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Takahashi, Kozo
Faculty of Science, Kyushu University

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CHAPTER 18

Paleoceanographic Changes and Present Environment of the Bering Sea

Kozo Takahashi
Faculty of Science, Kyushu University, Fukuoka, Japan

Abstract

The process of efficient biological pumping with high biological productivity was determined for the Bering Sea by employing a long-term time-series sediment trap deployed during 1990-1995. The present Bering Sea is an effective atmospheric CO_2 sink with significant drawdown of the CO_2. The high efficiency attributes to markedly high opal content of 69% in total mass flux, which is followed by 13% calcium carbonate content. The nodal location of the Bering Sea, in terms of the Pacific-Arctic-Atlantic gateway connection, makes this marginal sea significantly important for water circulation, balances of heat and salt, and various chemical properties, many of which affect global climate and mass balance. The present situations of the "opal" Pacific Ocean and the "carbonate" Atlantic Ocean were different during the glacial low stands primarily due to closure of the Bering Strait gateway caused by sea level drop. With a longer time scale than the Milankovitch cycles, Beringia (or the Bering land bridge) subsided a number of times due to tectonic movement, allowing intrusion of Atlantic signals. Based on mollusk faunal distribution in northern Japan, the Bering gateway must have been open initially at earlier than 5.1 Ma in the Late Miocene, followed by a number of openings and closures due to tectonics during the Pliocene. Detailed history of such openings and closures must be investigated with scientific drilling in the Bering Sea. The formation of the North Pacific Intermediate Water is established by evidence including stable isotopes, microfossils, and detritus sediments. The Meiji Drift is composed of sediments derived from the past Bering Sea, forming contourite deposits on the flank of the northern Emperor Seamount region just south of Kamchatka Strait.

Introduction

Subpolar regions, including marginal seas, play significant roles in the global carbon cycle and hence are important factors of global climate change (e.g., Tans et al. 1990, Wong et al. 1995). Surface waters in these regions, which have the potential to absorb atmospheric CO_2, contribute to this change due to high biological productivity. There are three principal belts of high biological productivity in the world oceans, including the subarctic belt (both Pacific and Atlantic oceans), the equatorial upwelling belt (Pacific, Atlantic, and Indian oceans), and the circumpolar subantarctic belt (Berger et al. 1987). Moreover, the high biological productivity in the upper ocean involves either emission or absorption of atmospheric CO_2. It is generally concluded that the equatorial belt is the largest natural source of atmospheric CO_2 (Tans et al. 1990, Murray 1995). The remaining two subpolar belts are generally regarded as CO_2 sinks. Based on measured carbon and opal particle fluxes using sediment traps, Wong et al. (1995) showed that the western subarctic Pacific is also a CO_2 sink with a fairly effective biological pump. Analogous information from the northern marginal seas of the Pacific region, such as the Bering Sea, has been meager (Takahashi et al. 1997). However, available evidence suggests that the Bering Sea plays a large role in the global material balance and, in turn, climate change (Takahashi et al. 1997; Takahashi et al., in press).

In this paper I review the current knowledge and discuss the importance of the Bering Sea as a northern marginal sea of the North Pacific, in terms of global mass balance and Atlantic-Pacific connections in the geologic past. Present-day high productivity in the Bering Sea based on biogenic particle fluxes will be presented and compared with those in other marginal seas and pelagic regions. The processes of water mass exchange between the marginal sea and the Pacific Ocean and/or the Arctic Ocean are important for understanding material and heat balances as well as climate change. Studies of paleoceanographic changes recorded in the sea provide pertinent information concerning the evolution of Northern Hemisphere glaciation in association with the Milankovitch orbital cycles, and other high frequency cycles such as Dansgaard-Oeschger cycles. The past climatic-paleoceanographic changes and the need for further studies in these regions will also be discussed

Geomorphology

The Bering Sea has a surface area of 2.29×10^6 km^2, a volume of 3.75×10^6 km^3, and is the third largest marginal sea in the world, surpassed only by the Mediterranean and the South China seas (Hood 1983). Three major rivers empty into the Bering Sea: the Kuskokwim and Yukon, draining central Alaska, and the Anadyr draining western Siberia (Fig. 1). The Yukon is the longest, supplying the largest discharge. Its discharge from the land is 4×10^4 m^3/s, peaking in August, which roughly equals the amount of the

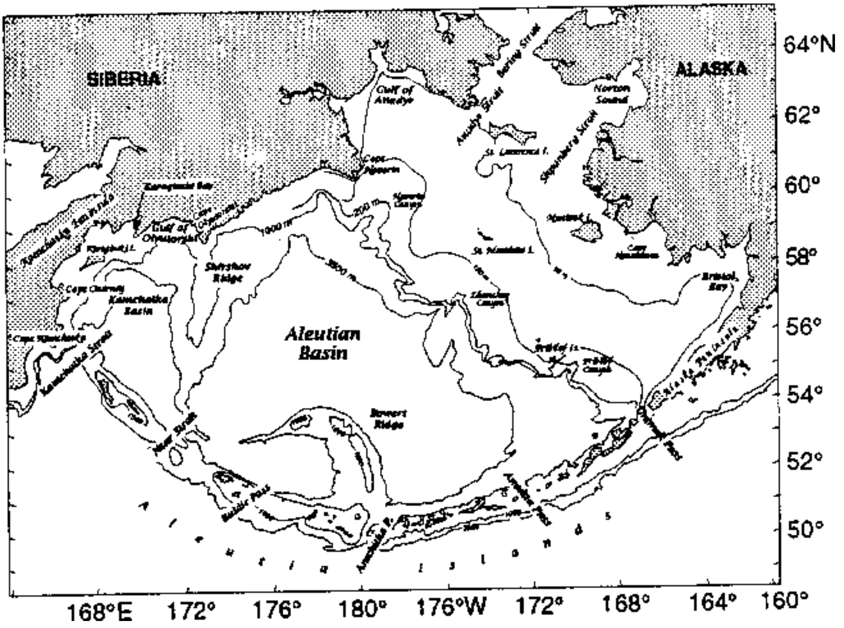

Figure 1. Major topographic features of the Bering Sea and Aleutian Islands. Contours of 100, 200, 1,000, and 3,500 m are shown. (Basic map from U.S. GLOBEC 1996.)

