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Sea-ice distribution and atmospheric pressure patterns in southwestern Okhotsk Sea since the Last Glacial Maximum

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A B S T R A C T

Sea-ice diatom taxa (*Fragilariopsis cylindrus* and *Fragilariopsis oceanica*) and their relative abundance in the Okhotsk Sea were used to reconstruct the history of sea-ice distribution and atmospheric pressure patterns since the Last Glacial Maximum (LGM). The temporal state of sea-ice distribution and atmospheric pressure patterns since the LGM can be divided into three modes: northern Aleutian Low mode, southern Aleutian Low mode, and strong Siberian High mode. The Southern Aleutian Low mode was dominant before 15 ka and after 6.5 ka, respectively, showing expanded sea-ice distribution into the central and southern Okhotsk Sea. During the deglaciation period (15 ka to 10 ka), sea-ice retreated from the southern Okhotsk Sea because of the pronounced westerly winds under the strong Siberian High mode. However, sea-ice distribution expanded in the northern Okhotsk Sea, which favors the development of extensive polynyas on the northern continental shelf. Occurrences of northern Aleutian Low mode were frequent between 10 and 6.5 ka, while sea-ice distribution expanded into the eastern Okhotsk Sea. Formation of the Okhotsk Sea Intermediate Water, inferred from radiolarian species *Cycladophora davisiana*, intensified under both northern Aleutian Low mode and strong Siberian High mode.

1. Introduction

The present-day Okhotsk Sea, located in the southern limits of sea-ice extent in the Northern Hemisphere, is characterized by seasonal sea-ice cover. Sea-ice formation affects seawater density, albedo, and evaporation (Smith et al., 2003) which are crucial factors in forming dense intermediate waters (e.g., Martin et al., 1998). In particular, the mechanism of sea-ice extent and decay in the Okhotsk Sea is governed by atmospheric circulation around the Arctic Ocean (e.g., Rikiishi and Takatsuji, 2005). Furthermore, the present-day Okhotsk Sea plays an important role as the direct ventilation source for the North Pacific Intermediate Water (NPIW) (Yasuda, 1997). Rapid advance and retreat of sea-ice and the degree of intermediate water formation are regarded as significant controlling factors for global paleoclimatic conditions (e.g., Gorbarenko et al., 2007b). Therefore, better knowledge of sea-ice distribution in the Okhotsk Sea can greatly assist the understanding of paleoclimate change with respect to the atmospheric pressure systems.

Distribution patterns of microfossil diatoms and radiolarians are strongly influenced by seawater hydrographic conditions such as nutrient availability, salinity, and dissolved oxygen concentration. Diatoms are by far the most abundant plankton in the Okhotsk Sea (Sorokin and Sorokin, 1999). Diatoms, as important primary producers, have also been used as environmental proxy for the reconstruction of surface-water conditions (e.g., Shiga and Koizumi, 2000). In contrast to surface-water dwelling diatoms, siliceous radiolarians live at various depths throughout the water column. Hence, radiolarian fossil assemblages are often used to reconstruct vertical water-mass structures (Nimmergut and Abelmann, 2002; Matul et al., 2003; Abelmann and Nimmergut, 2005; Okazaki et al., 2006; Itaki et al., 2008).

In addition to oceanographic investigations (e.g., Martin et al., 1998; Itoh et al., 2003), paleoenvironmental and micropaleontological studies have also been accomplished successfully in the Okhotsk Sea (e.g., Gorbarenko, 1996; Keigwin, 1998; Shiga and Koizumi, 2000; Ternois et al, 2001; Narita et al., 2002; Seki et al., 2003, 2004a,b; Okazaki et al., 2005, 2006; Harada et al., 2006; Sakamoto et al., 2006;

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Gorbarenko et al., 2007a,b; Itaki et al., 2008). According to above cited reports, paleoenvironmental changes in the Okhotsk Sea are regionally specific. In particular, paleoenvironmental changes in the southern Okhotsk Sea have received increasing attention during the last 5 years, including Holocene sediment studies (Kawahata et al., 2003; Shimada et al., 2004; Itaki and Ikehara, 2004; Okazaki et al., 2005; Harada et al., 2006; Sakamoto et al., 2006, Itaki et al., 2008). Temporal and spatial distribution of sea-ice in the Okhotsk Sea since the Last Glacial Maximum (LGM) was demonstrated by Shiga and Koizumi (2000) and Sakamoto et al. (2005). They showed sea-ice distribution changes along the east–west transect in the central Okhotsk Sea. However, information on historical sea-ice status along the north–south transect remains porous and limited only to data presented by Shiga and Koizumi (2000). Therefore, in order to compile information on sea-ice distribution patterns in the entire Okhotsk Sea since the LGM, comparative data of fossil assemblages from the literature were integrated with newly presented data in this study.

