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Biological and climatic consequences of a cold, stratified, high latitude ocean

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ABSTRACT

The flux from deep- and shallow-living radiolarian assemblages provides evidence of a glacial, high latitude, cold ocean stratification that increased biological pump efficiency and promoted ocean carbon sequestration. Greater deep (>200 m) than shallow-living (<200 m) radiolarian assemblage flux characterizes glacial North Pacific (>45° N) sediments with the deep-living *Cycladophora davisiana* dominant (>24%). By contrast modern radiolarian flux consists primarily of shallow-living species (*C. davisiana* <10%). Clues to the cause of this unusual glacial radiolarian flux come from the presently, strongly stratified Sea of Okhotsk. Here beneath a thin nutrient depleted mixed layer radiolarian and zooplankton faunas conform to the sea's physical stratification with lower concentrations of both in a Cold (−1.5 to 1 °C) Intermediate Layer (CIL) (20–125 m) and higher concentrations in waters between 200 and 500 m (Nimmergut and Abelmann, 2002). This biological stratification generates a radiolarian flux echoing that of the glacial northwest Pacific with *C. davisiana* 26% of total flux. Widespread *C. davisiana* percentages (>20%) in high latitude (>45°) glacial sediments of both hemispheres is evidence that these oceans were capped with an Okhotsk-Like Stratification (O-LS). O-LS provides mechanisms to (1) strip nutrients from surface waters depriving the deep-ocean of preformed nutrients, increasing biological pump efficiency and (2) deepen carbon re-mineralization increasing deep-ocean alkalinity. Both may have contributed to lower glacial atmospheric CO_2 concentrations. O-LS would also have amplified glacial climatic cycles by promoting the spread of high latitude sea ice in winter as occurs in the Sea of Okhotsk today, and reducing gas exchange between ocean and atmosphere in summer.

1. Introduction

Positive correlations between temperature and CO_2 concentration in ice cores have led to a consensus that atmospheric CO_2 variations amplified ice age climate change (Berner et al., 1979; Petit et al., 1999) but the cause of these variations are poorly understood (Sigman et al., 2010). The partial pressure of atmospheric CO_2 (pCO_2) is controlled by the average steady state of ocean surface water pCO_2 weighted by area and gas exchange kinetics (Archer et al., 2000), which in turn varies with temperature and major nutrient concentrations. Much of the present-day ocean's mixed layer is stripped of major nutrients by an efficient biological pump; however, large areas of the Antarctic, equatorial Pacific and North Pacific are not. Increased glacial biological pump efficiency in these areas could cause more complete nutrient utilization and consequent atmospheric CO_2 drawdown. The Antarctic Ocean is especially important, for today its unused nutrients are convected to the deep-ocean as so called preformed nutrients. Thus atmospheric pCO_2 depends on both surface ocean nutrient and deep-ocean preformed nutrient concentrations. Deeper glacial carbon re-mineralization could also have lowered atmospheric pCO_2 by triggering deep-ocean alkalinity changes (Broecker and Peng, 1987; Boyle, 1988).

Increased glacial ocean carbon sequestration is suggested by lower glacial than Holocene deep-ocean oxygen levels (Thompson et al., 1990; Francois et al., 1997; Gebhardt et al., 2008; Jaccard et al., 2009) and more depleted glacial $\delta^{13}C$ below 2000 m than above (Herguera, 1992; Keigwin, 1998; Curry and Oppo, 2005). Proxies for productivity and export, e.g. opal and barium flux, to subarctic North Pacific sediments do not support increased glacial relative to Holocene primary productivity (Narita et al., 2002; Kienast et al., 2004; Haug et al., 2005; Jaccard et al., 2005; Shigemitsu et al., 2007). So lower North Pacific diatom $\delta^{15}N$ (increased surface water nitrogen utilization) values in glacial relative to interglacial