Mississippi River. The Yukon's annual mean flow is 5 × 10^3 m^3/s, which is about two-thirds the annual flow of the Columbia River (Hood 1983).

Approximately one-half of the Bering Sea is covered by a shallow (0-200 m) neritic area (Fig. 1). The majority of the continental shelf spans the eastern side of the sea off Alaska, from Bristol Bay in the south to the Bering Strait in the north. The northern continental shelf is seasonally covered by ice, while ice is rarely present over the deep southwest areas (Japan Meteorological Agency 1990-1994). The continental slope occupies only 13% of the total Bering Sea area and has a slope of generally 4-5 degrees (Hood 1983).

Other than the shelf regions, two significantly high topographic features provide better calcium carbonate preservation than the basins (Supko 1973). One is the Shirshov Ridge which extends south from Kamchatka along 170°E, separating the Aleutian Basin into eastern and western parts. The second is Bowers Ridge (sometimes referred to the North Rat Island Ridge/Bank) and extends 300 km north from the Aleutian Island Arc (Fig. 1). The Aleutian Basin is a vast plain lying at a depth of 3,800-3,900 m with sloping hollows to depths of as much as 4,151 m (Hood 1983).

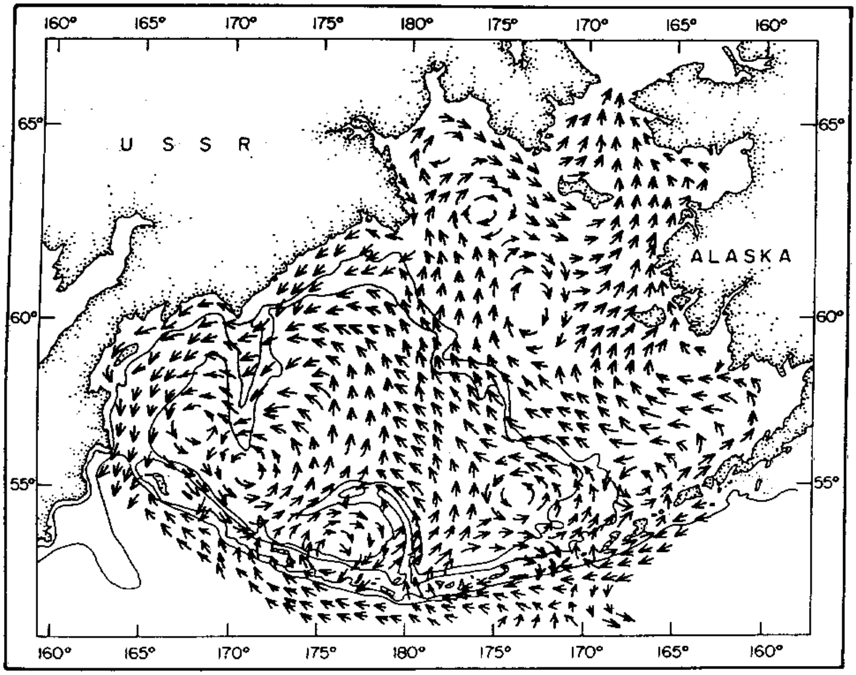

Figure 2. Map showing surface currents in the Bering Sea. (From Arsenev 1967, cited in Hood 1983.)

Physical Oceanography

The Alaskan Stream, which is an extension of the Alaskan Current flowing westward along the Aleutian Islands in the subarctic Pacific, mainly enters the Bering Sea through the Amchitka Pass and the pass west of Attu Island in the eastern Aleutian Islands (Favorite et al. 1976, Arsenev 1967 cited in Hood 1983). A part of the Subarctic Current also joins the northward flow coming from the Alaskan Stream, resulting in a combined volume transport of 11 Sv (Ohtani 1965, 1973). Much of the Pacific water masses entering the Bering Sea leaves through passes in the Aleutian Islands (Fig. 2). The most significant one is through the Kamchatka Strait whose present depth is 4,420 m. If the glacial North Pacific Intermediate Water mass was formed in the Bering Sea, the Kamchatka Strait was the major passage through which it flowed out, followed by a secondary one at the Commander-Near Strait at 2,000 m present-day depth. A part of the water in the Bering Strait flows out to the Chukchi Sea in the Arctic, whose detail will be discussed in a later section since it has a paramount importance to global mass balance and climate. Inside of the Bering Sea a large scale counterclockwise surface water circulation is recognized along the continental slope and the Aleutian Islands in the Aleutian and Kamchatka basins (Fig. 2; Ohtani et al. 1972, Arsenev 1976 cited in Hood 1983). However, in the Bowers Basin the direction of the surface water flow is clockwise. Furthermore, on the Bering Sea Shelf there are at least three clockwise surface water circulation patterns recognized (Fig. 2).

