sea (K. Dunton, unpubl. data). Observations of black, sulfide-rich muds near the head of Barrow Canyon suggest a shunting downslope of organic shelf-derived materials (Grebmeier and Cooper, 1994; Devol *et al*., 1997). Ultimately, changes in the overlying flow directly impact benthic community structure, carbon deposition, and sediment composition. Sediment grain size is directly related to the current strength, and individual species of benthic infauna require specific sediment regimes within which to feed and grow.

The St. Lawrence Island Polynya (SLIP) Region

In the Bering Sea south of St. Lawrence Island (SLI), the water transport is predominantly from south to north. However, in the ice-covered winter/early spring period, the area is influenced by the seasonal SLI polynya (SLIP), an area of open water that develops south of SLI as prevailing northerly winds force sea ice away from wind-sheltering land-masses (Kozo *et al*., 1990). The SLIP extends 20-40 km (sometimes further) south over a shelf 30-70 m deep (Schumacher *et al*., 1983; Smith *et al*., 1990; Stringer and Groves, 1991). This brine injection sets up periodic baroclinic currents that transport water and likely entrained organic matter to the south and then west as geostrophic balance is reached (Schumacher *et al*., 1983). Recent benthic studies indicate that the benthos underlying this cold pool area southwest of SLI has the highest oxygen uptake as well as benthic biomass on the northern Bering Sea shelf, suggesting that low temperatures do not limit benthic carbon cycling (Grebmeier *et al*., 1990, 1995). Very high standing stocks of benthic infauna (primarily bivalves) are maintained by nearshore primary production enhanced by SLIP dynamics, and subsequent baroclinic transport of carbon-rich waters southwestward from the island (Grebmeier, 1992; Grebmeier and Cooper, 1995). Total organic carbon content and C/N ratios of surface sediment also indicate deposition of high quality organic carbon southwest of St. Lawrence Island (Grebmeier and Cooper, 1995).

Recent studies south of St. Lawrence Island suggest that changes in the bivalve populations over the last few decades are likely linked to changes in the northward transport of water across the shelf (Walsh *et al*., 1989; Grebmeier and Cooper, 1995; unpubl. data; Roach *et al*., 1995). Benthic productivity is directly linked to higher trophic levels since the regional foodweb is dominated by marine mammal predation on bivalves and amphipods. The prey base for both gray whales and walruses is apparently declining as these apex predators approach or exceed carrying capacity (Lowry *et al*., 1980; Highsmith and Coyle, 1992; Brendon Kelly, pers. comm.), so that environmental changes affecting prey communities are likely to have significant effects. In addition, the spectacled eider, a diving seaduck which winters under very harsh conditions in the Bering Sea (Petersen *et al*., 1995; Larned and Tiplady, 1997), has been observed to dive for benthic food in sub-freezing water 40-60 m deep south of St. Lawrence Island. Ephemeral openings in the shifting pack ice are typically used. The wintering area was first located south of

St. Lawrence Island in March 1995; up to 40,000 eiders from U.S. and Russian populations were packed together in single leads with bodies touching in water kept open only by movements of the eiders themselves (W. Larned, U.S. Fish & Wildl. Serv., pers. comm.).

Sediment oxygen uptake rates show a distinctive southwestern excursion away from SLI, implying an enhanced flux of particulate carbon to the benthos downstream from the SLIP (Figure 4a-c). However, a declining trend in sediment oxygen uptake in the productive areas to the southwest of SLI has recently been observed, with oxygen uptake decreasing from 35 mmol O_2 m^{-2} d^{-1} in 1988 to 20-25 mmol O_2 m^{-2} d^{-1} in 1993-1994 (Figure 4a-d). This decline in sediment oxygen uptake is indicative of a reduction of carbon supply to the benthos interannually. Multivariate community analyses indicate that there are different benthic communities to the southwest of the island relative to nearshore and much further offshore to the south and to the east (Figure 5a-c; Grebmeier and Cooper, 1995; unpubl.data). Although benthic biomass fluctuates among years, there is also an indication of a declining trend in benthic biomass from 1990 to 1994 (Figure 5d; Grebmeier and Cooper, unpubl. data), and recent studies indicate this trend has continued in 1998 and 1999. This biomass decline coincides with indications since the late 1980s that benthic community structure has also been changing in the region (Sirenko and Koltun, 1992).

