Geography of the seasonally ice covered seas

Hajime ITO and Miki Yoshioka

National Institute of Polar Research, Tokyo, Japan

Abstract

The Okhotsk Sea and the Barents Sea are known to be ice covered during a part of the year and ice free in the rest of the year. The conditions surrounding both seas constitute their environment and contribute to the creation and maintenance of this particular state, which are investigated in geographic terms in this article. The common features of the two seas as well as the contrasting ones are elucidated. The results serves the investigation of a seasonally ice covered sea generally.

Introduction

Among the seas which are ice covered in winter and ice free during the summer months, the Barents Sea and the Okhotsk Sea are located at the northernmost and the southernmost extremes in the northern hemisphere, respectively. This article compares the seas in terms of geography, on which many, if not all, studies are based. There can be some similarities in geographic elements, since both seas belong to an identical type, i.e. the seasonally ice covered sea. The problem can be, however, formulated differently for each sea: why is the sea at that high/low latitude open in summer or frozen in winter, respectively. Hence contrasting elements are also expected. Through the comparative study, not only the characteristics of the two seas but that of a seasonally ice covered sea in general may be elucidated.

Scope

The Barents Sea and the Okhotsk Sea are shown in Figure 1. The surface area of each is defined to be the area inside of the curves drawn on the plane of the sea surface for the purpose of discussion: coast line of the continent, that of islands, linear lines connecting pairs of peninsulas facing to each other. Each sea is then defined to be the water body underneath the area. The Barents Sea and the Okhotsk Sea thus defined have particular shape and extent, and are placed at a particular location relative to the earth. The seas are described in this aspect in the next chapter.

The boundary of the seas consists of three different materials: rock, air and water. The water body in question is thus surrounded by the sea bed, by the overlying atmosphere and by the adjacent sea, and interact with them. The attaching neighbors are described in separate chapters in this order.

The Barents Sea and the Okhotsk Sea obtain certain characteristics and present a particular state at a given time under the influence of these geographic elements. The detailed investigation of the seas themselves are certainly the most interesting and important topic, but are beyond the scope of the current article. The state of the sea is in fact merely regarded as the results of the geographical conditions. Nevertheless, a brief sketch of the present state of both seas is given in the succeeding chapter to get some idea to make the comparison possible. In the last section the similarity and difference of the Barents Sea and the Okhotsk Sea are discussed.

Geometry

The Okhotsk Sea is bounded by land, i.e. a continent or large islands at northeast, north, west and south. Two straits cut the land boundary, which connect the Okhotsk Sea to the

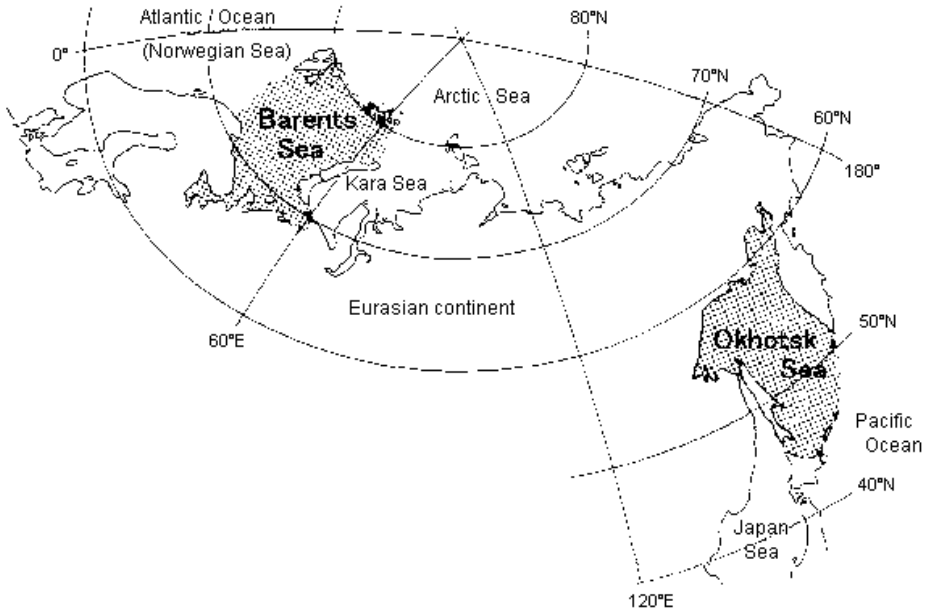

Fig. 1 Two seasonally ice covered seas.

neighboring Japan Sea. An island chain, Kuril Islands, draws the southeastern boundary, where the water body has direct contact to the Pacific Ocean.