According to Ohtani et al. (1972), the Bering Sea is a source region for Western Subarctic Pacific water which plays a major role in the circulation of the western subarctic Pacific. The Western Subarctic Pacific water is characterized by marked stratification with cold upper layers in winter and a remarkable dichothermal layer at around 100 m in summer. He further stated that vertical structure of temperature and salinity in the Aleutian Basin varies widely, from significant stratification to homogenous gradient in the upper 500 m. During winter, the patterns of vertical profiles become near vertical with much less stratification due to strong mixing which is caused by severe wind stress. Although there are varieties of summer vertical structures, they are characterized by the presence of a dichothermal layer. One example of the variation is that double dichothermal layers are found in the northeastern corner of the Aleutian Basin along the continental shelf (Ohtani et al. 1972).

Significance of Present High Biological Productivity

The Bering Sea is one of the most biologically productive areas in the world (Berger et al. 1987), as evidenced by large quantities of fish caught annually in the region (Ohtani and Azumaya 1995). A measure of this productivity was made with a time-series sediment trap, deployed at a fixed station. Particle fluxes were continuously measured beginning in August 1990 through the present (1998) in the Bering Sea (Fig. 1; Station AB: 53.5°N, 177°W; water depth: 3,788 m; trap depth: 3,198 m). The 5-yr record for 1990-1995 shows a mean daily total mass flux or export production of 177 mg/m^2 per day (see Takahashi et al. 1997; Takahashi et al., in press; Maita et al., chapter 16, this volume) which is one of the highest in the world. This value contrasts with a pelagic station just outside the Bering Sea, Station SA (49°N, 174°W; water depth: 5,406 m; trap depth: 4,812 m), in the central subarctic Pacific. At Station SA a 5-yr mean total mass flux of 91 mg/m^2 per day was measured (Takahashi et al. 1997; Takahashi et al., in press). Thus, Bering Sea data reveal that this sea produces approximately twice as much total mass flux as found in the pelagic Pacific station. The same trend is also seen in diatom flux (Fig. 3; Takahashi et al. 1996, 1997).

Furthermore, based on species list and percentage contribution of each taxon of siliceous and calcareous shell-bearing plankton fluxes, it

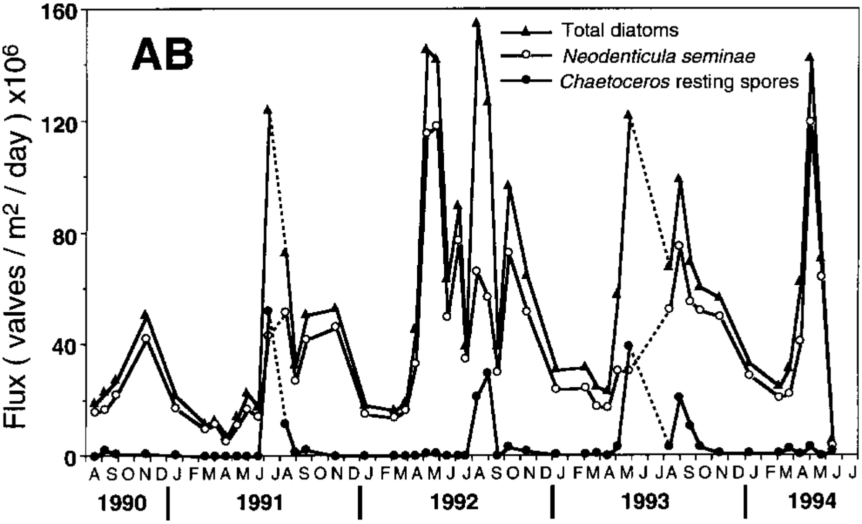

Figure 3. Four-year-long fluxes of total diatoms, Neodenticula seminae, and Chaetoceros resting spores measured with a sediment trap at Station AB in the Aleutian Basin of the Bering Sea, August 1990-July 1994. (From Takahashi et al. 1996.)

appears that biological ecosystems operating in the two regions are slightly different in detail, but major components and structures are similar to each other. The number of constituting diatom species in flux at Stations AB and SA are 53 and 29 taxa, respectively, which appear substantially different. However, many minor diatom species only occurring at Station AB do not contribute significantly to total diatom fluxes. Therefore, the minor species are numerically unimportant, although they have values as tracers of neritic, benthic, and/or hemipelagic environmental conditions. *Chaetoceros radicans* and other *Chaetoceros* resting spores are exceptional in that they can be included as major species category only at Station AB, but not at Station SA. *Chaetoceros radicans* resting spores on the average contributed 4.0% at Station AB (1990-1994 record: Takahashi et al., in press). In contrast they contributed only negligible fluxes during fall 1991 and fall-winter 1993-1994 at Station SA (Takahashi et al. 1996). *Chaetoceros* resting spores have more hemipelagic and neritic characteristics rather than pelagic characteristics reflecting the differences at the two stations.

Moreover, *Neodenticula seminae,* a dominant pennate diatom taxon, contributed similarly 81.4% and 70.2% of the total diatom valve fluxes at Stations AB and SA, respectively (1990-1994 record: Takahashi et al. 1996; Takahashi et al., in press). Furthermore, flux percentage contribution of *Coccolithus pelagicus,* a dominant coccolithophore species in the Bering

Sea, to total coccolithophore assemblage, is similar at the two stations (Station AB: 56.2%; and Station SA: 39.7%), followed by *Emiliania huxleyi* making up the remaining percentage at these sites; the minor species *Gephyrocapsa oceanica* and *Calcidiscus leptoporus* were negligible (<0.01%: 1990-1995 record: Takahashi et al., in press). Thus, it is fair to conclude that although the Bering Sea has more hemipelagic to neritic characteristics and is twice as productive relative to the pelagic counterpart, flux percentages of the major diatoms and coccolithophores are similar, suggesting qualitatively similar ecosystems are operating in the two regions.