Here we document the absolute and relative abundance changes of fossil siliceous plankton assemblages in piston cores (GH00-1002 and MD01-2412) from the southwestern Okhotsk Sea (Fig. 1) for the purpose of elucidating historical sea-ice cover and atmospheric pressure conditions.

2. Oceanographic setting

The Okhotsk Sea is one of the many typical marginal seas in the northwest Pacific (Fig. 1). Sea-ice formation in the Okhotsk Sea is caused by an influx of freshwater from the Amur River as well as the strong westerly to northwesterly cold winds during the winter, derived from interaction between the Siberian High (SH) and Aleutian Low (AL) pressure systems (Martin et al., 1998; Wong et al., 1998). In winter, the robust SH pressure occupies the Asian continent with strong AL pressure to its east. The AL pressure dominates the northern North Pacific from late fall to spring of the next year. The intensity and position of these pressures are associated with air circulation around the Arctic Ocean (Kutzbach, 1970). The inter-annual variability of the AL pressure system during the 20th century was on the decadal scale, lasting at least three winters in each decade. This variability is not only associated with the Arctic Oscillation but also with the Pacific-North America Pattern (Overland et al., 1999). Inter-annual variability of sea-ice distribution is mainly controlled by atmospheric conditions including air temperature and geostrophic wind (Kimura and Wakatsuchi, 2004). Such inter-annual variability is negatively correlated with the amount of freshwater discharge from the Amur River (Ogi and Tachibana, 2006). The inflow of warm freshwater tends

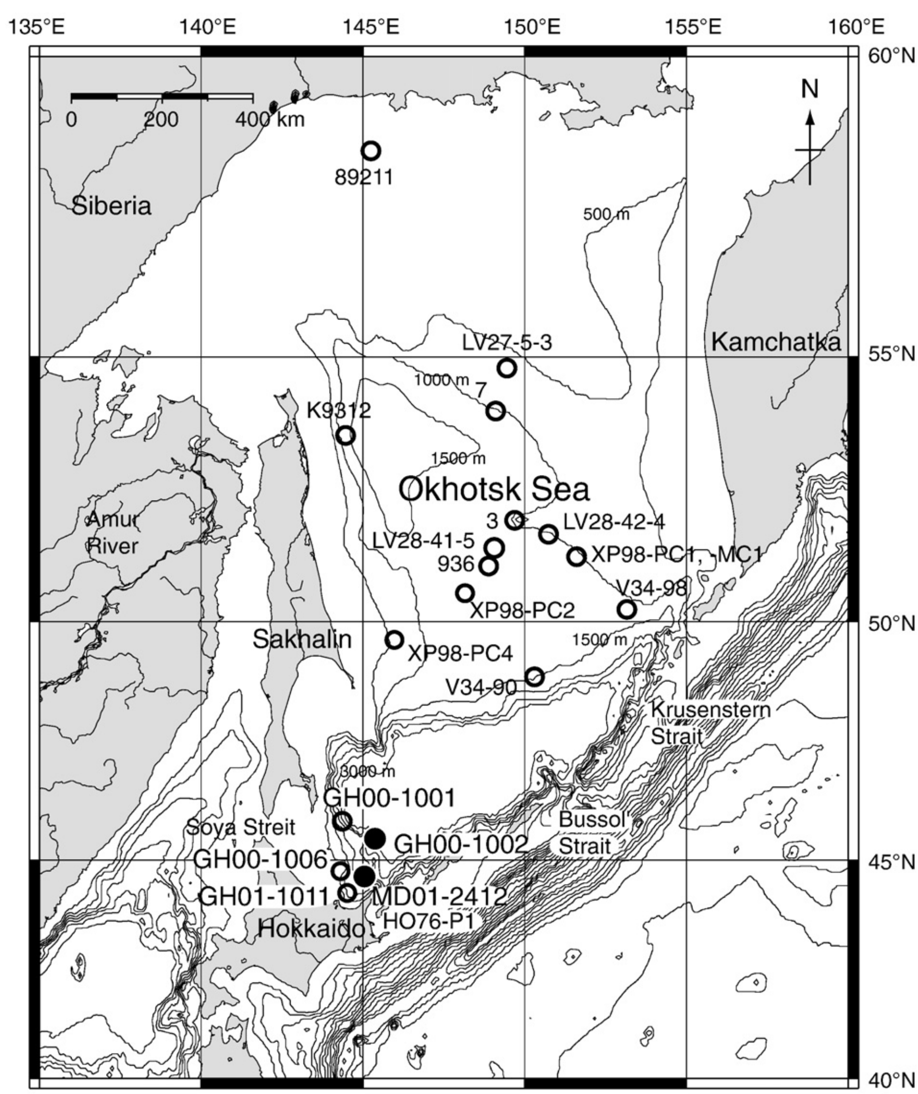

Fig. 1. A map showing the bathymetry of study area with locations of sediment cores in this study (GH00-1002 and MD01-2412: solid circles) and previously published reports (open circles). The map was drawn by Online Map Creation.