The Okhotsk Sea covers an area of 1.5×10^6 km^2. The mean depth is 0.8×10^3 m, and the total volume is 1.2×10^6 km^3 (National Astronomical Observatory, 1995). The total length of the boundary is 10043 km (6787 km), of which 9483 km (6227 km) is the coast line and 560 km is the boundary running on water. The contact with the Pacific prevails with the length of 513 km, whilst that to the Japan Sea is 47 km, through 7 km of Tatar Strait and 40 km of Soya Strait. These measurement were made from maps (Energy, Mines and Resources Canada, 1990; Nomura, 1997) where no reference is given.

The coast line length can be increased arbitrarily by using a large scale map, especially where the coast line is complicated in the shape, e.g. fjord. The comparison in the length with the boundary on the water, which is a linear line according to the definition, would be difficult. The coast line was smoothed for this purpose only, by cutting off the small bays with an entrance width of 100 km or less. The boundary length of thus smoothed sea is given in the parenthesis. The Okhotsk Sea is a water body surrounded in the first place by a land mass, 92 % of the boundary length, with some opening to adjacent seas, 8 %.

The Barents Sea covers an area of 1.4×10^6km^2 including the White Sea. Mean depth is 0.2×10^3m (Dzhenyuk and Zykova,1992), and the volume is 0.3×10^6 km^3. The southern side is bordered by a continent and the eastern and northwestern sides by large islands. Three straits cut through the land boundary to the east: Malygina Strait of 8 km wide, Karskiye Vorota Strait of 61 km wide, Matochkin Shar Strait of 4 km wide which connects the Barents Sea with the Kara Sea (Dzhenyuk and Zykova,1992). Scattered small islands, Zemlya Frantsa Iosifa, are located on the northeastern boundary, through which the Barents Sea has contact with the Arctic Sea and Kara Sea. The western boundary has a single small island, Bear Island, and is practically open to an ocean, the Norwegian Sea.

The total boundary length is 9955 km (5639 km), of which the coastline is 8399 km (4083 km). The length of the border to other sea is 1556 km,

of which 640 km is the boundary to the Norwegian Sea (75% of the border is land). The contact length to the Norwegian Sea occupies 41% of the total water boundary.

The Okhotsk Sea is located at the latitude of 45°N to 60°N and the Barents Sea is at 68°N to 80°N. The latitudes of the centers are assumed to be 53°N and 74°N, respectively. Latitude has a direct influence on the potential solar radiation. The cosine is considered to its index and is calculated for both latitudes, and for different position of the sun. In summer, they are 0.870 for the Okhotsk Sea and 0.636 for the Barents Sea and do not differ from each other so much as the latitude difference would indicate. In the fall and spring, they are 0.602 and 0.276. The Okhotsk Sea receives double the amount of solar radiation in comparison to the Barents Sea. The difference becomes more clear in winter, they are 0.233 and 0, the cosine value being negative in Barents Sea.

Geology

Both seas with the given geometry are placed on the surface of the earth, where the distribution of the land has been established. They are placed at rather contrasting locations in relation to the land mass. The Barents Sea is attached to a northern coast at the west of the Eurasia Continent, and Okhotsk Sea is located on the southern coast at the east of the same continent.

The northern coast of Asia is attached to the widest continental shelf in the world. The Barents Sea is located entirely on the shelf. Caledonian and Uralian trends dominate in the old platform probably originating in the Archaean. The basement is covered by several layers of sediment (Embleton, 1984). This continental shelf is suspected to have been completely covered by an ice sheet in the last glacier age, hence the Barents Sea became filled quite recently. The sea bottom is not completely flat, but retains the landscape created underneath the ice sheet. Two wide submerged valleys run toward southwest and north respectively. The Barents Sea itself is shallow with the depth range of 100 m to 400 m, but to the north the shelf drops to the Nansen Basin with the depth exceeding 3000 m and to the west to the Norwegian Basin with depth exceeding 2000 m.