Sediment trap data from the northern Aleutian Basin (58°N, 179°E, north of Station AB) had a total mass flux of 144 mg/m^2 per day (Honjo et al. 1995) during 1991-1992, 34% less than the total mass flux measured at Station AB (193 mg/m^2 per day during the same 1991-1992). This difference indicates a geographic variability within the basin that is smaller than between the basin and the North Pacific. In addition, Honjo and his colleagues deployed sediment traps at Shoyo Station in the northern Okhotsk Sea and measured a mean flux of 129 mg/m^2 per day during the 1990-1991 period (Honjo et al. 1995), illustrating a similarly high flux in the northern marginal sea of the Pacific.

These data from traps clearly indicate higher total mass fluxes in marginal seas with respect to the world's oceans (Honjo 1990, Honjo et al. 1995). One should recognize that the high fluxes are associated with high opal contribution (Fig. 4) mainly due to diatoms (Takahashi 1991, Takahashi et al. 1997: Fig. 3). Five-year means for the percent weight contribution of the total mass fluxes measured at Station AB are as follows: biogenic opal (opal hereafter): 69%; calcium carbonate: 13%; and organic matter: 10% (Fig. 4). Such a high opal contribution is unprecedented in flux measurements. For a comparison, the 5-year mean of opal values at Station SA in the central subarctic Pacific is 53%, which is substantially lower than that of the Bering Sea, but still significantly high for the world standard. Furthermore, opal flux contributions in the Equatorial Pacific ranging from 9°N to 12°S represent 12-35% of total mass flux, which ranges from 14 to 132 mg/m^2 per day (Honjo et al. 1995).

The particle flux constituents from the Bering Sea, which are made of high opal and relatively low calcium carbonate contents, are ideal for an effective biological pump. The major reason for this is that the production of siliceous plankton with opal shells involves only cytoplasmic organic carbon which draws CO_2 into the upper ocean, without incorporating carbon in their shells. This organic carbon production does not cause CO_2 emission. Production of shells by the calcareous plankton, on the other hand, involves both CO_2 incorporation by organic matter formation and CO_2 emission by calcium carbonate shell formation. Ratios depend on various factors such as taxon, season, and physiological conditions. A ratio of organic carbon to inorganic carbon (C_{org}/C_{inorg}) is an important indicator when determining whether a CO_2 sink or source situation exists (Berger and Kier 1984). The C_{org}/C_{inorg} ratios measured at Station AB were almost

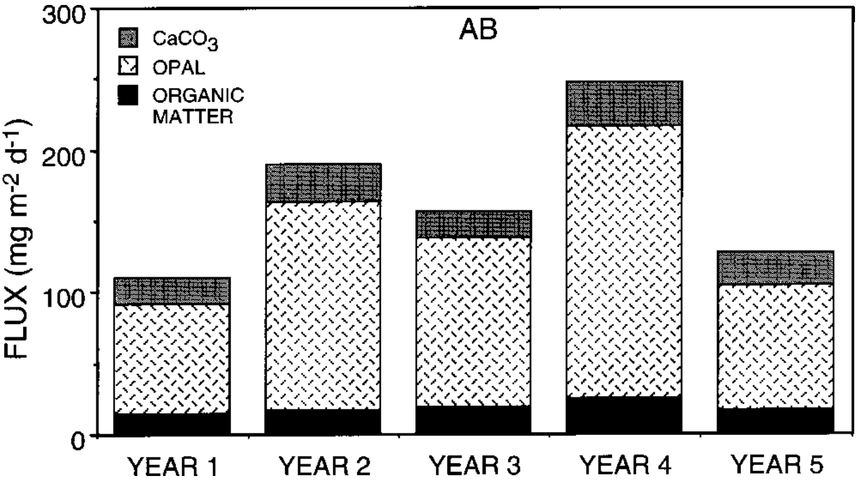

Figure 4. Five-year record of annual mean fluxes of organic matter, opal, and $CaCO_3$ at Station AB in the Bering Sea. (From Takahashi et al. 1997.)

always greater than one throughout the 5 years of the measurements, indicating that the Bering Sea is an efficient atmospheric CO_2 sink (Takahashi et al. 1997; Takahashi et al., in press). Furthermore, although values are slightly less than those at Station AB, Station SA in the central subarctic Pacific also represents a CO_2 sink. Therefore, both the Bering Sea and the central subarctic Pacific play a significant role as CO_2 sinks in the carbon cycle.

It is of interest to delineate how the Bering Sea may have behaved during past glacial and interglacial cycles in terms of the carbon cycle and climate change. Much has to be considered: siliceous and calcareous microfossils, carbon isotopes, organic compounds and other relevant indicators that are preserved in the sediments of these regions.

