An increase in the ventilation of the abyssal North Pacific Ocean at the end of the last ice age

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The rate at which a portion of the ocean interior exchanges gases with the atmosphere is generally described in terms of "ventilation". Ventilation predominantly occurs where dense waters outcrop at high latitudes, pumping radioactive ^{14}C from the atmosphere into the ocean, while simultaneously undoing the work of the 'biological pump'—releasing the CO_2 excess to the atmosphere and replenishing the oxygen shortfall resulting from the decay of organic matter in the ocean interior. As biologically sequestered carbon would be less readily released to the atmosphere if ventilation of the ocean were reduced, some explanations for the low atmospheric pCO_2 of the last ice age have invoked a poorly ventilated deep glacial ocean (Toggweiler, 1999; Stephens and Keeling, 2000; Sigman and Boyle, 2000). However, paleoceanographic evidence to support this has been sparse and often ambiguous, particularly in the Pacific Ocean.

In the modern North Pacific Ocean, the balance between organic matter respiration and the circulation of the ocean interior produces a broad nutrient maximum and oxygen minimum in the upper 1.5 km of the water column (Fig. 1b,c). Upward mixing of the nutrient-rich thermocline waters supplies the fertile North Pacific ecosystem with the ingredients necessary for growth, simultaneously leaking respired CO_2 to the atmosphere. A lid of low-salinity waters impedes local ventilation of deep waters at the subarctic surface, so that abyssal waters are ventilated only at the distant surfaces of the North Atlantic and Southern Ocean. The rapid attenuation of organic matter flux with depth leads to a deep sea that is better oxygenated and contains lower concentrations of remineralized nutrients and carbon, even though exchange with the atmosphere is slower, as indicated by the extremely low $\Delta^{14}C$ (Fig. 1d). Multiproxy records from two sediment cores in the deep subarctic Pacific were developed to investigate how these patterns may have differed during the last ice age. These paleoceanographic records from a little-studied region of the global ocean provide a new perspective on the deep ocean chemistry and surface ocean fertility over the last glacial-interglacial transition (Galbraith et al., 2007).

First, past values of deepwater $\Delta^{14}C$ were estimated by separately measuring the $\Delta^{14}C$ of co-occurring fossil benthic and planktic foraminifers. Using calibrated calendar ages of the planktic foraminifers, the benthic foraminiferal $\Delta^{14}C$ can be decay corrected to the time of growth to give the paleo bottom water $\Delta^{14}C$. These values are shown in Figure 2, calculated in parts per thousand relative to the contemporary atmospheric $\Delta^{14}C'_{cont\text{-}atm}$, as described in Galbraith et al. (2007).

The $\Delta^{14}C$ results clearly show that the deep North Pacific Ocean was more poorly ventilated during the Last Glacial Maximum (LGM) than it is today and that the ^{14}C ventilation improved during deglaciation. This is similar to results from the Panama Basin at 3.2 km depth (Shackleton et al., 1988) but contrasts with measurements previously made at shallower depths in the equatorial Pacific Ocean, which show a scattered range of glacial deep ocean $\Delta^{14}C$ that overlaps with present-day values (Broecker et al., 2004). Although it is difficult to evaluate the cause of this discrepancy, it may reflect a vertical gradient in ventilation, with ventilation similar to today in the upper 2.5 km of the water column, and relatively unventilated water below this. Intriguingly, the sole published glacial-age benthic-planktic pair from the deep South Pacific (Sikes et al., 2000) shows a more ^{14}C-depleted value, suggesting that a lateral gradient also existed across the glacial deep Pacific Ocean at depths of 3-3.5 km, with the most poorly ventilated waters in the south.

Geochemical measurements made on the sediment in which the foraminifers were buried provide additional information on the state of the glacial North Pacific. The analyses of two sedimentary components are shown in Figure 2 (see Galbraith et al., 2007 for more proxy records). The first, opal, suggests decreased diatom export during the LGM, consistent with many previously published records from the subarctic Pacific, which show reduced algal growth during the glacial (Kienast et al., 2004; Jaccard et al, 2005; Brunelle et al., 2007, and references there-