Changes in Benthic Fauna and Oceanographic Processes

Recent retrospective studies of benthic communities indicate a changing marine system in the Bering and Chukchi Seas (Sirenko and Koltun, 1992; Grebmeier and Cooper, 1995; unpubl. data; Francis *et al*., 1996). In particular, the region just north of Bering Strait has historically been a settling basin for organic carbon, resulting in high benthic standing stock and oxygen uptake rates (Grebmeier *et al*., 1988; 1989; Grebmeier, 1993). Specifically, the benthic productivity in a region north of Bering Strait near 67°30 N, 169° W has historically maintained the highest benthic faunal biomass of the entire Bering/Chukchi system (Stoker, 1978; 1981; Grebmeier, 1993; Grebmeier and Cooper, 1994; Grebmeier *et al*., 1995; Reed, 1998). Although benthic biomass remains high in the area, a change in dominant benthic fauna has occurred regionally and is likely an indication of changing hydrographic conditions (Grebmeier,1993; Grebmeier *et al*. 1995; Grebmeier, unpubl. data).

With respect to the St. Lawrence Island polynya region, any change in regional oceanography due to physical effects of the Gulf of Anadyr gyre position or size would ultimately be related to northward transport of water through Bering Strait, and geostrophic balance within the Arctic Ocean basin. This balance drives the northward current regime in the northern Bering Sea (Walsh *et al*., 1989). Recently Roach *et al*. (1995) indicate reduced transfer of Pacific Ocean water north through Bering Strait, which suggests coincident reduction in northward transport of waters south of St. Lawrence Island. Water-column primary production and the final location of carbon deposition to the benthos is related to ice production and brine formation in the SLI polynya during late winter-early spring. The Gulf of Anadyr "cold pool" is maintained by ice production/brine formation in the SLIP. Reduced ice production south of SLI might decrease renewal of nutrients for early-season production by ice algae and phytoplankton, and baroclinic currents that would move it to the southwest (Grebmeier and Cooper, 1995). Both these factors would limit benthic populations. Alternatively, an enhanced and more energetic polynya with global warming might maintain a chemostatic-type system as occurs north of St. Lawrence Island (Walsh *et al*., 1989), allowing a longer growing season with increased production and subsequent transport. On-going studies in the region are currently investigating a variety of these hypotheses (Grebmeier, Cooper, and Lovvorn, unpubl. data).

Current Regional Studies

There are a variety of ecosystem-type studies currently being undertaken in the northern Bering and Chukchi Seas, including work on long-term status and change of hydrography and benthic processes in the Bering Strait region (Cooperative Institute for Arctic Research /NOAA). Another collaborative program is investigating hydrographic forcing of benthic ecosystem change south of St. Lawrence Island (National Science Foundation [NSF]).

A new collaborative NSF and Office of Naval Research program was recently initiated called the Western Arctic Shelf-Basin Interactions (SBI) project that has as its goal to investigate and interpret global change impacts on biogeochemical cycling and trophic dynamics in the Chukchi and Beaufort Seas (Grebmeier *et al*., 1998; SBI home page: <http://utk-biogw.bio.utk.edu/SBI.nsf>). Sea ice extent and duration is a key element of the physical, biological, and geochemical aspects of this program and results from this current sea ice workshop will provide valuable insights for the objectives of the SBI program.

Also, an Environmental Observatory was recently funded by NSF to monitor the physical and biochemical parameters of waters that flow past Little Diomede Island in Bering Strait throughout the year (home page: <http://eco53.bio.utk.edu>). The program also includes annual oceanographic sampling of water column and benthic parameters at select high productivity sites south and north of Bering Strait. In addition, this observatory will rely on local Alaska Natives for many activities, such as collection of daily water samples at the land-based observatory and assistance with marine mammal and sea ice observations.