The northern half of the Okhotsk Sea is also on the continental shelf. Forty percent of the area has the depth 200m (Wadachi, 1987). The Kuril Island chain was created as an island arc while the Pacific Plate submerges underneath the continent. A trench was made on the ocean side of the arc, and a basin on the other side, in the Okhotsk Sea. Thus the southeastern part of the Okhotsk Sea is quite deep. The area with a depth > 3000 m is 1.6×10^5 km^2, 10% of the entire sea (Wakatsuchi and Martin, 1990). The age of the basement of Kuril Basin is estimated to be 120 to 140 million years, the Cretaceous. The thickness of the sedimentary cover in the Okhotsk Sea exceeds 6 km in some place. Buried and submarine volcanic structures are found in the Kuril Basin (Shilo et al., 1982). The land surrounding the Okhotsk Sea is mountainous and volcanically active.

The total annual discharge of freshwater into the Okhotsk Sea is estimated to be 590 km^3 (Groves and Nunt, 1980), of which the continental runoff is 463 km^3/year (Zuenko and Yurasov, 1997). The majority of the freshwater is supplied by the Amur River, 315 km^3 /year (Zuenko and Yurasov, 1997). The drainage area of the Okhotsk Sea is 2.6×10^6 km^2 (4.1×10^6 km^2, including the sea surface), of which the drainage basin of Amur is 1.8×10^6 km^2.

The Dvina and the Pechora are major rivers flowing into the Barents Sea. The drainage area of the Barents Sea is 1.3×10^6 km^2 (2.7×10^6 km^2, including sea surface),of which the Dvina is 0.3×10^6 km^2 and the Pechora is 0.2×10^6 km^2. The discharge into the Barents Sea is concentrated in the short summer season. (Cattle, 1985).

Zemlya Frantsa Iosifa, located at the northern margin of the Barents Sea, consists of many ice capped islands and the archipelago has 2600 km of tidewater ice cliffs. The archipelago supplies 1.5 km^3/year of fresh water to the Barents Sea in the form of icebergs. (Løset and Carstens, 1996).

Climate

In winter, the Siberian high pressure develops on the continent adjacent to the Okhotsk Sea and the westerly wind blows onto the sea. The cold continental air meets the warm sea water and causes a considerable amount of precipitation. The large part of the Okhotsk Sea is classified as "Dfc" in Köppen climate classification, meaning that the monthly mean temperature of the coldest month is below -3°C, that of the warmest month is above 10°C but that of the fourth warmest month does not exceed 10°C, and that the region has rich precipitation all year through. The northwestern part is classified "Dwc", which describes the difference from Dfc, being dry in winter.

The systematic weather record for a certain time length is available on the coastal stations. For instance, at Abashiri, at the southernmost boundary, the annual mean air temperature is 6.0°C, the monthly mean temperature stays below 0°C for 4 months (National Astronomical Observatory, 1995). At the western boundary, at Chaivo Bay on Sakhalin Island, the air temperature ranges from 20°C to -30°C in a year (Shirasawa et al., 1996). Mean air temperature at Okhotsk Sea is estimated to be -6°C in winter and 18°C in summer (Groves and Nunt, 1980), using the data obtained on the sea and at the coastal stations. Extreme winter temperatures on the sea assumes the range from 0°C at the southern part in a warm year to -32°C at the northern part in a cold year (Wakatsuchi and Martin, 1990). The annual precipitation at Nemuro, at the southern boundary, is recorded to be 1370 mm, which is distributed in all the months of the year. At Okhotsk City, at the northern boundary, 467 mm of the precipitation is concentrated in summer. At Ust Khayryuzovo, at the eastern boundary, 766 mm of the annual precipitation is obtained and at Nikolaevskna-Amure, at the western boundary, 657 mm, mostly in summer and autumn at the both stations (Korzun et. al., 1974).

The precipitation over the Okhotsk Sea is estimated using these observations. At the southern Okhotsk Sea, annual precipitation is 1200 mm and in the northern part, 600 mm. It decreases toward the center of the sea, where the minimum value of 400 mm is calculated. Annual evaporation is estimated to be 400 mm in the central part of the Okhotsk Sea. It increases to the south and southeast (Korzun et.al., 1974).

At the stations on the continental coast, along the northern boundary, the northerly wind prevails at the speed around 4.5 m/s in January (Fukutomi, 1952). The northwesterly wind prevails at Val, Sakhalin Island at an annual mean speed of 4 m/s. The wind speed is slightly higher during the winter (Shirasawa et al., 1996). At stations on the southern boundary, the monthly wind is reported: north or northwest at 4.6 m/s in February and March and south-southwest at 4.4 m/s in April (Fukutomi, 1952). At the Okhotsk Sea the wind seems to blow from the north, northeast, or northwest in winter (Parkinson and Gratz, 1983) and this northerly wind transports sea ice from the northwest continental shelf region to the southern area (Wakatsuchi and Martin, 1990).

