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Deglacial variability in Okhotsk Sea Intermediate Water ventilation and biogeochemistry: Implications for North Pacific nutrient supply and productivity

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ABSTRACT

The modern North Pacific plays a critical role in marine biogeochemical cycles, as an oceanic sink of CO_2 and by bearing some of the most productive and least oxygenated waters of the World Ocean. The capacity to sequester CO_2 is limited by efficient nutrient supply to the mixed layer, particularly from deeper water masses in the Pacific's subarctic and marginal seas. The region is in addition only weakly ventilated by North Pacific Intermediate Water (NPIW), which receives its characteristics from Okhotsk Sea Intermediate Water (OSIW). Here, we present reconstructions of intermediate water ventilation and productivity variations in the Okhotsk Sea that cover the last glacial termination between eight and 18 ka, based on a set of high-resolution sediment cores from sites directly downstream of OSIW formation. In a multi-proxy approach, we use total organic carbon (TOC), chlorin, biogenic opal, and $CaCO_3$ concentrations as indicators for biological productivity. C/N ratios and XRF scanning-derived elemental ratios (Si/K and Fe/K), as well as chlorophycean algae counts document changes in Amur freshwater and sediment discharge that condition the OSIW. Stable carbon isotopes of epi- and shallow endobenthic foraminifera, in combination with ^{14}C analyses of benthic and planktic foraminifera imply decreases in OSIW oxygenation during deglacial warm phases from c. 14.7 to 13 ka (Bølling-Allerød) and c. 11.4 to 9 ka (Preboreal). No concomitant decreases in Okhotsk Sea benthic-planktic ventilation ages are observed, in contrast to nearby, but southerly locations on the Japan continental margin. We attribute Okhotsk Sea mid-depth oxygenation decreases in times of enhanced organic matter supply to maxima in remineralization within OSIW, in line with multi-proxy evidence for maxima in primary productivity and supply of organic matter. Sedimentary C/N and Fe/K ratios indicate more effective entrainment of nutrients into OSIW and thus an increased nutrient load of OSIW during deglacial warm periods. Correlation of palynological and sedimentological evidence from our sites with hinterland reference records suggests that millennial-scale changes in OSIW oxygen and nutrient concentrations were largely influenced by fluvial freshwater runoff maxima from the Amur, caused by a deglacial northeastward propagation of the East Asian Summer Monsoon that increased precipitation and temperatures, in conjunction with melting of permafrost in the Amur catchment area. We suggest that OSIW ventilation minima and the high lateral supply of nutrients and organic matter during the Allerød and Preboreal are mechanistically linked to concurrent maxima in nutrient utilization and biological productivity in the subpolar Northwest Pacific. In this scenario, increased export of nutrients from the Okhotsk Sea during deglacial warm phases supported subarctic Pacific shifts from generally Fe-limiting conditions to transient nutrient-replete

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regimes through enhanced advection of mid-depth nutrient- and Fe-rich OSIW into the upper ocean. This mechanism may have moderated the role of the subarctic Pacific in the deglacial CO_2 rise on millennial timescales by combining the upwelling of old carbon-rich waters with a transient delivery of mid-depth-derived bio-available Fe and silicate.

1. Introduction

Today, no new deepwater is formed in the subarctic North Pacific, because the surface water masses are not dense enough to sink to significant water depths and initiate convection due to low surface salinities and an associated strong halocline (Emile-Geay et al., 2003; Warren, 1983). Accordingly, the deep North Pacific is only weakly ventilated and carries high concentrations of macronutrients, in particular nitrate and silicate. In contrast, the intermediate-depth level is occupied by a relatively fresh and oxygen-enriched layer of North Pacific Intermediate Water (NPIW, Reid, 1965; Talley, 1993). NPIW is today mainly characterized through a ventilated precursor water mass, the Okhotsk Sea Intermediate Water (OSIW, Watanabe and Wakatsuchi, 1998). Modern NPIW and OSIW are highly variable in their biogeochemical characteristics, even on relatively short (i.e. multidecadal) instrumental timescales (Emerson et al., 2004; Tadokoro et al., 2009), and keep mid-depth waters in the North Pacific moderately oxygenated. While the North Pacific overall is a large modern oceanic sink for atmospheric CO_2 (Takahashi et al., 2009), surface utilization of nutrients by primary producers and export production of carbon (the "biological pump") remains incomplete in the Western Subarctic Pacific (WSAP) Gyre, mainly due to the rapid seasonal depletion of iron (Fe) as micronutrient (see review by Takeda, 2011), and silicate ($Si(OH)_4$; Harrison et al., 2004). On glacial-interglacial timescales the export production and degree of surface nutrient utilization, as evidenced by studies of $\delta^{15}N$, are anti-correlated, implying more effective use of available nutrients during glacial periods (e.g. Galbraith et al., 2008; Jaccard et al., 2005). This more effective utilization allowed a lower primary production to export carbon from the surface into the deep ocean more efficiently. Thus, indicators for export production varied in phase with atmospheric CO_2 concentrations for at least the last 800 ka (Jaccard et al., 2010).

