



Deglacial weakening of the oceanic soft tissue pump: global constraints from sedimentary nitrogen isotopes and oxygenation proxies



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ABSTRACT

Among the many potential explanations for the ~80 ppm rise of atmospheric CO₂ concentrations at the end of the last ice age, most involve a weakening of the oceanic soft tissue pump. Here we use global data compilations of sedimentary nitrogen isotopes and benthic oxygenation proxies to provide a synoptic global perspective on the deglacial soft tissue pump weakening. The net change between the Last Glacial Maximum and Holocene shows a removal of respired carbon everywhere that proxy data is available, with the exception of the upper 1.5 km of the North Pacific, while excess nitrate accumulated in polar oceans. These observations could be explained by intensifying iron limitation, a shoaling of organic matter remineralization, and/or a change in ocean circulation, but are inconsistent with a change in the magnitude or position of the Southern mid-latitude westerlies. The net soft tissue pump weakening was front-loaded in the early deglaciation (~17.5–~14 ka), when atmospheric δ¹³C and Δ¹⁴C were changing rapidly, and appears to have contributed little net change thereafter. Superimposed on the overall deglacial trend were pronounced transient changes that coincided with variability in the Atlantic Meridional Overturning Circulation (AMOC) and bipolar seesaw. The seesaw variability is most clearly expressed as anti-phased oxygenation changes between the upper 1.5 km of the North Pacific and the deep North Atlantic, consistent with an Atlantic–Pacific ventilation seesaw, but it dominated transient variability in records throughout the world. Although the soft tissue pump seesaw made little contribution to the contrast between the glacial and interglacial states, it could have contributed to deglacial variability in atmospheric CO₂ and might have catalyzed the deglaciation.

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1. Introduction

The correlation of atmospheric CO₂ concentrations and global temperature through ice–age cycles has proven remarkably difficult to attribute to specific mechanisms (Archer et al., 2000; Kohfeld and Ridgwell, 2009). Box- and zonally-averaged models have been used to illustrate a range of potential explanations (Köhler et al., 2005; Peacock et al., 2006; Hain et al., 2010; Bouttes et al., 2011; Brovkin et al., 2012), but more realistic general circulation models cannot satisfactorily reproduce the observed CO₂ changes (Chikamoto et al., 2012; Menviel et al., 2012). Yet, studies have shown that the CO₂ changes played a critical role in causing

the ice–age cycles, amplifying the impact of orbitally-modulated insolation and ice sheet dynamics (Timmermann et al., 2009; Shakun et al., 2012; Abe-Ouchi et al., 2013). Thus, we cannot understand the ice age cycles without knowing what controlled CO₂.

The ocean's biological pump has long been considered a primary contender to explain the CO₂ variations. By extracting dissolved inorganic carbon from the surface through photosynthesis and exporting it to depth as sinking organic matter, the 'soft tissue' pump lowers the concentration of CO₂ at the air–sea boundary, thereby drawing CO₂ out of the atmosphere. The net effect of the soft tissue pump increases with a greater flux of sinking organic matter to the deep sea, and weakens under a more rapid ventilation of the deep sea by physical ocean circulation. It is important to emphasize that the 'soft tissue pump', as intended here, includes the net result of all biological and physical processes leading to the accumulation of Dissolved Inorganic Carbon from soft tissue

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respiration (DIC_{soft}) within the ocean, including ocean circulation, and is not simply the sinking flux of organic matter. Theoretical arguments have shown that the soft tissue pump could have been more effective during the Last Glacial Maximum (LGM) due to changes in the marine ecosystem, the physical ocean circulation, or both, most of which involve a reduction of the preformed nutrient concentration (Fig. 1) (Sarmiento and Toggweiler, 1984; Sigman and Boyle, 2000; Marinov et al., 2008; Sigman et al., 2010; Hain et al., 2013). Such changes in the soft tissue pump-derived DIC_{soft} would have been joined by changes in the three other components of DIC, as conceptualized here: 1. the saturation DIC concentration (DIC_{sat}), dependent on temperature, salinity, alkalinity and $p\text{CO}_2$; 2. the degree of disequilibrium in surface waters that ventilate the

deep ocean ($\text{DIC}_{\text{diseq}}$), dependent on the exposure time at the ocean surface relative to the rate of air–sea exchange, the cooling history of the waters prior to subduction, and the inherited disequilibrium in upwelled waters (mostly caused by DIC_{soft}) (Ito and Follows, 2013); and 3. remineralized CaCO_3 (DIC_{carb}) from the dissolution of sunken calcite and aragonite shells. Note that although the carbonate pump moves DIC from the surface to the deep sea, it removes twice as much alkalinity from the ocean surface, such that overall it raises the $p\text{CO}_2$ of surface waters (Archer et al., 2000; Hain et al., 2013).

Despite the potential for the soft tissue pump to have played a major role in the CO_2 variations, conclusive proof has remained elusive. The role of the soft tissue pump can be calculated in models, but there are no direct proxy records of DIC_{soft} . The stable isotopes of dissolved inorganic carbon ($\delta^{13}\text{C}_{\text{DIC}}$) provide a clue, as low $\delta^{13}\text{C}_{\text{DIC}}$ is a hallmark of respired carbon, but this signal can be overwhelmed by the large imprint of air–sea exchange (Schmittner et al., 2013). Sedimentary records of biogenic detritus (Kohfeld et al., 2005) provide an indication of export, as viewed through the clouded lens of variable preservation, but since the soft tissue pump depends on the net result of biology and ocean circulation, export alone provides an incomplete picture (Gnanadesikan and Marinov, 2008). Reconstructions of radiocarbon activity ($\Delta^{14}\text{C}$) in the ocean and atmosphere (Marchitto et al., 2007; Skinner et al., 2010; Burke and Robinson, 2012) and patterns of export (Anderson et al., 2009; Martínez-García et al., 2009) have been invoked as circumstantial evidence that the Southern Ocean was behind the deglacial changes, due to both increasing ventilation and decreasing iron fertilization by dust therein (Köhler et al., 2005; Fischer et al., 2010; Jaccard et al., 2013). But without a clear global record of changes in the overall effectiveness of the soft tissue pump these mechanisms remain speculative, leaving its role in the CO_2 rise uncertain relative to changes in solubility, changes in $\text{DIC}_{\text{diseq}}$, or to alternative carbon sources such as outgassing from geological reservoirs (Huybers and Langmuir, 2009; Stott and Timmermann, 2011).

