Deep-Sea Research II 61-64 (2012) 73–84

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Responses of the Okhotsk Sea environment and sedimentology to global climate changes at the orbital and millennial scale during the last 350 kyr

Sergey A. Gorbarenko[a,*], Naomi Harada[b], Mikhail I. Malakhov[c], Tatyana A. Velivetskaya[d], Yuriy P. Vasilenko[a], Aleksandr A. Bosin[a], Aleksandr N. Derkachev[a], Evgenyi L. Goldberg[e,†], Aleksandr V. Ignatiev[d]

[a] V.I. Il'ichev Pacific Oceanological Institute, Far East Branch of Russian Academy of Science, Vladivostok, Russia
[b] Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan
[c] North-Eastern Interdisciplinary Scientific Research Institute, Far East Branch of Russian Academy of Science, Magadan, Russia
[d] Far Eastern Geological Institute, Far East Branch of Russian Academy of Sciences, Vladivostok 690022, Russia
[e] Limnological Institute of Siberian Branch of Russian Academy of Science, Irkutsk, Russia

ARTICLE INFO

Available online 27 May 2011

Keywords:
Okhotsk Sea
Productivity and lithophysical sediment properties
Orbital and millennial climate changes
Last 350 kyr

ABSTRACT

We measured productivity proxies (chlorin, carbonate and organic carbon, opal, and biogenic Ba content) and lithophysical proxies (magnetic susceptibility, water content, density, and coarse sediment fraction) in sediment of central Okhotsk Sea core PC-7R. The age model covering the last 350 kyr of this core was constructed by correlating the dated series of relative paleointensity lows recognized in geomagnetic intensity records, marine isotope stage (MIS) boundaries determined in broad variations of the lithophysical and productivity proxies, and tephrochronology. The orbital changes of the lithophysical and productivity proxy stacks lag behind Northern Hemisphere summer radiation by approximately 6.3 and 5.9 kyr, respectively. This lag is consistent with a Milankovich model of climate control by solar radiation through the northern ice sheet volume and sea surface and surrounding land responses, which are fast compared with sedimentological evidence. Productivity proxies of the Okhotsk Sea also demonstrate 52 abrupt, pronounced productivity minima associated with regional climate coolings during the last 350 kyr, which present useful indicators of millennial-scale climate changes in this marginal sea. Based on the postulated synchronicity of Dansgaard–Oeschger cycles in the Northern Hemisphere and the established simultaneity of 11 Okhotsk Sea coolings in the last 77 kyr with abrupt severe cold events in the Greenland ice core and North Atlantic Heinrich events, all of these may be regarded as Heinrich-equivalent event anomalies. The Okhotsk Sea events have their counterparts in the records of North Atlantic sediments, the Greenland ice sheet, East Asia summer monsoon, and the Antarctic ice sheet. Probably the Arctic Oscillation was the main factor determining orbital and millennial climate oscillations in the high-latitude Northern Hemisphere, including the Okhotsk Sea region.

1. Introduction

Orbital-scale climate changes have been widely identified in Quaternary sediments (Martinson et al., 1987; Bassinot et al., 1994; Lisiecki and Raymo, 2005), Greenland and Antarctic ice cores (Bond et al., 1993; Jouzel et al., 2007), China loess (An and Porter, 1997), speleothems (Wang et al., 2001), and other records, including sediments from the Okhotsk Sea (OS) (Nürnberg and Tiedemann, 2004). Millennial-scale climate changes superimposed on the orbital changes demonstrate significant variability of modern climate and underlines the vulnerability of human society. Abrupt climate changes were initially discovered in the Greenland ice core records (Dansgaard et al., 1993) and are now called Dansgaard–Oeschger (DO) oscillations. DO cycles have subsequently been found in many parts of the Northern and Southern Hemispheres (Voelker et al., 2002; Wang et al., 2001; Jouzel et al., 2007). Cold Heinrich events (HE), initially discovered in North Atlantic sediments (Heinrich, 1988) and correlated with the coldest DO stadials (DOS) (Bond et al., 1993), have been recognized in other regions in the Northern Hemisphere (An and Porter, 1997). High-resolution reconstruction of the abrupt climate changes in different regions is of paramount importance for understanding the cause and mechanisms of millennial climate cycles. However, the high-resolution record in the

* Corresponding author. Tel.: +7 4232 31 23 82 (work), +7 4232 89242365129 (mobile); fax: +7 4232 31 25 73.
E-mail address: gorbarenko@poi.dvo.ru (S.A. Gorbarenko).
† Deceased.