The Barents Sea is in the Atlantic Arctic Frontal Zone, where the Arctic air mass and the polar air mass contact each other. The warm cyclones from the northern Atlantic and the cold anticyclones from the Arctic meet each other in the region (Groves and Nunt, 1980). Compared with other circum-Arctic seas, the Barents Sea has high air temperature and precipitation (Groves and Nunt, 1980). The Barents Sea area is classified as "E" in the Köppen climate classification, meaning that the mean monthly temperature of the warmest month does not exceed 10°C.

At Murmansk, on the southern boundary of Barents Sea, the annual mean air temperature is reported to be –0.1°C, and during six months of the year the monthly mean stays <0°C (National Astronomical Observatory, 1995). The annual mean air temperature decreases toward the east along the southern boundary, -2.9°C at North Kolguev, and -5.6°C at Varandey. At Varandey, the monthly mean air temperature of February is -18.3°C and the absolute recorded minimum is –48°C (Strass et al., 1997). The air temperature on the Barents Sea is estimated to fall as one moves from south to north and from west to east

within the area. The annual mean air temperature ranges from <0°C to 10°C (Strass et al., 1997).

At Vardo, at the southern boundary, the annual precipitation is recorded to be 1043 mm, most of which falls in winter. At Murmansk, also at the southern boundary but shifted a couple of hundreds of kilometers toward east, it is 589 mm, which is distributed throughout the year. At Bear Island, at the western boundary, it is 560 mm, where the summer precipitation is only half of that in winter. At Zemlya Frantsa Iosifa, at the northern boundary, it is 254 mm and at Mal. Karmakuly, at the eastern boundary, it is 413 mm. Most of the precipitation at the last two stations are recorded in summer and autumn. In the Barents Sea, the annual precipitation is estimated to be 1000 mm in the southwestern part, and decreases toward north and east to 300-400 mm. The seasonal change is considerably variable in pattern within the region.

The annual evaporation is estimated to be 800 mm in the southwestern part of the Barents Sea, and decreases toward north. In the northern part it reaches the minimum value of 100 mm (Korzun et al., 1974). At Kolguev Island, at the southern boundary, the southwesterly wind prevails at mean wind speed of 8.2 m/s in winter, but is scattered in all the directions in summer. The wind speed is higher in winter than in summer (Strass et al., 1997). At Hopen Island, at the western area, the monthly mean wind speed of 13-16 m/s is reported for November (Løset and Carstens, 1996). In the western part of the Barents Sea, the annual mean wind speed is estimated to exceed 9 m/s, with a maximum of 36 m/s. The wind speed decreases to the east and to the north. The wind speed is higher in winter, and is lowest in July (Strass et al., 1997). The wind direction is generally scattered in all directions. However, the strong wind has a particular direction, which is variable from a place to another; southwesterly wind in the western part and easterly wind in the northern and eastern parts.

Adjacent ocean

The cross section, through which the Okhotsk Sea and Pacific Ocean maintain the direct contact to each other, has an area of 200 km (Wadachi, 1987). The surface water temperature of the Pacific Ocean near the cross section is reported to be 1°C to 2°C in February, and around 10°C in August. The surface salinity is 33 psu in February (Wadachi, 1987).

At the surface, the Pacific Ocean water enters the Okhotsk Sea through the northern part of Kuril chain and the water flows out from the Okhotsk Sea into the Pacific Ocean through southern part of Kuril chain (Wadachi, 1987). At depth, the water flows out to the Pacific Ocean at the upper layer, e.g. through Bussol Straits at the southern Kuril chain, but the Pacific water flows in at the deep layer below 1500 m (Wadachi, 1987; Wakatsuchi and Martin, 1990). The Pacific water is warmer, more saline and poor in oxygen at all the depth compared with the water of Okhotsk Sea (Wakatsuchi and Martin, 1990). Hence the Pacific water is the source of the heat and salt but a sink for oxygen, when an exchange takes place across the cross section.