Present Gateway to the Arctic Ocean and Its Significance

As the largest semi-enclosed marginal sea of the Pacific rim, the Bering Sea's indisputable importance has been recognized in various oceanographic processes (Tsunogai et al. 1979, Lisitzin 1972, Ohtani et al. 1972, Edmond et al. 1979, Craig et al. 1981, Sancetta 1981, Sambrotto et al. 1984). The northerly outflow of Bering Strait surface water is important since it flows one way out to the Chukchi Sea in the Arctic Ocean, although the amount is less than water exchange through the Aleutian passes. The amount of water passing into the Chukchi Sea is estimated to be 0.8 Sv (Coachman and Aagaard 1981). This "Pacific" origin water eventually flows out to the Atlantic via the Arctic Ocean. The Bering Strait also provides one of the highest biologically productive areas in the world approaching 324 gC/m^2 per yr over a wide area (2.12×10^4 km^2: Sambrotto et al. 1984). Much of the biological production of organic matter and associated nutrients flowing into the Arctic Ocean are due to today's northerly current direction.

One-way flow into the Arctic Ocean, however, may not have been always true in the past, and this high nutrient, biologically productive flow may have had a profound effect in the nature of the greater carbonate production in the Atlantic and opal production in the Pacific: the carbonate ocean versus silica ocean hypothesis (Honjo 1990). During glacial periods the Bering Strait, which is about 50 m deep today, was aerially exposed due to sea level drop closing the Bering-Arctic gateway. What was the impact on global water circulation then? The Bering water mass circulation and river discharge during the glacial periods was exclusively southward. The glacial Yukon River discharge, for example, had no alternative but to eventually come out of the Bering Sea to the North Pacific, affecting the salinity of Pacific waters.

A unidirectional flow of Bering Strait water which reaches the Atlantic should affect not only heat balance, but also salt balance and hence the formation of deep water masses in the Atlantic. It is known that during glacial intervals, the Atlantic Ocean became more Pacific-like, and that the Pacific Ocean became more Atlantic-like with regard to circulation as well as carbonate and siliceous microfossil preservation. This situation is known as the basin-to-basin fractionation model by Berger (1970). Thus, the siliceous and carbonaceous sedimentary record provides one of the clues to changes in the past water circulation. Glacial intervals are characterized by better preservation of calcareous plankton in the Pacific, which can be considered as a shift to more of an Atlantic type (Berger 1970). Such a shift made the two great oceans far more even in water mass chemistry than they are today, as evidenced in the microfossil records. Since the global circulation of water masses significantly affects climate, we need to investigate paleoceanographic changes recorded in Bering Sea and perhaps Arctic Ocean sediments in order to solve how this type of excursion occurred and how quickly it shifted from one state to the other.

Beringia and the Bering Gateway in the Past: Atlantic Connection through the Arctic Ocean

Prior to presenting the Quaternary glacial events, let us briefly discuss major tectonic events which occurred with a longer time scale than the Milankovitch cycles. This includes the Bering land bridge called Beringia as well as the intrusion of the Bering marine gateway. Detailed paleogeography of the Tertiary Period, especially the Paleogene, has not been well understood (Worrall 1991). However, the history of the Neogene Bering gateway is slightly better understood. The North Atlantic-Arctic Ocean-North Pacific connection can be argued for on the basis of paleobiogeography of mollusks. Uozumi et al. (1986) found *Tridonta alaskensis* and *Tridonta borealis* in the Atsuga Formation in central Hokkaido, Japan. These bivalve species are known to have intruded from the North Atlantic. The age of the Atsuga Formation has been determined to be older than 5.1 Ma, employing a fission truck method (Uozumi et al. 1986). Sagayama et al. (1992) examined diatoms and placed the Atsuga Formation in the lower part of the *Neodenticula kamtschatica* partial-range zone, which ranges from 6.3 to 3.1 Ma (Barron 1985). Thus, the Atlantic-Pacific connection dates back to the Late Miocene. Furthermore, Ogasawara and Gladenkov (1995), analogous to the above, showed that the marine gateway connection through the Bering region initially occurred around 4.2-3.0, and subsequently at 2.5 and 2.2 Ma, based on biogeographic occurrences of mollusks originating from the northern Atlantic or northern Pacific regions.

Bering Sea Deepwater Exchange with the Pacific Ocean: Past and Present

There is one piece of geological evidence suggesting that bottom water of the North Pacific Ocean was generated in the Bering Sea in the past. Mammerickx (1985) discussed the possibility of bottom thermohaline circulation as a cause of the Meiji sediment tongue (Ewing et al. 1968) or the Meiji Drift (Scholl and Stevenson 1997), whose features are similar to the North Atlantic drifts in their general shape, length, and thickness (Scholl et al. 1977). In this scenario, the sediments in the Meiji Drift were supplied from the Bering Sea through Kamchatka Strait. Kamchatka Strait represents the only deep strait (4,420 m) where deepwater masses can exit from the Kamchatka Basin (i.e., Commander Basin) to the North Pacific. Other deep straits include the Commander-Near Strait (2,000 m), and the rest of the straits in the Aleutian Islands which are less than 1,155 m deep. The fact that the Meiji Drift thickens toward the Kamchatka Strait implies that the Bering Sea source of the past bottom water flow (D. Scholl, pers. comm., 1998). According to Scholl et al. (1997), from approximately 30 to at least 5 Ma, the Oligocene to the early Pliocene, the sediments from the Bering Sea were carried into the Pacific and distributed along the Meiji Drift by bottom water impinging against the northern flank of the submerged Emperor Seamounts. In addition, evidence for recent contact of the bottom waters with the atmosphere in the past 40 years is provided by Warner and Roden (1995). They found anthropogenic chlorofluorocarbons in bottom waters of the Aleutian Basin, an indication of recent ventilation of the deep Bering Sea.