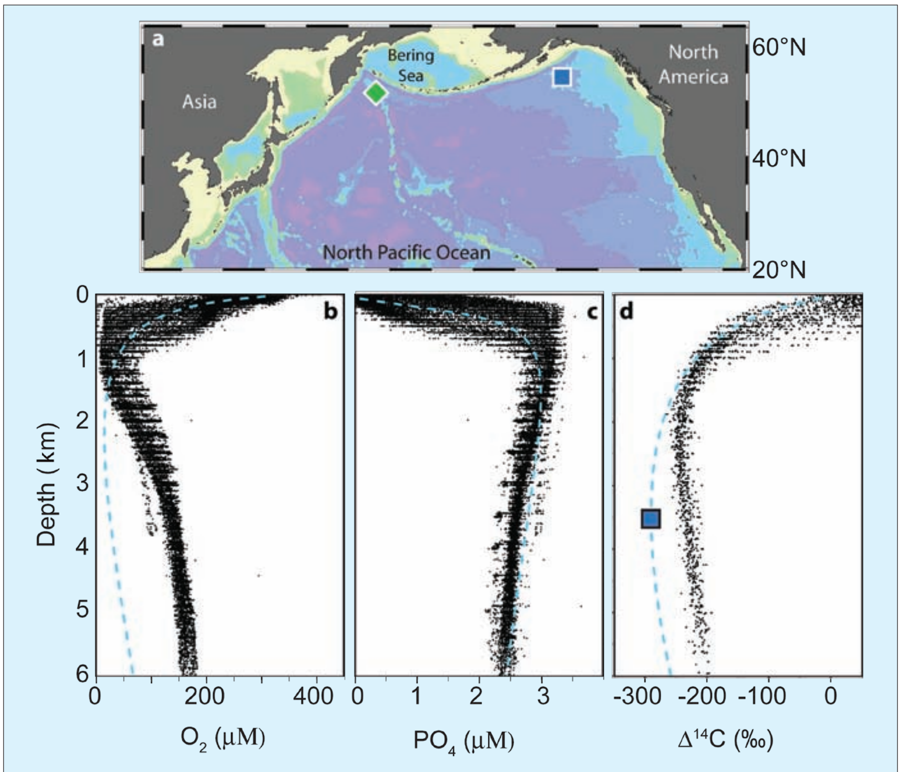

*Figure 1: **a**) Core sites: ODP 882 (50.35°N, 167.58°W, 3244 m; green diamond) and ODP 887 (54.37°N, 148.45°W, 3647 m; blue square); (**b**) Dissolved oxygen, (**c**) phosphate, and (**d**) radiocarbon in the North Pacific. All measurements available in GLODAP north of 20°N in the Pacific Ocean are shown (Key et al., 2004). Reconstructed $\Delta^{14}C'_{cont\text{-}atm}$ of bottom waters at Site 887 during the LGM is shown by the blue square in plot d. Dashed blue lines of b, c and d represent hypothetical North Pacific water-column profiles that appear to be consistent with the available data for the LGM. Note that these are highly speculative sketches based on a small amount of qualitative data.*

in). Studies of the nitrogen isotopic composition of sedimentary organic matter indicate that reduced export production coincided with increased relative nitrate consumption during the glacial (Brunelle et al., 2007; Galbraith et al, in press), suggesting that the upward flux of macronutrients to the surface was reduced. Yet, despite the weakened downward flux of organic matter, the concentration of U in subarctic Pacific sediments—an element typically enriched under low oxygen conditions—was higher during the LGM (Fig. 2). This, therefore, most likely resulted from a significant decrease in bottom water oxygen concentrations—an indirect but robust sign that respired CO_2 concentrations were markedly higher in the deep North Pacific during the LGM.

Together, these proxies indicate that the glacial deep Pacific Ocean was more effectively isolated from the atmosphere, and that the biological pump had succeeded in storing a greater concentration of respired CO_2 in the deep ocean. Although direct causality cannot be proven, this is consistent with models that achieve lower atmospheric pCO_2 by reducing ventilation. Ventilation could theoretically have been impeded in the past by a reduced rate of mixing between surface and deep waters (Toggweiler, 1999), an intensified barrier to ocean-atmosphere exchange (such as expanded sea ice; Stephens and Keeling, 2000), or both. Whatever the case, elevated storage of respired CO_2 within the deep ocean would have enhanced $CaCO_3$ dissolution at the seafloor, elevating the global $CaCO_3$ inventory and thereby contributing to greater CO_2 solubility at the global scale, as hypothesized by Boyle (1988). The evidence for invariant deep Pacific PO_4 concentrations—as inferred by foraminiferal Cd/Ca across the glacial-interglacial transition (Boyle, 1992)—appeared to contradict prior evidence for a buildup of respired carbon in the glacial deep sea. Given our evidence, however, we suggest that increased respired CO_2 arose from a relative decrease in the preformed PO_4 concentration of deep Pacific waters, rather than from an increase of the total PO_4 concentration, alleviating the apparent conflict (Jaccard et al., in prep). The highly schematic water column profiles shown in Figure 1 suggest a possible reconciliation of the available data from the glacial North Pacific.

