Earth and Planetary Science Letters 488 (2018) 36–45

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Precession and atmospheric CO_2 modulated variability of sea ice in the central Okhotsk Sea since 130,000 years ago

Li Lo[a,b,*], Simon T. Belt[c], Julie Lattaud[d], Tobias Friedrich[e], Christian Zeeden[f], Stefan Schouten[d,g], Lukas Smik[c], Axel Timmermann[e,h], Patricia Cabedo-Sanz[c], Jyh-Jaan Huang[i,1], Liping Zhou[j], Tsong-Hua Ou[k], Yuan-Pin Chang[l], Liang-Chi Wang[m], Yu-Min Chou[n], Chuan-Chou Shen[i], Min-Te Chen[o], Kuo-Yen Wei[i], Sheng-Rong Song[i], Tien-Hsi Fang[o], Sergey A. Gorbarenko[p], Wei-Lung Wang[q], Teh-Quei Lee[r], Henry Elderfield[b,2], David A. Hodell[b]

[a] State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[b] Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK
[c] Biogeochemical Research Centre, School of Geography, Earth and Environmental Sciences, Plymouth University, Plymouth PL4 8AA, UK
[d] NIOZ, Royal Netherlands Institute for Sea Research, Department of Marine Microbiology and Biogeochemistry, and Utrecht University, PO Box 59, 1790 AB Den Burg, The Netherlands
[e] International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii at Monoa, Honolulu, HI 96822, USA
[f] IMCCE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Univ. Lille, 75014 Paris, France
[g] Faculty of Geosciences, Department of Earth Sciences, Utrecht University, PO Box 80.021, 3508 TA, The Netherlands
[h] Institute for Basic Science, Center for Climate Physics, Pusan National University, Busan 46241, Republic of Korea
[i] Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan, ROC
[j] Laboratory for Earth Surface Processes, Department of Geography, and Institute of Ocean Research, Peking University, Beijing 100871, China
[k] Institute of Applied Mechanics, National Taiwan University, Taipei 10617, Taiwan, ROC
[l] Department of Oceanography, National Sun Yat-sen University, Kaohsiung 80424, Taiwan, ROC
[m] Department of Earth and Environment Sciences, National Chung Cheng University, Chiayi 62102, Taiwan, ROC
[n] Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen, Gongdong 518055, China
[o] Institute of Applied Geosciences, National Taiwan Ocean University, Keelung 20224, Taiwan, ROC
[p] V.I. Il'ichev Pacific Oceanological Institute, Far East Branch Russian Academy of Science, Vladivostok 690041, Russia
[q] Department of Biology, National Changhua University of Education, Changhua 50074, Taiwan, ROC
[r] Institute of Earth Sciences, Academia Sinica, Taipei 11529, Taiwan, ROC

A R T I C L E   I N F O

Article history:
Received 8 December 2017
Received in revised form 30 January 2018
Accepted 1 February 2018
Available online xxxx
Editor: D. Vance

Keywords:
Okhotsk Sea
sea ice
insolation
greenhouse gases
precession cycle

A B S T R A C T

Recent reduction in high-latitude sea ice extent demonstrates that sea ice is highly sensitive to external and internal radiative forcings. In order to better understand sea ice system responses to external orbital forcing and internal oscillations on orbital timescales, here we reconstruct changes in sea ice extent and summer sea surface temperature (SSST) over the past 130,000 yrs in the central Okhotsk Sea. We applied novel organic geochemical proxies of sea ice (IP_{25}), SSST (TEX^L_{86}) and open water marine productivity (a tri-unsaturated highly branched isoprenoid and biogenic opal) to marine sediment core MD01-2414 (53°11.77′N, 149°34.80′E, water depth 1123 m). To complement the proxy data, we also carried out transient Earth system model simulations and sensitivity tests to identify contributions of different climatic forcing factors. Our results show that the central Okhotsk Sea was ice-free during Marine Isotope Stage (MIS) 5e and the early-mid Holocene, but experienced variable sea ice cover during MIS 2–4, consistent with intervals of relatively high and low SSST, respectively. Our data also show that the sea ice extent was governed by precession-dominated insolation changes during intervals of atmospheric CO_2 concentrations ranging from 190 to 260 ppm. However, the proxy record and the model simulation data show that the central Okhotsk Sea was near ice-free regardless of insolation forcing throughout the penultimate interglacial, and during the Holocene, when atmospheric CO_2 was above ∼260 ppm. Past