Paleoceanography of North Pacific Marginal Seas

Sancetta (1981) derived four diatom assemblages based on factor analysis on diatoms from the surface sediments of the Bering Sea (Fig. 5). She demonstrated that diatom assemblages show close correlation to the distribution of major water masses. The most important is the Bering Basin assemblage, which occupies the entire Aleutian Basin and extends to the Commander Basin (Fig. 5a). This assemblage is also found on the eastern continental slope, but it decreases rapidly with decreasing depth and is absent above 200 m. This assemblage is dominated by *Neodenticula seminae* with minor contributions from *Rhizosolenia hebetata* forma *hiemalis* and *Thalassiosira trifulta.* The distribution of this assemblage matches closely with the water mass typical of the Alaskan Stream (9°C at the surface) and its derivative (6°C) with admixture of waters coming from tidal mixing in the Aleutian passes and the Bering Shelf (Sancetta 1981).

Moreover, she showed three additional assemblages, Bering Shelf, productivity, and sea-ice assemblages (Fig. 5b-d), each of which has significantly characteristic distribution with water masses. The Bering Shelf assemblage is associated with benthic littoral genera such as *Melosira/ Paralia* and *Delphineis.* The productivity assemblage is dominated by *Chaetoceros* resting spores, which are indicative of high productivity with large surface water temperature fluctuations from spring to fall. The sea-ice assemblage is found on the northern Bering Shelf and the Chukchi Sea and is principally composed of *Thalassiosira nordenskioldii, Nitzschia grunowii*, and *Nitzschia cylindrus* (Sancetta 1981).

Gorbarenko (1996) recently published paleoceanographic changes in the Bering Sea and adjacent regions during the Late-Glacial and Holocene based on stable isotopic and sediment measurements on a number of cores raised in the regions. Based on core K-119 (50°25′N, 167°44′E, 2,440 m) from the Detroit Seamount in the western subarctic Pacific, he concluded that with better ventilation during the glacial period, the formation of the intermediate water occurred in the Bering Sea and spread into the western subarctic Pacific to a depth of 2,440 m. He also discussed that ice-rafted debris observed in the Bering Sea and western subarctic Pacific were transported by sea ice, but not icebergs, and left a strong sediment signature in the Kamchatka Strait and immediately adjacent parts of the western subarctic Pacific. One of the major conclusions which Gorbarenko (1996) presented was that the North Pacific low salinity surface water signal did not propagate from the North Atlantic; instead, the low saline surface waters of both oceans independently and simultaneously spread quickly in the northern regions. Moreover, calcium carbonate peaks observed at the terminations 1A and 1B in core 2594 raised from the Shirshov Ridge in the Bering Sea (56°56′N, 169°53′E; Fig. 6) are synchronous in the western subarctic Pacific and its marginal seas as well as in the North Atlantic and

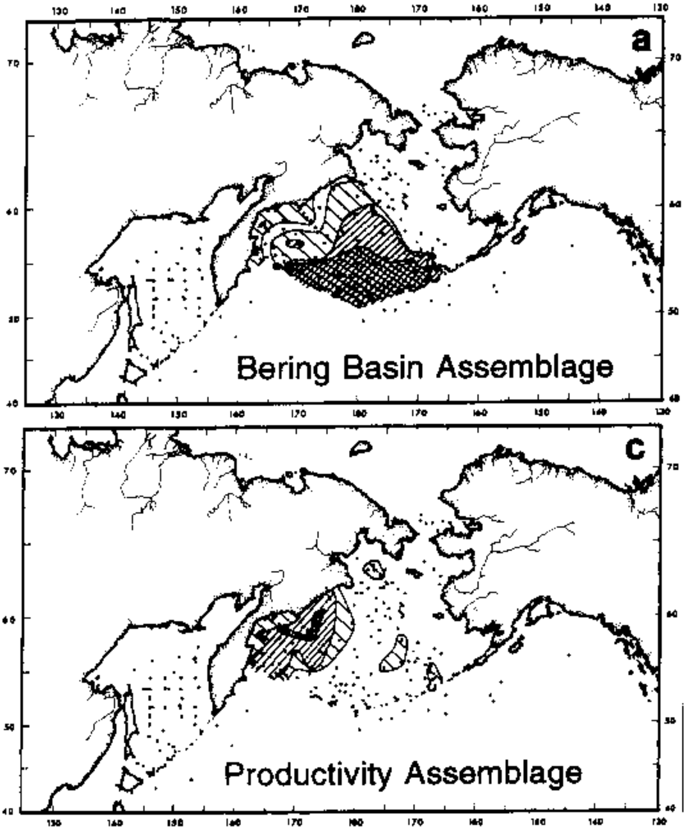

Figure 5. *Distribution of four diatom assemblages derived by a factor analysis in the Bering Sea: Bering Basin assemblage, Bering Shelf assemblage, productivity assemblage, and sea-ice assemblage. Contours at factor loadings of 0.900 (cross hatch), 0.600 (fine hatch), and 0.300 (coarse hatch) (from Sancetta 1981).*