The Barents Sea has cross sections through which it has contact with adjacent seas: 160 km^2 to the Norwegian Sea, 53 km^2 to the Arctic Sea and 166 km^2 to the Kara Sea (Dzhenyuk and Zykova, 1992). A comparatively warm (4 to 12°C) and saline (> 35 psu) Atlantic water, a branch of the Gulf Stream, flows into the Barents Sea through the western boundary between North Cape and Bear Island (Groves and Nunt, 1980). The Atlantic water serves as the source of heat and salt. The surface current enters the Barents Sea with a speed of 0.75 to 0.8 m/s passing by Tromsoflaket from west. Cold Arctic water flows into the Barents Sea across its northern boundary through two routes, between Svalbard and Zemlya Frantsa Iosifa, and between Zemlya Frantsa Iosifa and Novaya Zemlya (Løset and Carstens, 1996). The Barents Sea contacts the ice sea at the northern boundary; the ice concentration in the area im-

mediately to the north of the Barents Sea is reported to have exceeded 80% in the summer of 1980 (Løset et al., 1997). Multi-year ice is dominant and the mean ice thickness exceeds 2.0 m. The Arctic Sea is thus a two-fold heat sink, i.e. cold water (sensible heat) and ice supplier (latent heat) to the Barents Sea, and is an additional source of the fresh water in the solid form.

State of the sea

At the Okhotsk Sea, the temperature of the surface water ranges from -1.8°C in winter to 18°C in summer (Groves and Nunt, 1980). The salinity of the surface water is reported to be 32 to 32.5 psu in summer (Wadachi,1987). There is counterclockwise current on the surface in the Okhotsk Sea.

The sea ice is first formed in the northern part of the sea in the middle of November. The maximum development is reached in the middle of March; 80 % of the total area is covered by sea ice (Wadachi, 1987). There is no sea ice found in the summer months, from July to October. All sea ice is first year ice or younger in the Okhotsk Sea. The mean ice thickness in March is reported to be 1.0 m in the northern part, and 0.4 to 0.5 m in the southern part. (Wadachi, 1987; Aota and Uematsu, 1989).

At the Barents Sea, the temperature of the surface water ranges from -2°C in winter to 8°C in summer (Wadachi, 1987). The salinity of the surface water is around 34 psu in summer. The current is directed eastward in the southern part and westward and southward in the northern part (Løset and Carstens, 1996). The first sea ice appears in the northern and eastern area in October, and the maximum extension is reached in April. There is no sea ice in August and September. The southern quarter of the sea is ice free year round, except some bays and fjords (Groves and Nunt, 1980). The most common ice is first year ice. The ice thickness can be up to 2 m for first-year ice, and 3 to 5 m for multi-year ice. The mean ice thickness of the region is estimated to be 0.9 to 1.2 m (Løset et al., 1997). Icebergs are also found in the Barents Sea. Mean sail height is estimated to be 15 m, and the mean diameter is 92 m (Løset and Carstens, 1996).

Comparison

The Okhotsk Sea and Barents Sea have several common features. The areal extent of the seas is quite similar, and the both are attached to the same continent and bounded by islands of various size, so that they have characteristics of a semi-mediterranean sea. A large part of the seas are shallow, but adjacent oceans are quite deep.

The air temperature, precipitation and evaporation have a similar range over the both seas. Hence, the climatic condition of the seas does not differ much in spite of the latitude difference. They are both generally windy seas and the wind speed is greater in winter. The strong wind is oriented in particular directions. Although the drainage area of the Barents Sea is half that of the Okhotsk Sea and the total precipitation is similar in both basins, a similar amount of total discharge is expected due to the difference in the terrestrial evaporation. Both seas have abundant fresh water supply in similar quantity.

The northern boundaries connect the seas to the coldest part of the continent and the coldest part of the ocean in the northern hemisphere respectively. Toward south both seas are connected to the water bodies, which are relatively warm and salty.

Differences are also found in the geographic elements of the Okhotsk Sea and that of the Barents Sea. The Okhotsk Sea has a geometry of a bay, where the current can make a round trip in the sea, whilst the Barents Sea is a wide channel, where two oppositely directed parallel currents can pass by each other within the region.

The Okhotsk Sea is strongly influenced by the climatic conditions of the continent, which invade the region. The maritime climate governs the Barents Sea, and it can be treated as a branch of the Atlantic Ocean. Although both seas are windy, there is a difference in the magnitude. The mean wind speed at the Barents Sea is esti-

mated to be almost twice as large as that at the Okhotsk Sea. The transport efficiency of pack ice is thus quite high in the former. The climate conditions of surrounding areas of the seas especially on the continent may differ from each other, even when they are similar on the seas. For instance, the latitude difference may lead different evaporation in river basins. The climate in enlarged area can thus influence the seas indirectly and possibly in different way. The Barents Sea has a supply of sea ice from the adjacent ocean, but no sea ice is produced in the sea around the Okhotsk Sea. Hence, the former has an additional fresh water supply in a solid form.