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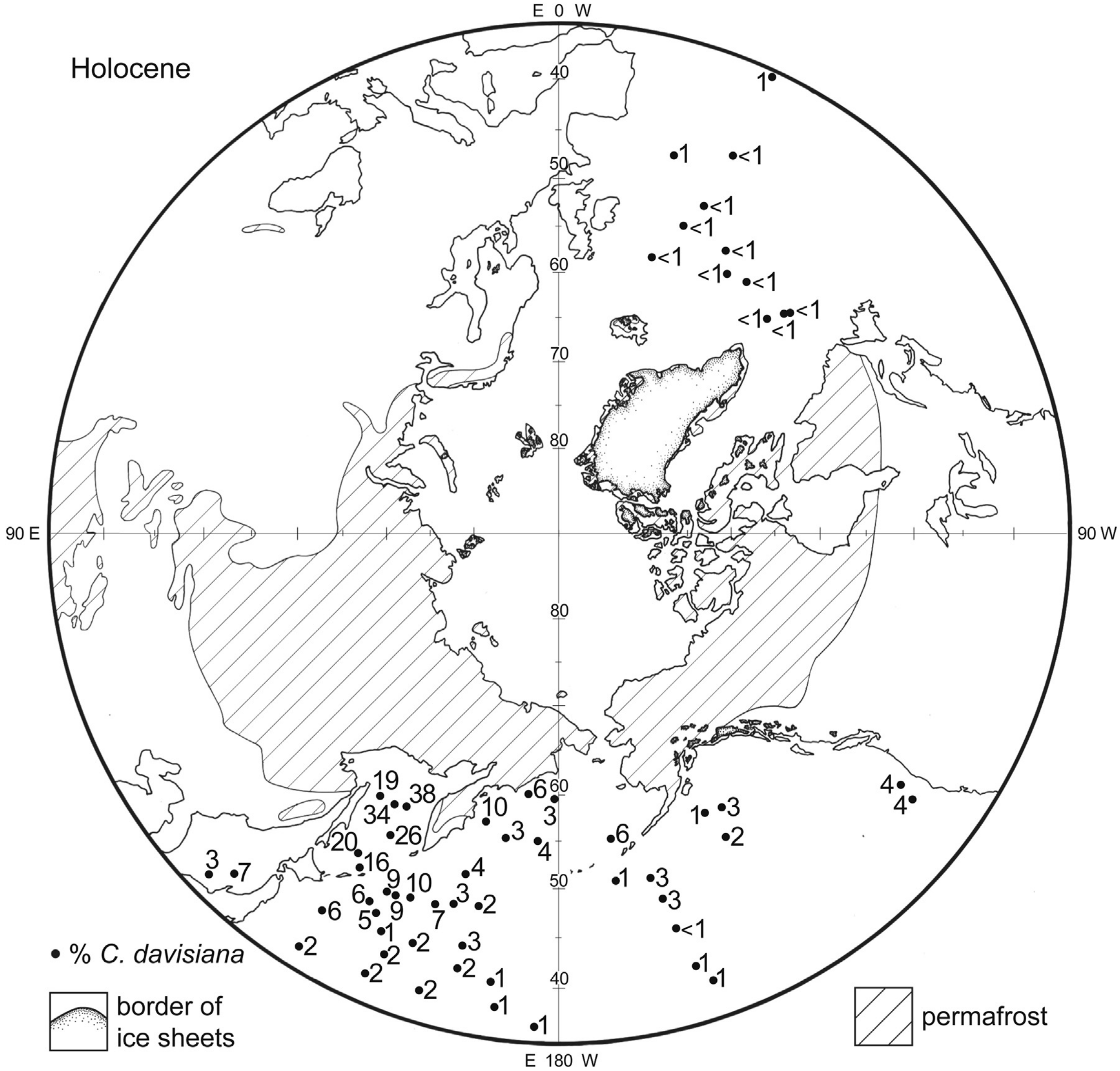

Fig. 1. Recent distribution of northern he misphere permafrost (Washburn, 1980 and references therein) and percent *C. davisiana* in ocean floor sediments (Morley and Hays, 1983; Morley, 1983; and Pisias personal communication). Holocene high percentages of this species occur only within the Sea of Okhotsk and adjacent Pacific.

sediments, have been attributed to lower upward nutrient flux caused by increased stratification, rather than higher primary productivity (Sigman et al., 1999; Galbraith et al., 2008). Glacial stratification has also been invoked in the Antarctic (Francois et al., 1997), however the biological consequences of this stratification are poorly understood in either the Antarctic or North Pacific.

Although organic carbon export is often linked to primary productivity (Eppley and Peterson, 1979), it can also vary with little or no primary production change (Boyd and Newton, 1995) because the quantity of sinking organic carbon is strongly affected by consumer community structure (Michaels and Silver, 1988) that can be influenced by physical water column properties (Hargrave, 1975; Gardner et al., 1993). Glacial Ocean cooling has been suggested as a water column change that could reduce heterotrophic consumption rates and thereby increase biological pump efficiency relative to today (Matsumoto, 2007).

The remains of shallow (<200 m) and deep-living (>200 m) organisms can provide information about past depths of organic carbon respiration but few members of the deep-living community leave a fossil record. Of those that do, polycystine radiolarians are the most abundant and diverse group (Kling, 1979; Gowing, 1986; Takahashi, 1991; Abelmann and Gowing, 1997; Itaki, 2003; Okazaki et al., 2004; Abelmann and Nimmergut, 2005; Tanaka and Takahashi, 2005). Radiolarians, as trophic generalists, feeding on sinking organic detritus and associated microorganisms including bacteria (Anderson, 1983; Gowing, 1986), respond to changing organic flux. Because their shells suffer less from dissolution than diatoms (Shemesh et al., 1989; Morley et al., in press) fossil radiolarians should record production changes at different levels within the water column.

Shallow-living species (0–200 m) dominate radiolarians captured by plankton tows (Kling and Boltovskoy, 1995; Tanaka and Takahashi, 2008) but a deep-living species, *Cycladophora davisiana*, dominates Last Glacial Maximum (LGM) high latitude (>45°) radiolarian faunas of both hemispheres (Hays et al., 1976; Morley et al., 1982; Morley, 1983; Gersonde et al., 2003). In Holocene sediments only those of the Sea of Okhotsk approach the high *C. davisiana* percentages found in high latitude glacial ocean sediments (Fig. 1). In the Okhotsk water column radiolarian concentrations below 200 m exceed those above, reaching a maximum between 200 and 500 m, where *C. davisiana* dominates (Nimmergut and Abelmann, 2002; Okazaki et al., 2004). This