0967-0645/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.dsr2.2011.05.016

Northern Hemisphere encompasses only the last 140 kyr in the Greenland ice cores (North Greenland, 2004) and 224 kyr in the Eastern Asia monsoon records (Wang et al., 2008).

The OS, located between the Siberian High and Aleutian Low atmospheric centers, is subject to strong influences of atmosphere processes through variability in East Asian monsoon activity, precipitation and river runoff intensity, and sea ice cover. On the other hand, the hydrology of this marginal basin has extensive water exchange and a strong mutual relationship with the North Pacific Ocean. Abrupt DO oscillations in the OS have been documented during the last 80, 190, and 350 kyr (Gorbarenko et al., 2004; Ono et al., 2005; Goldberg et al., 2005a; Harada et al., 2006; Gorbarenko et al., 2007, 2010a). This study reports new insights into orbital and millennial climate changes during the past 350 kyr using lithophysical and geochemical records in a core from the central OS. We present a sequence of 52 significant millennial-scale climate coolings during the last 350 kyr in the OS, which expands the Northern Hemisphere record of millennial climate oscillations beyond those recorded in Greenland and SE Asia (for the last 140 and 224 kyr, respectively) and has higher resolution and better documentation than North Atlantic records (Heinrich, 1988; van Kreveld et al., 1996; McManus et al., 1999).

2. Hydrology

The surface hydrography of the OS is characterized by a large cyclonal gyre with inflow of Pacific water through Kruzenshterna Strait and outflow of cold and freshened water through Bussol' Strait (Fig. 1). Relatively saline and warm Pacific waters flow northward in the OS as the West Kamchatka Current; after mixing at the northern shelf they turn and flow southward off Sakhalin Island as the East Sakhalin Current and exit the OS as the Oyashio Current (Alfutis and Martin, 1987) (Fig. 1). In addition, Japan Sea saline water flows into the southwestern part of the sea through Soya Strait. The summer surface water temperature varies from

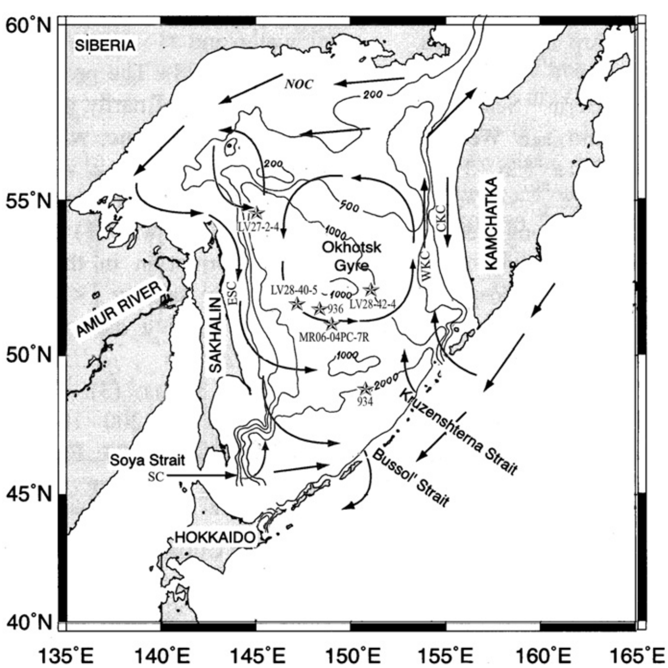

Fig. 1. Location of the core PC-7R and previously studied cores LV 28-40-5 (Gorbarenko et al., 2007), LV 27-2-4 (Gorbarenko et al., 2010b), and 934 and 936 (Gorbarenko et al., submitted for publication). ESC – East Sakhalin Current, NOC – North Okhotsk Current, WKC –West Kamchatka Current, CKC – Compensation Kamchatka Current, SC – Soya Current, and OC-Oyashio Current.