References

Aota, M. and Uematsu, E. 1989. The study on the polar ocean and the sea of Okhotsk. *J. Geogr. (Chigaku-zasshi), 98(5),* 70–82.

Cattle, H. 1985. Diverting Soviet rivers: some possible repercussions for the Arctic Ocean. *Polar Record, 22(140),* 485–498.

Dzhenyuk, S.L., Zykova, G.G. 1992. Hydrometeorological studies of sea of the Northern Eurogean basin. *Proc. Arctic Antarctic Sci. Res. Inst., 426,* 1–215. (in Russian).

Embleton, C. (ed.) 1984. *Geomorphology of Europe*. Macmillan Press (Japanese translation by M. Ohya and K. Saka, 1997, Taimeido Publishing Co., Tokyo, 703 pp.)

Energy, Mines and Resources Canada. 1990. *The National Atlas of Canada, 5th edition,* North circumpolar region, 1:10000000.

Fukutomi, T. 1952. Study of sea ice. (18th report). Drift of sea ice due to wind in the Sea of Okhotsk, especially in its southern part. *Low Temp. Sci., 9,* 137–144.

Groves, D.G. and Nunt, L.M. 1980. *The Ocean World Encyclopedia*. McGraw-Hill, New York, 443 pp.

Korzun V. I. et.al. 1974. *Atlas of World Water Balance*. Chief administration of hydrometeorological service under the council of ministers of the USSR, Moscow, 65 sheets.

Løset, S. and Carstens, T. 1996. Sea ice and iceberg observations in the western Barents Sea in 1987. *Cold Regions Sci. Tech., 24,* 323–340.

Løset, S., Shkhinek, K., Strass, P., Gudmestad, O.T., Michalenko, E.B. and Kärnä, T. 1997. Ice conditions in the Barents and Kara seas. pp. 173–181. In *OMAE and POAC, vol. IV,* H. Yamaguchi et al. (eds.), The American Society of Mechanical Engineers, New York.

National Astronomical Observatory. 1995 . *Rika nenpyo (Chronological Scientific Tables).* Maruzen Co., Tokyo, 1043 pp.

Nomura, S. (ed.) 1997. *The Atlas of the Modern World*. Shobunsha Publications, Tokyo, 214 pp.

Parkinson, C.L. and Gratz, A.J. 1983. On the seasonal sea ice cover of the sea of Okhotsk. *J. Geophys. Res., 88(C5),* 2793–2802.

Shilo, N.A., Kosygin, Yu.A., Bersenev, I.I., Zhuravlyov, A.V., Kulinich, R.G., Sergeyev, K.F., Tuezov, I.K. and Khvedchuk, I.I. 1982. The structure and history of geological evolution of Earth's crust in the Japan and Okhotsk Sea regions. pp. 59–80. *In Geology of Japan Sea*. Hoshino, M. and Shibasaki, T. (eds.), Tokai University Press, Tokyo.

Shirasawa, K. et al. 1996. Meteorological data report for the sea ice studies at Val, Chaivo and Kleye Strait, northern Sakhalin. *Low Temp. Sci., Ser. A, 55, Data Rep.,* 135–203.

Strass, P., Løset, S., Shkhinek, K., Gudmestad, O.T., Kärnä, T. and Michalenko, E.B. 1997. Metocean parameters of the Barents and Kara seas – An overview. pp. 165–172. In *OMAE and POAC, vol. IV,* Yamaguchi, H. et al. (eds.), The American Society of Mechanical Engineers, New York.

Wadachi, K. 1987. *Encyclopedia of Oceanography*. Tokyodo Publishing Co., Tokyo, 589 pp.

Wakatsuchi, M. and Martin, S. 1990. Satellite observations of the ice cover of the Kuril basin region of the Okhotsk Sea and its relation to the regional oceanography. *J. Geophys. Res., 95(C8),* 13,393–13,410.

Zuenko, Y.I. and Yurasov, G.I. 1997. Structure of the coastal waters of the Sea of Okhotsk. *Russian Meteorol. Hydrol., 3,* 32–37.