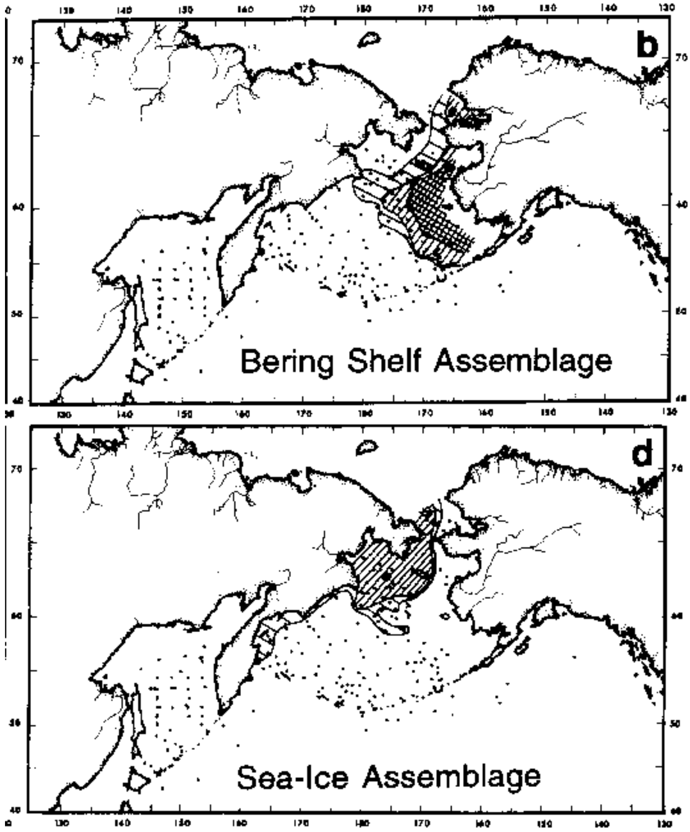

Figure 5. (Continued.)

have ages of 12,500 and 9,300 yr B.P., respectively. Paleoproductivity in the Bering Sea was lower during the glacial period than today, based on organic carbon contents. This is demonstrated by low glacial diatom contents (Fig. 6). Such a decreased glacial productivity is due to partial ice cover which prevented insolation during the glacial period. The diatom contents increased after termination 1A and decreased once, but increased again after termination 1B which continued into the present (Fig. 6).

Further, the northern marginal seas of the North Pacific (Bering, Okhotsk, and Japan seas) experienced major climate changes during the late Pleistocene. Because of the semi-closed nature of the marginal seas, strong signatures due to environmental changes of millennial time scale, which have a higher frequency than the Milankovitch cycles, can be faithfully recorded in the sediments. For instance, a sequence of laminated and non-laminated sediments in the Japan Sea testifies that exchange of

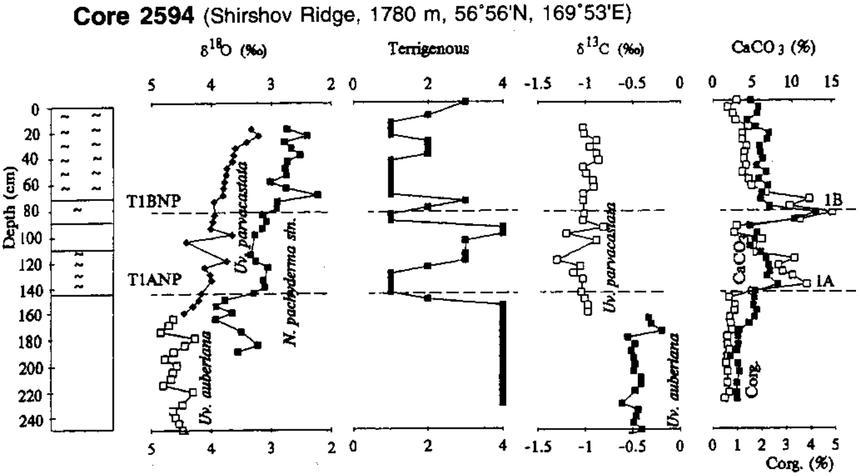

Figure 6. Paleoceanographic measurements on core 2594 raised from the Shirshov Ridge (56°56′N, 169°53′E, 1,780 m), Bering Sea. Illustrated are layers of diatomaceous sediments, $\delta^{18}O$ and $\delta^{13}C$ of planktonic foraminifera Neogloboquadrina pachyderma sinistral and benthic foraminifera Uvigerina parvacastata, percent terrigenous matter, percent $CaCO_3$, and percent C_{org} (from Gorbarenko 1996).

Japan Sea water with that of open pelagic Pacific water occurred and was periodically restricted during the Pleistocene (Tada et al. 1992). The laminated sequence can be correlated with Dansgaard-Oeschger cycles which were identified in the Greenland ice core record (Dansgaard et al. 1993) and represents global events rather than regional phenomena (Broecker 1994, Tada et al. 1992). According to Broecker (1994), there are seven locations in the world (outside the North Atlantic) which can be correlated on the basis of Dansgaard-Oeschger cycles, Heinrich events, or the Younger Dryas. The atmospheric temperature recorded in Greenland ice cores, as well as lake sediment records, can be linked with high resolution marine sedimentary records in the marginal seas. Moreover, Behl and Kennett (1996) recently found that a cyclic sedimentary sequence in the Santa Barbara Basin, analogous to the Japan Sea laminated and non-laminated sequence, was formed under the influence of a northern source of oxygenated Pacific Intermediate Water. A part of the North Pacific Intermediate Water is thought to be presently formed in the Bering Sea (Tally 1991). Riser (1997), however, suggests the likelihood of NPIW formation in the Okhotsk Sea, instead.

Paleoenvironmental work generated very useful predictions for future climate. Scholl and Stevenson (1997) argue that the condition that once existed in the Aleutian Islands may return. The paleoenvironmental conditions in the Aleutian Arc and adjacent marine realm include the growth of redwood with open skies and increased surface water evaporation during the Oligocene to the early Pliocene, 30 to at least 5 Ma.