During the last deglaciation, export production increased dramatically ca. 14.5-15 kyr BP, while the oxygenation of bottom waters increased. The remarkable temporal coincidence of changes in the deep and surface oceans suggests that the arrival of better-oxygenated deep waters was mechanistically linked to an increase in the upward flux of nutrients to the surface. At the same time, intense oxygen depletion developed in the upper water column of the North Pacific, as previously described at multiple sites (e.g., Zheng et al., 2000; Cook et al., 2005), even as oxygen concentrations increased in the abyssal waters below. The close occurrence of this with the start of the Bølling warm period in the North Atlantic hints that a tight physical relationship linked the North Pacific circulation and the reinvigoration of the Atlantic meridional overturning at this time. The observation of increased export production and intensified thermocline oxygen-minimum zones during a period of more vigorous North Atlantic Deep Water formation, are consistent with the model results of Schmittner et al. (2007), which were based on freshwater-forced manipulations of the Atlantic circulation in a global GCM with a prognostic biogeochemical model. However, the apparent rapidity of the transition in the North Pacific is surprising and the relationship to the progression of the overall deglaciation remains to be clarified.

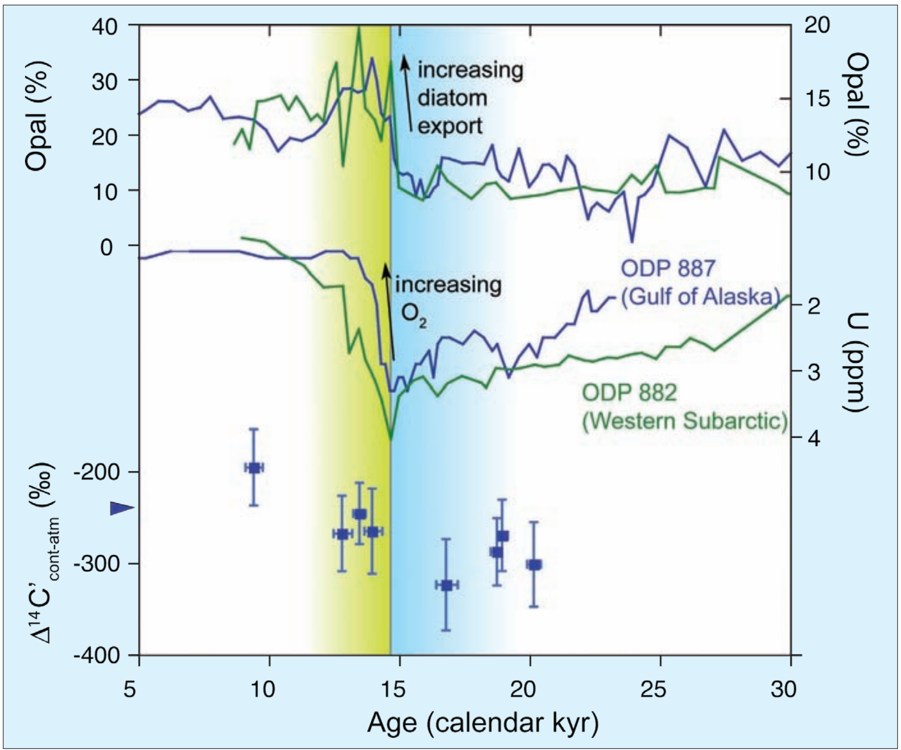

Figure 2: Sedimentary records from the subarctic Pacific, selected from those presented in Galbraith et al., 2007. See Figure 1 for core sites. ***Top****: sedimentary opal concentrations in weight %, measured by spectrophotometry of an alkaline extract.* ***Middle****: U concentrations measured on ODP cores 882 and 887 by ICP-MS and ICP-OES, respectively.* ***Bottom****: $\Delta^{14}C'_{cont-atm}$ of bottom waters at site ODP 887 calculated from benthic-planktic foraminiferal pairs, as described in Galbraith et al., 2007. Blue triangle on axis indicates the present-day $\Delta^{14}C$ of bottom waters near the core site (Key et al., 2004).*

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