Summary and Future Research

The wide shelves of the northern Bering and Chukchi Seas support an extremely productive and dynamic benthic system. The high nutrient inflow of Pacific waters across these shelves supports high primary production which settles quickly to the underlying benthos. Both consumption by benthic organisms and benthic carbon cycling are extremely important for sequestering and recycling carbon over the shelves as well as supporting higher trophic levels utilized by local Inuit. These shelves are covered by sea ice for 6-9 months of the year and the role of sea ice in influencing the hydrographic structure in the region is critical for both water mass formation and carbon production and transport through the system.

Important questions for future studies related to sea ice and benthic systems include:

- What is the role of sea ice in ice algal community vs. open water production and how will changes in the extent and duration of the ice cover influence these processes?
- What is the interaction between ice extent and organic carbon flux to the benthos and how does the timing of ice melt interact with stimulating benthic production and carbon cycling?
- How will a projected reduction in ice thickness and extent influence the quantity and spatial location of organic carbon reaching the benthos?
- How will a reduced ice cover impact higher trophic level populations and their associated predation on the benthos?

An understanding of the interactions between sea ice formation and extent on water column and sediment carbon production and recycling processes is essential to predict the potential impact of global change on ecosystem dynamics in the seasonally-ice covered northern Bering and Chukchi Seas.

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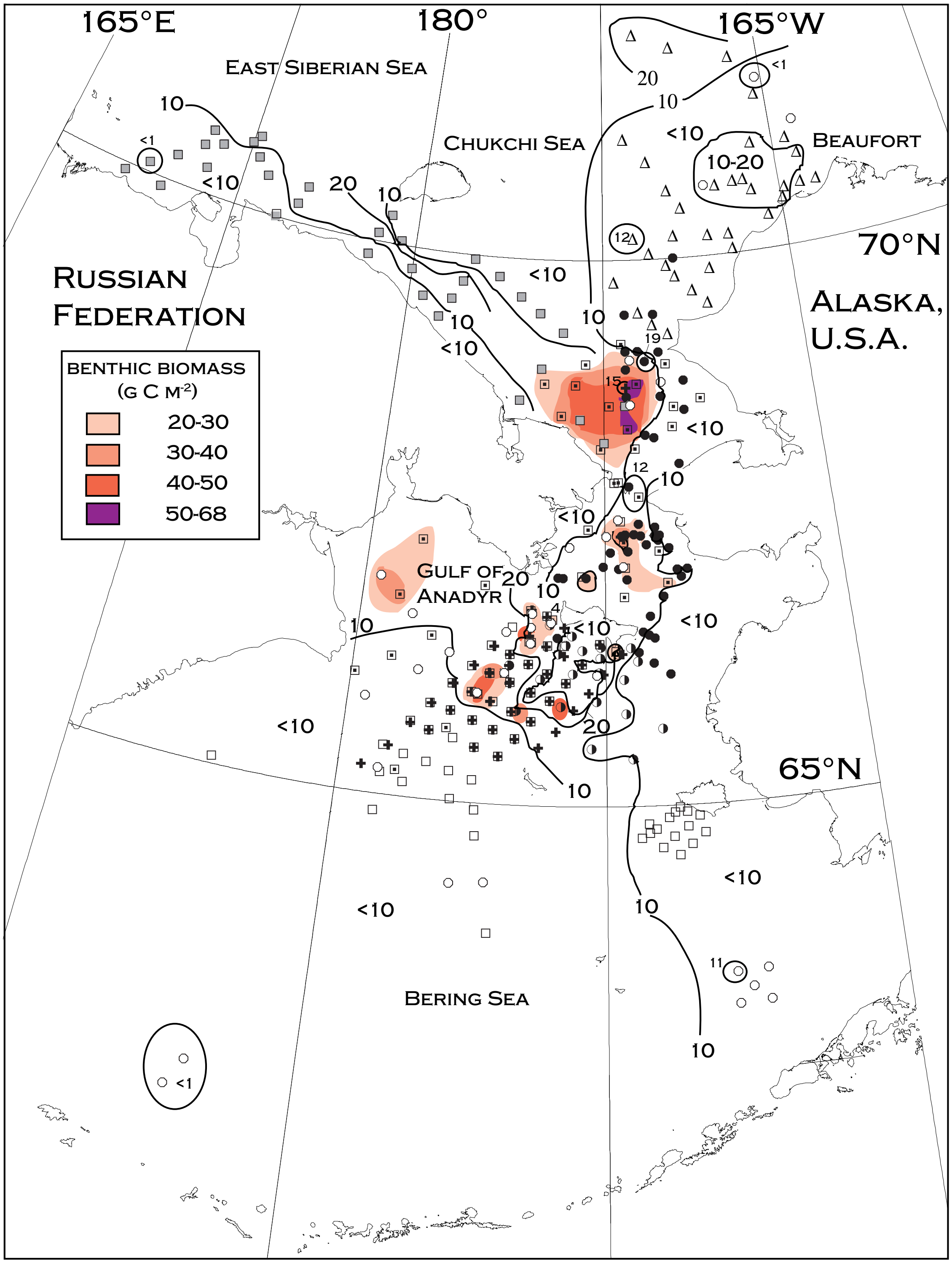