* Corresponding author at: State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China.
E-mail address: lilo@gig.ac.cn (L. Lo).

[1] Now at Institute of Geology, University of Innsbruck, Innrain 52, A-6020, Innsbruck, Austria.
[2] Deceased.

https://doi.org/10.1016/j.epsl.2018.02.005

sea ice conditions in the central Okhotsk Sea were therefore strongly modulated by both orbital-driven insolation and CO_2-induced radiative forcing during the past glacial/interglacial cycle.

1. Introduction

Sea ice is one of the crucial components of the Earth's climate system, in part, due to its high reflectance or albedo, which influences energy budgets at both high and low latitudes (Serreze et al., 2016; Turner et al., 2016). In addition, brine rejection during seasonal sea ice formation supplies dense and well ventilated water to global deep/intermediate water circulation, while sea ice melt in spring causes stratification between near-surface and deeper water masses. Furthermore, the area bound by the retreating sea ice margin during spring and summer (the so-called marginal ice zone) represents a region of significant open water (pelagic) productivity.

Major changes in the extent and thickness of sea ice across the Arctic-subarctic and Antarctic regions during the last three to four decades have been revealed by direct and remote sensing observations (Serreze et al., 2016; Turner et al., 2016). In the Arctic, the average reduction rate in September sea ice extent, 13.4% per decade during 1981–2010, is higher than predicted by most model simulations (Serreze et al., 2016). This discrepancy emphasizes the limited knowledge of the high-latitude climate system to radiative perturbations and natural variability. In addition, a slow overall increase in annual mean sea ice extent in the Southern Ocean (ca. 1.6% per decade during 1979–2013), raises further questions regarding the relationships between anthropogenic radiative forcings, temperature, winds, and sea ice cover (Turner et al., 2016).

The Okhotsk Sea in the subarctic Pacific Ocean has responded rapidly to recent climate change (Mesquita et al., 2011; Kashiwase et al., 2014) and has been shown previously to be dynamically connected to Northern Hemispheric cooling events (e.g. Heinrich and Dansgaard–Oeschger (D/O) events) during the last glacial period (Ono et al., 2005; Sakamoto et al., 2005; Harada et al., 2008; Max et al., 2012, 2014). For example, Harada et al. (2008) demonstrated a strong link between a $U^{K'}_{37}$-derived sea surface temperature (SST) record and Greenland Ice Sheet Project 2 ice core D/O events back to ∼120 ka in the southwestern Okhotsk Sea. Further, sedimentary magnetic mineral and composition data have been used to reconstruct sea ice derived ice rafted debris (IRD) in the same region (Sakamoto et al., 2005) with larger fluctuations during the last glacial period (Marine Isotope Stage, MIS 2–4) compared to interglacial periods (Holocene and MIS 5) for the southwestern Okhotsk Sea. Also within the study region, freshwater input from the Amur River and polar atmospheric dynamics are potential candidates responsible for controlling sea ice dynamics in the southwestern Okhotsk Sea (Sakamoto et al., 2005; Harada et al., 2008). Previous low resolution sea ice reconstructions based on the Arctic sea ice biomarker proxy IP_{25} (Ice Proxy with 25 carbon atoms, Belt et al., 2007; Belt and Müller, 2013), when combined with compiled SST data, have shown that sea ice extent variations in the central-west subarctic Pacific Ocean are tightly link to Atlantic meridional overturning circulation and atmospheric circulation between North Atlantic and North Pacific during the last termination (Max et al., 2012, 2014). More recently, Méheust et al. (2016) used IP_{25} and other geochemical proxies to show that sea ice expanded significantly during Heinrich event 1 (H1) and the Younger Dryas (YD) in the western Bering Sea, in contrast to the Bølling-Allerød (B/A) and early Holocene, which experienced low/absent sea ice.

