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Distal and proximal controls on the silicon stable isotope signature of North Atlantic Deep Water

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ABSTRACT

It has been suggested that the uniquely high δ^{30}Si signature of North Atlantic Deep Water (NADW) results from the contribution of isotopically fractionated silicic acid by mode and intermediate waters that are formed in the Southern Ocean and transported to the North Atlantic within the upper limb of the meridional overturning circulation (MOC). Here, we test this hypothesis in a suite of ocean general circulation models (OGCMs) with widely varying MOCs and related pathways of nutrient supply to the upper ocean. Despite their differing MOC pathways, all models reproduce the observation of a high δ^{30}Si signature in NADW, as well showing a major or dominant (46–62%) contribution from Southern Ocean mode/intermediate waters to its Si inventory. These models thus confirm that the δ^{30}Si signature of NADW does indeed owe its existence primarily to the large-scale transport of a distal fractionation signal created in the surface Southern Ocean. However, we also find that more proximal fractionation of Si upwelled to the surface within the Atlantic Ocean must also play some role, contributing 20–46% of the deep Atlantic δ^{30}Si gradient. Finally, the model suite reveals compensatory effects in the mechanisms contributing to the high δ^{30}Si signature of NADW, whereby less export of high-δ^{30}Si mode/intermediate waters to the North Atlantic is compensated by production of a high-δ^{30}Si signal during transport to the NADW formation region. This trade-off decouples the δ^{30}Si signature of NADW from the pathways of deep water upwelling associated with the MOC. Thus, whilst our study affirms the importance of cross-equatorial transport of Southern Ocean-sourced Si in producing the unique δ^{30}Si signature of NADW, it also shows that the presence of a deep Atlantic δ^{30}Si gradient does not uniquely constrain the pathways by which deep waters are returned to the upper ocean.

1. Introduction

1.1. Marine Si cycling and the δ^{30}Si distribution

The cycling of nutrients in the sea is determined by a complex set of interactions between biota in the surface ocean and the physical circulation across a range of spatial and temporal scales. At the global scale, the export of nutrients to the abyss in biogenic particles is balanced by the supply of dissolved nutrients via the upwelling of nutrient-rich deep waters in the MOC (Broecker and Peng, 1982; Sarmiento et al., 2007). At the scale of the thermocline, nutrient distributions are determined by how the location and timing of biological nutrient drawdown at the surface interacts with the subduction of water masses and their gyre- to basin-scale circulation (Sarmiento et al., 2004; Palter et al., 2005; Karleskind et al., 2011). These distributions in turn determine the magnitude, biogeography and distribution of low-latitude primary productivity (Marinov et al., 2006; Palter et al., 2010, 2011). The ocean interior distributions of nutrients thus both influence and are influenced by biological productivity, and bear the imprint of the interaction between productivity and the ocean's three-dimensional circulation, allowing them to be used to infer the physical and biological interactions that determine marine nutrient cycling. This study takes such an approach in order to trace the influence of physical–biological interactions on the large-scale transports associated with the marine cycle of silicon (Si).

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Of the ocean's photosynthesizing primary producers, diatoms are the most important group for the export of organic carbon from the surface ocean (e.g. Buesseler, 1998). As a result, they play a key role in the biological pump, a mechanism by which the ocean modulates atmospheric pCO_2 (Hain et al., 2014a). Whilst their opaline cell wall, or frustule, provides diatoms protection from predators (Smetacek, 1999) and is less energy-intensive to produce than an organic cell wall (Raven, 1983), it also makes them vitally dependent on the presence of Si dissolved in seawater. The boom-bust behavior of diatom populations that leads to their importance for carbon export also means that diatoms are very efficient exporters of Si to depth (Brzezinski et al., 2003), such that they are the main driver of marine Si cycling (Tréguer and De la Rocha, 2013). Diatom uptake of Si discriminates between its isotopes, with lighter Si isotopes being preferentially incorporated into the frustule (De la Rocha et al., 1997; Sutton et al., 2013), leaving the residual Si in seawater enriched in heavier Si isotopes. Diatom Si uptake at the ocean's surface thus produces a signal of biological cycling in the stable isotope composition of seawater Si (expressed in the standard delta notation as δ^{30}Si), which can be used as a tracer of the marine Si cycle (e.g. Cardinal et al., 2005; Reynolds et al., 2006; Beucher et al., 2008; de Souza et al., 2012a; Grasse et al., 2013). For instance, diatom uptake in the surface Southern Ocean produces elevated δ^{30}Si in the deep winter mixed layers from which the Southern Ocean mode/intermediate water masses Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) are ventilated (Fripiat et al., 2011). This isotopic signal is transported into the subtropical interior by the spreading of these water masses from their formation regions (de Souza et al., 2012b).

The clearest large-scale signal in the marine δ^{30}Si distribution is the δ^{30}Si gradient in the deep Atlantic Ocean (Fig. 1a; de Souza et al., 2012a; Brzezinski and Jones, 2015), with a systematic trend from high δ^{30}Si values in deep waters of the Si-poor North Atlantic, influenced by NADW, to lower values towards the Si-richer south, influenced by Antarctic Bottom Water (AABW). This coherent gradient is related to the quasi-conservative mixing of Si between these two water masses (Broecker et al., 1991), as reflected by the systematics (Fig. 1a) and water-column distribution (Fig. 1b) of δ^{30}Si in the Atlantic, both of which indicate water-mass control on the δ^{30}Si distribution. de Souza et al. (2012a) suggested that the high δ^{30}Si value of NADW ultimately results from the creation of a high-δ^{30}Si signal by diatom Si uptake in the surface Southern Ocean, a signal that is transported to the North Atlantic by SAMW/AAIW in the upper limb of the MOC. This mechanism has since been invoked to explain the isotope distributions of other biogeochemically-cycled elements, such as cadmium (e.g. Abouchami et al., 2014).