Figure 1. Benthic biomass (gC m^{-2}) obtained in the Bering, Chukchi and East Siberian Seas, 1984-1995. Each of the 309 data points shown is the mean of four or five replicated van Veen (0.1 m^2) grabs, sieved through a 1.0 mm screen. Data derived from Grebmeier (1987, 1993, unpubl. data), Grebmeier et al. (1989), Feder et al. (1994), Grebmeier and Cooper (1995), and Reed (1998).

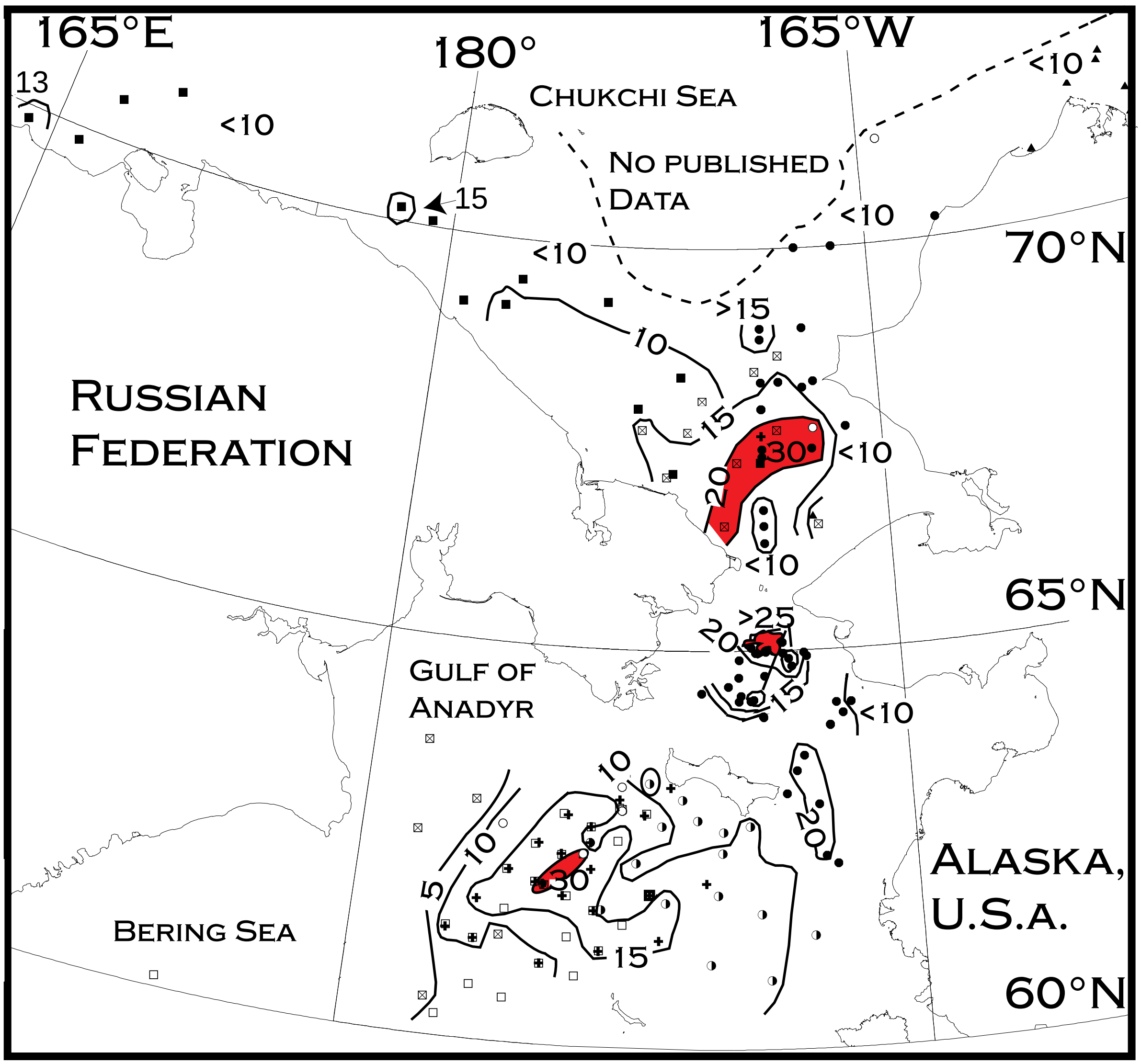

Figure 2. Sediment oxygen uptake rates (mmol O_2 m^{-2} d^{-1}) obtained in the Bering, Chukchi and East Siberian Seas, 1984-1995. Each of the 180 data points shown is the mean of two replicate HAPS (133 cm^2) cores incubated shipboard for approximately 12 hr at in-situ bottom temperatures. Data derived from Grebmeier (1987, 1993), Grebmeier and McRoy (1989), Grebmeier and Cooper (1994, 1995), and unpublished data.