They explain their scenario as follows. The present transport volume of relatively warm Alaskan Stream water, entering the Bering Sea through Aleutian Island passes such as the Near Pass, is sufficient to keep Bering Sea Basin surface water from winter freeze-over. The salinity of Bering Sea surface water is low because there is less evaporation than precipitation chiefly due to foggy and overcast summer weather conditions. The density of such low saline surface water does not sufficiently increase to initiate vertical thermohaline circulation in winter today. Sea ice at present only extends to the southern margin of the Bering Shelf. The Aleutian Arc is presently covered with a carpet of tundra.

Conditions can be changed, however, and the winter freeze-over of Bering Sea surface water can occur as follows. If and when Bering Sea deepwater channels, such as Kamchatka Pass, become shallow or narrow by tectonic movement, which will occur within 2 million years, the rate of water exchange between the Bering Sea and the Pacific will decrease. This will allow winter freeze-over, which subsequently forces the Aleutian Low to move toward the Gulf of Alaska. Such an atmospheric shift would further weaken the Bering/Pacific water exchange rate as well as weaken the Bering gyre. This will allow warmer Pacific water to drift into the Bering Sea, causing the return of the coniferous forest, increased surface water evaporation, and warmer summer days to the Aleutian Arc and adjacent region (Scholl and Stevenson 1997).

Future Work

In future studies of the Bering gateway region, a scientific drilling program should be initiated so that the history of water mass interchange between the Pacific and the Arctic/Atlantic can be thoroughly studied. Studies of calcium carbonate and biogenic opal microfossils will also shed light on the evolution of the Pacific (opal) and Atlantic (carbonate) type oceans. Production of the carbonaceous and siliceous plankton involve organic carbon production; hence their process is closely coupled with the global CO_2 system. Thus, with this type of work on the past material cycles, a better understanding of the paleoclimate will be achieved.

High resolution paleoceanographic investigations, including the North Pacific Intermediate Water formation during the entire Pleistocene glacial and interglacial intervals, are needed to decipher details of climatic change, with emphasis on understanding land-ocean links. On a longer time scale, large climatic changes such as the detailed evolution of Northern Hemisphere glaciation can also be studied due to high sedimentation rates in the Bering Sea. Pertinent parameters that should be investigated include ice algae, planktonic diatoms of shallow Bering Shelf origin, and coccolithophores such as *Coccolithus pelagicus*.

Conclusions

The Bering Sea, the largest semi-closed marginal sea of the Pacific Ocean, is located in the subpolar region and it plays a significant role in the global carbon cycle. This mainly stems from the highly efficient biological pump operating in the region, which results in the production of greater amounts of opal than calcium carbonate. Measured biogenic particle flux data indicate the Bering Sea has twice the annual production of adjacent Pacific waters. Therefore, the biological pump manifested in the marginal sea is efficient, not only in the quality of high opal content, but also in quantity in terms of high fluxes. It is concluded here that the Bering Sea acts as a CO_2 sink.

The nodal location of the Bering Sea between the Pacific Ocean and the Arctic Ocean mediates transport of Pacific water into the Arctic Ocean. The contrast between the opal ocean of the Pacific and the carbonate ocean of the Atlantic today is attributed to the one-way water flow of the Bering Shelf water through the Bering Strait to the Arctic and eventually to the Atlantic. During past glacial low stands the modern deep sill of the Bering Strait (50 m) was aerially exposed and the gateway closed. This had a major impact on water mass exchange between the Atlantic and Pacific. A large amount of runoff, such as from the Yukon River, had to flow out to the Pacific during the glacial low stand, whereas a part of it eventually reaches the Chukchi Sea today. Such a shift in circulation must have caused significant changes in intermediate and deepwater formation in the past.

With limited geological data, biological productivity of the Bering Sea was lower during the glacial period than today, judging from the lower organic carbon contents. Such a decreased glacial productivity is due to partial sea-ice cover. Sea ice did not fully cover the glacial Bering Sea since the formation of intermediate or deep waters such as North Pacific Intermediate Water by atmospheric cooling of the surface water was possible. A somewhat similar trend of the lower glacial productivity was seen in the Okhotsk Sea, but detailed comparisons with the Bering Sea have to be made in future work. The timing of terminations 1A and 1B in the Bering Sea and adjacent regions are synchronous with those in the Atlantic, suggesting that the deglaciation process occurred independently in the Pacific and Atlantic sides.

The Pacific-Atlantic connections existed several times on a longer geological time scale than the Milankovitch cycles. Based on the discovery of the Atlantic mollusk faunas in northern Japan, the initial connection due to a tectonic event was earlier than 5.1 Ma, the Late Miocene. Since then the Pacific-Atlantic connections recurred several times. After the series of the tectonic events, Beringia and the Bering gateway have been subjected to shorter time scale events such as the Milankovitch cycles of 100 ka frequency.

Water exchange rates between the Bering Sea and the subarctic Pacific significantly influence the weather conditions of the region. The Aleutian Arc is presently covered with a carpet of tundra. During the Oligocene to the early Pliocene, the Aleutian Arc was covered with redwood forests with clear summer skies. This may occur again when and if the Bering-Pacific water exchange decreases and the Aleutian Low moves toward the Gulf of Alaska. The geomorphology of the Kamchatka Strait has a key to this possible change since it allows substantial water exchange between the Bering Sea and the Pacific today.

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