However, on shorter, millennial timescales this relatively straightforward relation does not necessarily hold. During the last glacial termination, surface nutrient utilization and export production become partially decoupled in the WSAP (Brunelle et al., 2010; Kohfeld and Chase, 2011; Maier et al., 2015). During the deglacial warm Bølling-Allerød (B-A) and Preboreal (PB) phases, widespread productivity peaks were accompanied by more effective nutrient utilization, contrary to glacial-interglacial patterns (Kohfeld and Chase, 2011). Such millennial-scale structures call for additional mechanisms that regulate the nutrient dynamics in the mixed layer and their biological utilization. Potential candidates are changes in the ratio of macronutrients relative to bio-available iron (Brunelle et al., 2010; Kienast et al., 2004; Kohfeld and Chase, 2011) and changes in the physical stratification of the mixed layer (Lam et al., 2013; Riethdorf et al., 2013). In line with these deglacial changes in upper ocean processes, the North Pacific underwent drastic and rapid changes in intermediate to deep water circulation and ventilation (Duplessy et al., 1989; Okazaki et al., 2010), which are as well thought to being closely linked with changes in the utilization of nutrients and biogeochemistry (Crusius et al., 2004; Galbraith et al., 2007; Gebhardt et al., 2008). During the cold Heinrich Stadial 1 (HS-1, 17.5–15.0 ka), convection and the increased formation of new intermediate–deep water masses (down to 2800 m water depth) were proposed for the North Pacific (Okazaki et al., 2010), although newer evidence alternatively suggested that a potential Pacific overturning cell did not extend beyond 1400–2000 m water depth and was initiated through increased mid-depth ventilation in the marginal subarctic seas (Jaccard and Galbraith, 2013; Max et al., 2014; Okazaki et al., 2014). This early deglacial episode is sharply contrasted by subsequent oxygen declines in intermediate water depths during the B-A (14.7–12.9 ka) the PB, leading to widespread anoxia along the North American Pacific margins (Dean et al., 2006; Van Geen et al., 2003; Zheng et al., 2000), in the Bering Sea (Cook et al., 2005; Itaki et al., 2012; Kuehn et al., 2014), and on the western Pacific margin off Japan (Ikehara et al., 2006; Sagawa and Ikehara, 2008). In the pelagic abyssal North Pacific, no Oxygen Minimum Zones (OMZs) developed during this time (Jaccard and Galbraith, 2011; Jaccard et al., 2009). To explain the unusually severe and widespread O_2-depletion of intermediate waters during the Bølling-Allerød and Preboreal, increases in export production have been invoked (Davies et al., 2011; McKay et al., 2004; Mix et al., 1999). Alternatively, reduced or ceased ventilation of NPIW could have decreased O_2 concentrations across the North Pacific. (e.g. Duplessy et al., 1989; Keigwin et al., 1992; Zheng et al., 2000), or a combination of these processes was responsible for the decline in mid-depth O_2 concentrations by increased respiration of organic matter (OM) in initially well-ventilated NPIW, along its pathway in the Pacific (Crusius et al., 2004).

Previous works from the Okhotsk Sea and Bering Sea have shown that mixed layer stratification, sea ice action and export production varied on millennial timescales during the deglaciation, implying a combination of these potential factors, in addition to changes of freshwater runoff and the flooding of continental shelf areas by sea level rise (Gorbarenko, 2007a, 2008, 2012; Harada et al., 2008; Harada et al., 2012; Riethdorf et al., 2013). However, information used to infer changes often stemmed from single site locations, sometimes relatively distant to source regions of water formation processes or were affected by insufficient temporal resolution. In this study, we analyzed a suite of high-resolution sediment cores (with sedimentation rates between 20 and 200 cm/ka) retrieved directly downstream of the main ventilation region of OSIW, on the eastern continental margin of Sakhalin island in the Okhotsk Sea. We use a multi-proxy approach to discuss changes in ventilation and export production within the Okhotsk Sea as the most prominent modern NPIW ventilation source region. We put these outcomes into context with XRF-scanning based qualitative assessments of terrigenous supply of Fe as essential micro-nutrient and compare our results with earlier, published data that showed millennial-scale variations in ventilation and nutrient utilization during the last glacial termination (18–8 ka). We constrain potential causes for the observed rapid changes in OSIW/NPIW ventilation and productivity patterns, and assess their potential consequences for open-ocean WSAP nutrient supply and biogeochemistry.