5 to 13 °C, and its salinity from 31.5 to 33.2 psu, being influenced mostly by discharge of the Amur River (Kitani, 1973). A significant temperature-minimum layer (− 1.7 to 1.0 °C) at 50–150 m depth, called the dichothermal layer or subsurface water, forms during winter, mixing with surface water and persisting during summer time. Winter sea ice formation and brine rejection on the northern and western shelves create the cold, high-density Shelf Derived Water (SDW). The Sea of Okhotsk Intermediate Water (SOIW) is thought to be formed by SDW and inflowing Western Subarctic Pacific water, modified by diapycnal mixing within the OS (Yamamoto et al., 2002). SOIW is characterized by low positive temperature of 1–2 °C, low salinity of 33.4–34.3 psu, and high oxygen content of 2.5–6.5 ml/l at 200–1000 m depth (Kitani, 1973; Freeland et al., 1998). Below the SOIW, old and CO_2-enriched deep Pacific water enters the OS predominantly via Kruzenshterna Strait and exits mainly through Bussol' Strait (2300 m deep).

The Amur River entering the northern OS supplies most of the freshwater discharge and an extraordinarily high suspended sediment load (Ogi et al., 1995; Anikiev et al., 2001). A large autumn peak in freshwater input reflects the preceding monsoonal precipitation maximum in the Amur drainage area. The main pathway of fluvial discharge is southward in the East Sakhalin Current (Kitani, 1973).

As the OS is located between the Siberian High and the Aleutian Low, northerly winds and very low air temperatures in winter result in pronounced winter sea ice coverage (Alfutis and Martin, 1987). The sea ice extent advances by wind-driven ice advection controlled by wind speed (Kimura and Wakatsuchi, 1999). Main sea ice formation starts in November in the northern OS and reaches maximum extent during March, when on average 60–80% of the sea is ice covered (Lisitsin, 1994).

3. Materials and methods

Sediment core PC-7R was recovered by a piston corer in the central OS (51°16.87′N, 149°12.57′E; water depth 1256 m; core length 1722 cm) during cruise MR06-04 of R/V *Mirai*, supported by Japanese–Russian Project 83 (Fig. 1). The sediment magnetic susceptibility and density were measured using the GEOTEK Core system every 2 cm. The water content was calculated as the ratio of sediment weight loss after drying at 105 °C to the weight of the wet bulk sediment. Weight percentage of the coarse fraction or CF (> 63 μm and < 2000 μm), separated by sediment washing, was calculated as the ratio of CF weight to the weight of the dry bulk sediment. Terrigenous and volcanic grains make up most of this fraction because input of carbonaceous particles (planktonic and benthic foraminifera) is small and siliceous fragments are negligible. Foraminifera amount to less than 1% of the sediment weight, as $CaCO_3$ is less than 1–2% of the bulk sediment in most parts of the studied core whereas CF is 8–16%. Only interglacial and Holocene sediments in the OS have $CaCO_3$ content up to 10–15%, which may increase the minimal CF values during these warm intervals. Because we ignored values of all proxies measured in sediment layers affected by volcanic activity in our time scale records, measured CF values in the core may be used as a rough proxy for Ice Rafted Debris (IRD), carried to the open sea by sea ice and released during ice melting (Gorbarenko et al., 2003; Sakamoto et al., 2005).

The chlorin content (CC), a product of chlorophyll-*a* transformation in the sediment, was measured by a Shimadzu UV–Vis–NIR spectrophotometer UV-3600 according to the modified method of Harris et al. (1996). Water content, CF, and CC were measured every 1 cm.

Total carbon content and inorganic carbon were measured every 1 cm by coulometry using an AN-7529 analyzer (Gorbarenko et al., 1998). Total organic carbon (TOC) content was determined by the