Such a Southern-Ocean-focused mechanism is consistent with burgeoning evidence that the dominant MOC pathway by which dense and nutrient-rich deep waters are brought to the surface is the wind-driven upwelling in the Southern Ocean (Toggweiler and Samuels, 1993; Sarmiento et al., 2004; Lumpkin and Speer, 2007; Marshall and Speer, 2012; Morrison et al., 2015), contrary to the canonical view of upwelling through the low-latitude thermocline (Robinson and Stommel, 1959; Broecker and Peng, 1982). However, some recent observationally-based estimates of global overturning indicate a significant role of low-latitude upwelling in closing the MOC (Talley et al., 2003; Talley, 2008). By using numerical ocean models to examine the relationship between the NADW δ^{30}Si signature and the pathways by which Si is transported by the MOC, this study assesses de Souza et al.'s (2012a) hypothesis of large-scale controls on the Atlantic δ^{30}Si distribution, whilst also considering the constraints placed by these observations on pathways of upwelling associated with the MOC.

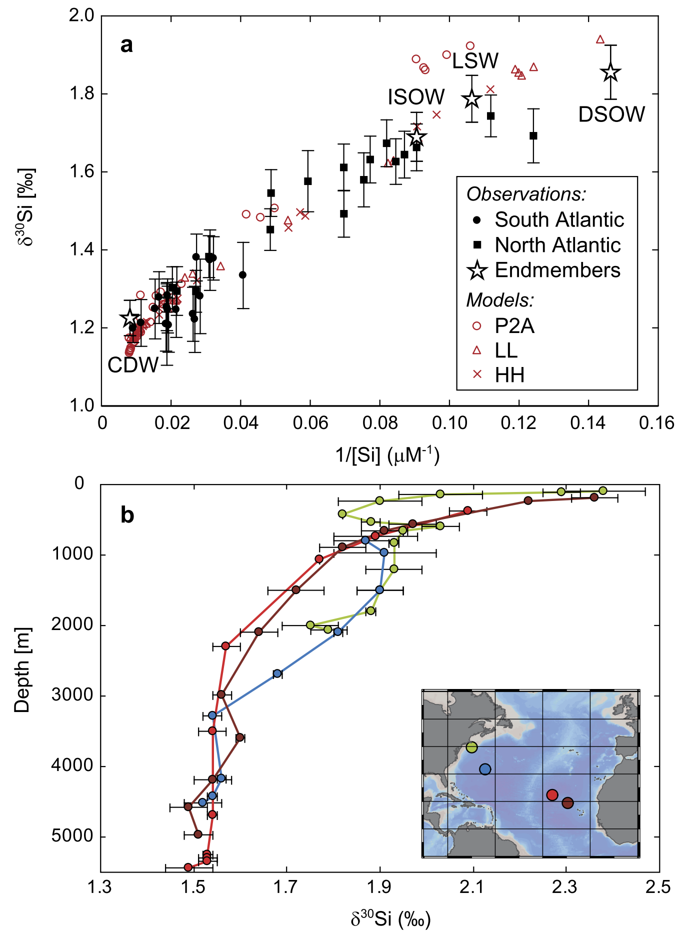

Fig. 1. Silicon isotope data from the Atlantic Ocean. (a) Data from the deep (>2000 m) Atlantic Ocean from latitudes ranging from ~60°N to ~60°S in isotope mixing space (de Souza et al., 2012a), illustrating the systematic variation of deep water δ^{30}Si values. The near-linear relationship between δ^{30}Si and 1/[Si] indicates quasi-conservative mixing of Si brought into the deep Atlantic by Si-rich Southern Ocean sources (CDW) as well as Si-poor North Atlantic (LSW) and Nordic (DSOW, ISOW) sources. Open red symbols are results from the OGCMs used in this study (see Section 2.1), subsampled at the observational sampling locations. (b) Depth profiles of δ^{30}Si from the GEOTRACES North Atlantic Zonal Transect at 20°–40°N (Brzezinski and Jones, 2015) reveal the elevated δ^{30}Si values associated with the southward transport of NADW at mid-depths in the western Atlantic Ocean (blue and green points; see inset). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.2. Support for a Southern Ocean control

Support for a Southern Ocean control on the NADW δ^{30}Si signature is provided by the model CYCLOPS, an ocean box model originally developed by Keir (1988) that has been modified to explicitly represent the physical and biogeochemical zonation of the surface Southern Ocean (Fig. 2a; Robinson et al., 2005; Hain et al., 2014b). A representation of the marine cycling of Si and its isotopes (see Supplementary Information) allows an assessment of the leading-order sensitivities of the large-scale δ^{30}Si distribution. As shown in Fig. 2b, the observed deep Atlantic Si concentration gradient (~110 μM) can be reproduced by simultaneously varying the length-scale defining the dissolution of opal export (which determines the partitioning of opal dissolution between the intermediate and deep ocean) and the degree of Si drawdown in the Subantarctic Zone (SAZ), from where the model's Southern Ocean mode/intermediate waters are ventilated. In contrast, the gradient in δ^{30}Si between NADW and the deep Southern Ocean is mostly insensitive to the opal dissolution length-scale, but varies systematically with Si drawdown in the SAZ, disappear-