Here, we make use of sedimentary oxygenation proxies to provide relatively direct constraints on the soft tissue pump over the last deglaciation. Oxygen is utilized in the ocean interior when organic carbon is respired, with a relatively consistent $\text{CO}_2:\text{O}_2$ stoichiometry of 0.7 under most conditions (Anderson and Sarmiento, 1994). Therefore, the degree of oxygen utilization in bottom waters provides an excellent monitor of DIC_{soft} concentrations, the direct effect of the soft tissue pump. The Apparent Oxygen Utilization (AOU) is defined as the difference between observed O_2 and the saturation O_2 calculated from water temperature and salinity; changes in AOU over the deglaciation can therefore be estimated from the sedimentary proxies of O_2 in combination with an estimate of the deglacial temperature rise and salinity drop (Jaccard et al., 2014). It is important to note that the AOU differs from true oxygen utilization due to surface ocean disequilibrium (i.e. the difference between the saturation and actual concentrations during deep-water formation) which is on the order of $20\ \mu\text{M}$ in deep-water formation regions (Russell and Dickson, 2003; Duteil et al., 2013). Any change in the degree of oxygen disequilibrium over the deglaciation would have imparted an additional change to oxygen concentrations in the interior. But because the equilibration time for O_2 (~ 1 month) is short relative to CO_2 (~ 1 year), the disequilibrium changes for O_2 should be relatively insensitive to the impact of sea ice extent on air–sea exchange compared to CO_2 , which can undergo large changes in its disequilibrium component (Keeling and Stephens, 2001). As a result, the conceptual framework here considers sea ice and other air–sea equilibration mechanisms as modifying $\text{DIC}_{\text{diseq}}$, distinct from the carbon sequestered by the direct soft tissue pump, DIC_{soft} .

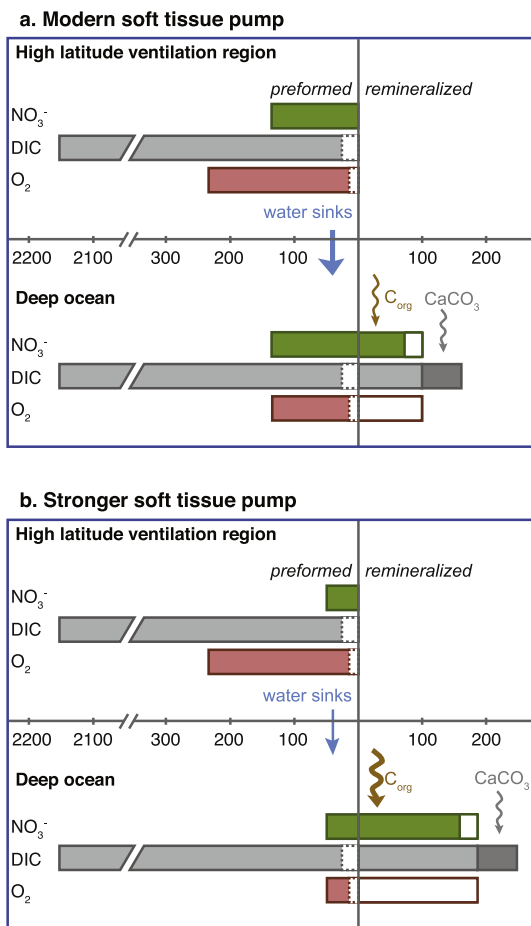


Fig. 1. Carbon storage, preformed nitrate, and oxygen. a. The upper box represents concentrations in high latitude regions that form deep waters, and thereby set the preformed concentrations for the global deep ocean. The lower box shows concentrations in the deep ocean, which include the preformed components plus sources/sinks from remineralization of sinking organic matter (C_{org}) and carbonate minerals (CaCO_3). The bars indicate approximate concentrations, scaled to DIC concentrations (μM) by a 'Redfield' $\text{NO}_3^-:\text{DIC}:\text{O}_2$ ratio of 16:106:150. Deep remineralized nitrate includes a deficit (white, green-outlined box) due to denitrification in the water column and sediments, estimated from DeVries et al. (2013). Preformed DIC includes a dominant saturation component, dependent on temperature, salinity and alkalinity, and a small disequilibrium undersaturation (dashed outline), within the estimated range of Ito and Follows (2013). Preformed O_2 includes a dominant saturation component, dependent on temperature and salinity, and a small disequilibrium undersaturation (dashed outline), as estimated by Duteil et al. (2013). Other concentrations are estimated from the World Ocean Atlas (Boyer, 2013). The white, red-outlined O_2 box represents oxygen utilization from C_{org} remineralization. b. A hypothetical example of a stronger biological pump, in which an identical nitrate inventory with a smaller preformed component drives greater respired carbon storage, under an identical atmospheric CO_2 concentration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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