Despite the importance of its location and role in the subarctic sea ice system, very few studies have been reported from the central region of the Okhotsk Sea (Liu et al., 2006; Wang and Wang, 2008; Chou et al., 2011) and no detailed sea ice reconstructions have been conducted on orbital timescales. As such, the roles of insolation (external) and greenhouse gas radiative forcing (internal) on sea ice variation remain poorly understood. Therefore, long-term reconstruction of sea ice extent in the central Okhotsk Sea would be especially informative in understanding the interaction of sea ice and external/internal climatic forcings.

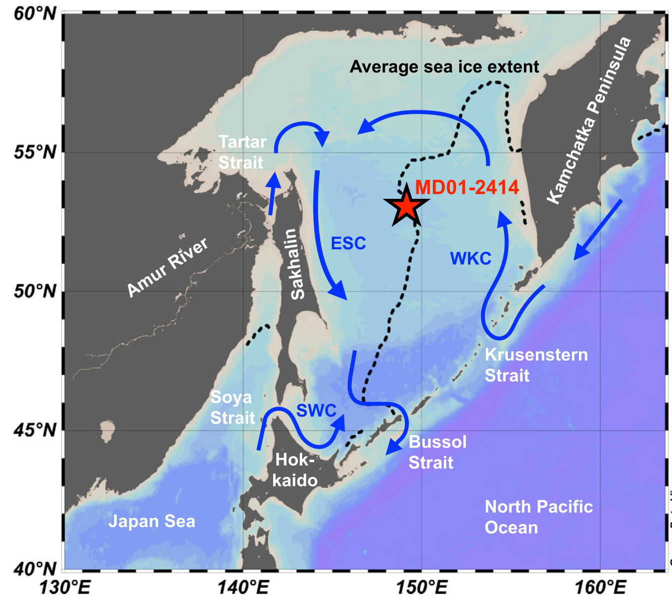

Fig. 1. Site location. Core MD01-2414 (53°11.77′N, 149°34.80′E, water depth 1123 m) is located in the Okhotsk Sea. The blue arrows indicate surface water circulation (WKC: West Kamchatka Current, ESC: East Sakhalin Current, and SWC: Soya Warm Current) and the dashed black line denotes the average position of modern seasonal sea ice extent, during the months of November to June. This map was generated with Ocean Data View (GMT) version 5 (Schlitzer, 2017).

In this study, we reconstruct variations in sea ice extent and summer SST (SSST) using organic geochemical proxies and compare the proxy-derived records with Earth system modeling results in order to identify controlling mechanisms and interactions between sea ice and atmospheric–oceanic forcings in the Okhotsk Sea during the past 130,000 yrs. Our results reveal a strong precession control and a potential greenhouse gas induced radiative forcing threshold on sea ice variations since the penultimate peak interglacial period.

2. Regional setting

The Okhotsk Sea represents the southernmost region of contemporary seasonal sea ice formation in the Northern Hemisphere and has experienced a large decline rate of 11.4% per decade in sea ice extent during the past three decades (Kashiwase et al., 2014). The regional current system is affected by the north- and south-ward flowing West Kamchatka Current (WKC), East Sakhalin Current (ESC), salty-warm Soya Warm Current (SWC) and freshwater input from the Amur River (Fig. 1). The SSST is in the range 5–13 °C, while salinity varies between 31.5 to 33.2‰, being influenced mostly by the Amur River discharge (Luchin et al., 2009). Sea ice easily forms on the shallow continental shelves in the north-west Okhotsk Sea and is also influenced by the large fresh