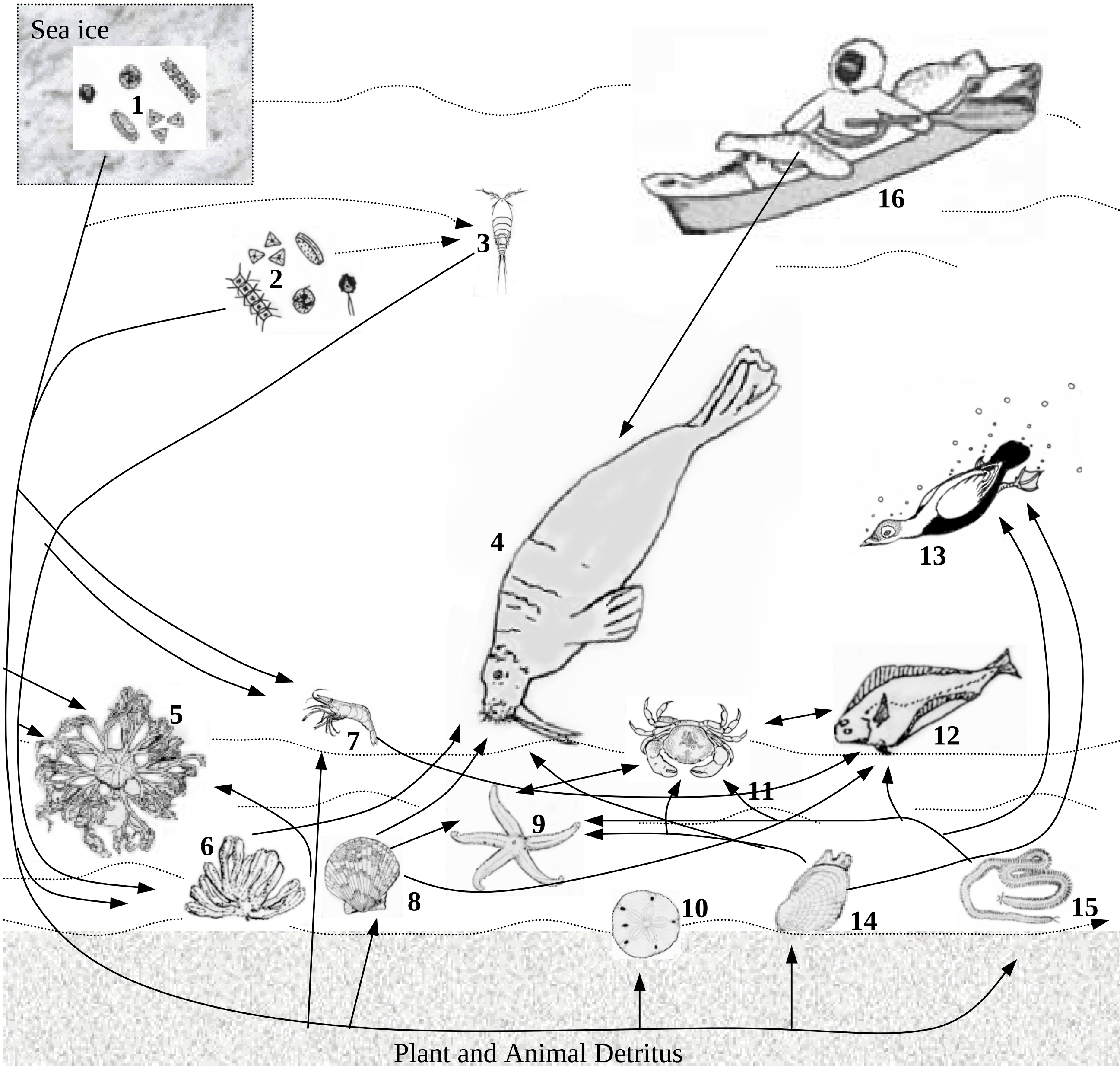

Figure 3. Representation of a simplified northern Bering/Chukchi Sea food web. The high density and abundance of benthic biota reflects the large proportion of phytoplankton that falls directly to the seabed, ungrazed by pelagic organisms. The direct assimilation of phytoplankton by the benthos results in shorter food chains and a more efficient transfer of carbon to large marine mammals and diving seabirds.

Organisms are: 1: ice algae; 2: phytoplankton; 3: copepods; 4: walrus; 5: basket stars; 6: ascidians; 7: shrimps; 8: filter-feeding bivalves; 9: sea stars; 10: sand dollars; 11: crabs; 12: bottom feeding fishes; 13: diving seabirds; 14: deposit feeding bivalves; 15: polychaetes, 16: native subsistence hunters.

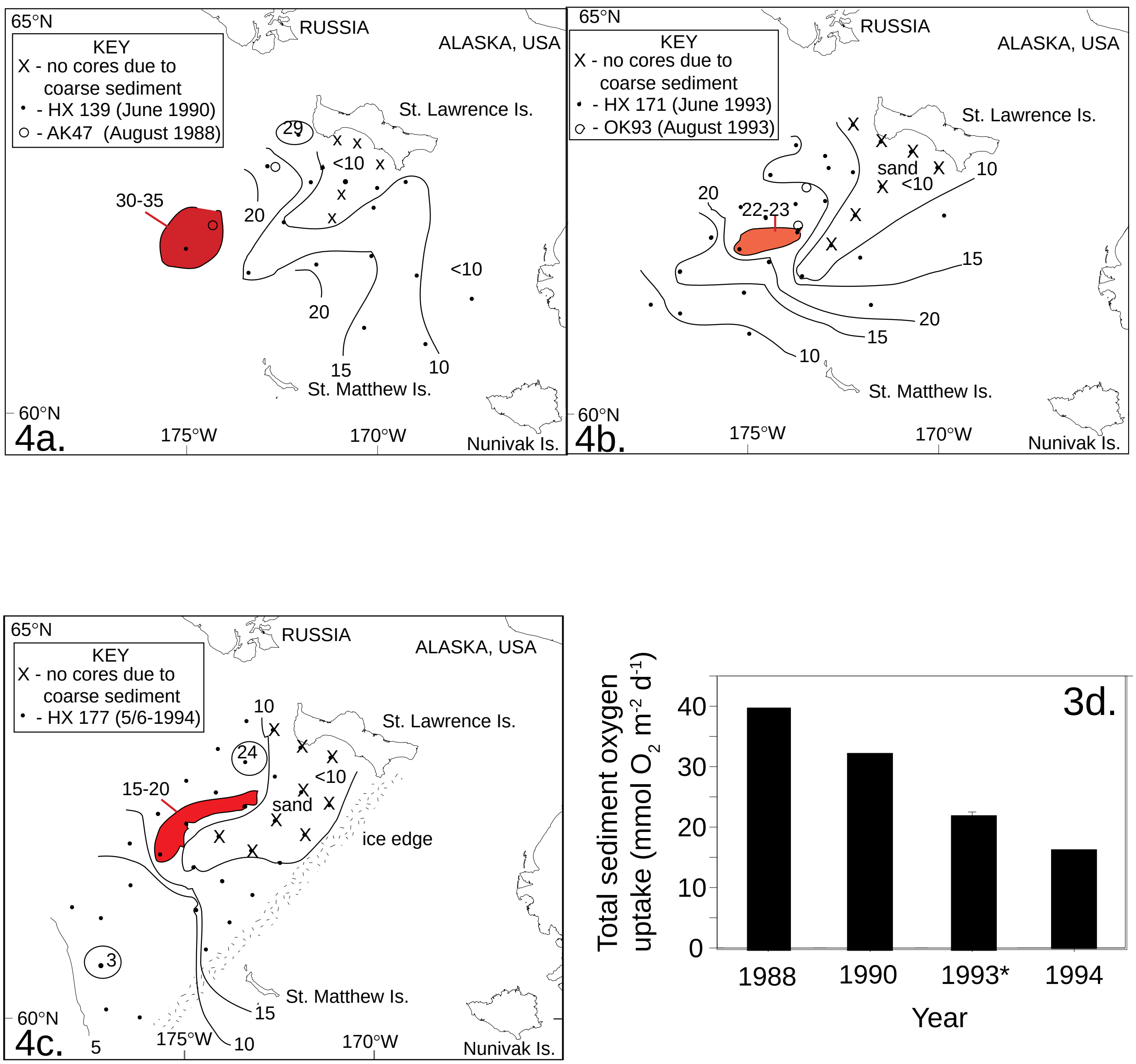

Figure 4. Total sediment oxygen uptake (mmol O_2 m^{-2} d^{-1}) south of St. Lawrence Is. during: a. June 1990 (Grebmeier and Cooper, 1995), b. June/July 1993 (Grebmeier and Cooper, unpubl. data), c. May/June 1994 (Grebmeier and Cooper, unpubl. data), d. bar graph of interannual variation at one site (NWC 5; red zone; *s.d. for 2 cruises) occupied during 1988-1994).

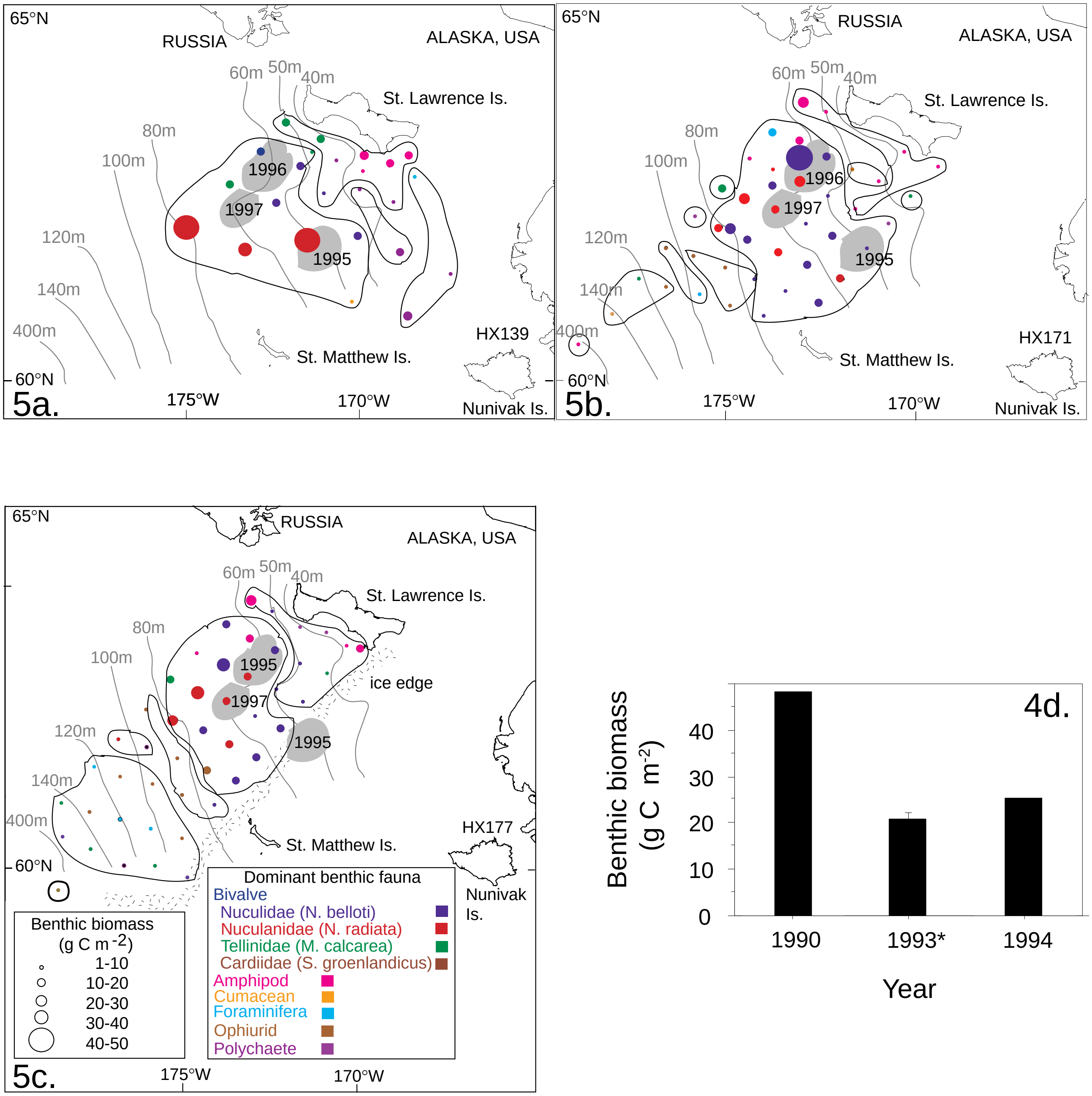

Figure 5. Benthic community structure (encircled in black; based on faunal abundance) in relation to total station benthic biomass (color coded by dominant faunal type) in the region south of St. Lawrence Island: a. June 1990 (from Grebmeier and Cooper, 1995), b. June/July 1993 (Grebmeier and Cooper, unpubl.data), c. May/June 1994 (Grebmeier and Cooper, unpubl.data), d. bar graph of interannual variation at one site (NWC5; same as Fig. 3 red zone). The shaded year indications are the general areas of Spectacled Eider flocks, March 1995-1997; pers. comm., W. Larned, USFWS).