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Inferring source regions and supply mechanisms of iron in the Southern Ocean from satellite chlorophyll data

Robert M. Graham [a,b,*], Agatha M. De Boer [a,b], Erik van Sebille [c,d], Karen E. Kohfeld [e], Christian Schlosser [f]

[a] Department of Geological Sciences, Stockholm University, 106 91 Stockholm, Sweden
[b] Bolin Centre for Climate Research, Stockholm, Sweden
[c] ARC Centre of Excellence for Climate System Science & Climate Change Research Centre, University of New South Wales, Sydney, Australia
[d] Grantham Institute & Department of Physics, Imperial College, London, UK
[e] School of Resource and Environmental Management, Simon Fraser University, Burnaby, B.C., Canada V5A 1S6
[f] GEOMAR, Helmholtz Centre for Ocean Research Kiel, D-24148 Kiel, Germany

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ABSTRACT

Primary productivity is limited by the availability of iron over large areas of the global ocean. Changes in the supply of iron to these regions could have major impacts on primary productivity and the carbon cycle. However, source regions and supply mechanisms of iron to the global oceans remain poorly constrained. Shelf sediments are considered one of the largest sources of dissolved iron to the global ocean, and a large shelf sediment iron flux is prescribed in many biogeochemical models over all areas of bathymetry shallower than 1000 m. Here, we infer the likely location of shelf sediment iron sources in the Southern Ocean, by identifying where satellite chlorophyll concentrations are enhanced over shallow bathymetry (<1000 m). We further compare chlorophyll concentrations with the position of ocean fronts, to assess the relative role of horizontal advection and upwelling for supplying iron to the ocean surface. We show that mean annual chlorophyll concentrations are not visibly enhanced over areas of shallow bathymetry that are located more than 500 km from a coastline. Mean annual chlorophyll concentrations >2 mg m^{-3} are only found within 50 km of a continental or island coastline. These results suggest that sedimentary iron sources only exist on continental and island shelves. Large sedimentary iron fluxes do not seem present on seamounts and submerged plateaus. Large chlorophyll blooms develop where the western boundary currents detach from the continental shelves, and turn eastward into the Sub-Antarctic Zone. Chlorophyll concentrations are enhanced along contours of sea surface height extending off the continental shelves, as shown by the trajectories of virtual water parcels in satellite altimetry data. These analyses support the hypothesis that bioavailable iron from continental shelves is entrained into western boundary currents, and advected into the Sub-Antarctic Zone along the Dynamical Subtropical Front. Our results indicate that upwelling at fronts in the open ocean is unlikely to deliver iron to the ocean surface from deep sources. Finally, we hypothesise how a reduction in sea level may have altered the distribution of shelf sediment iron sources in the Southern Ocean and increased export production over the Sub-Antarctic Zone during glacial intervals.

1. Introduction

Approximately one third of the world's oceans have been defined as High Nutrient Low Chlorophyll (HNLC) regions (Chisholm and Morel, 1991). Primary biological productivity in HNLC regions is lower than one would expect, given the high concentrations of macronutrients (nitrates and phosphates). The lower productivity in HNLC regions is because of the limited availability of the micronutrient iron (Martin, 1990). Mesoscale iron fertilisation experiments have shown that the addition of iron to surface waters in HNLC regions increases productivity locally (Coale et al., 1996; Cooper et al., 1996; Boyd et al., 2000, 2007; Bakker et al., 2005; De Baar et al., 2005; Aumont and Bopp, 2006; Law et al., 2006; Smetacek et al., 2012; Assmy et al., 2013). This iron fertilisation may also act to reduce atmospheric CO_2 concentrations, by

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[*] Correspondence to: Alfred Wegner Institute Helmholtz Centre for Polar and Marine Research, Potsdam, Germany and Norwegian Polar Institute, Tromso, Norway.
E-mail address: r.graham.1007@gmail.com (R.M. Graham).

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enhancing export production and the biological pump (Smetacek et al., 2012). For example, an increase in the supply of iron to the Southern Ocean (the largest HNLC region) is a leading hypothesis for explaining a substantial portion of the ~80 ppm reduction in atmospheric carbon dioxide concentrations during glacial periods (Martin, 1990; Moore et al., 2000; Watson and Naveira Garabato, 2006; Kohfeld and Ridgwell, 2009; Ziegler et al., 2013; Anderson et al., 2014; Lamy et al., 2014; Martinez-Garcia et al., 2014). Artificial iron fertilisation of HNLC regions has even been suggested as a method to combat the anthropogenic rise in atmospheric CO_2 (Chisholm and Morel, 1991; Robinson et al., 2014). Understanding the natural supply mechanisms of iron and other trace metals to the global oceans is a key goal of earth systems science, and has spurred several major research programs such as GEOTRACES, CLIVAR, CROZEX, KEOPS-I and KEOPS-II (Planquette et al., 2007; Pollard et al., 2007, 2009; Chever et al., 2010; Browning et al., 2014; Conway and John, 2014; Rijkenberg et al., 2014; Grand et al., 2015).

The bioavailability of different forms of iron to phytoplankton remains a topic of debate (Shaked and Lis, 2012; Schallenberg et al., 2015). Dissolved inorganic species of iron are assumed to be the most readily accessible for phytoplankton (Raiswell and Canfield, 2012). However, the vast majority of dissolved iron in the ocean is complexed by organic ligands (Gledhill and Buck, 2012). These organically complexed species are believed to be less available to phytoplankton than inorganic species of iron. However, the photochemical reduction of ligands is thought to make organically complexed iron more bioavailable (Gledhill and Buck, 2012). There is also increasing evidence that particulate iron can be accessible to some phytoplankton under certain conditions (Nodwell and Price, 2001; Frew et al., 2006; Van der Merwe et al., 2015). The bioavailability of different iron species should therefore be treated as a spectrum, rather than available/unavailable (Shaked and Lis, 2012).

Shelf sediments are thought to represent one of the largest sources of dissolved inorganic iron to the global ocean (Johnson et al., 1999; Elrod et al., 2004; Moore et al., 2004; Moore and Braucher, 2008; Tagliabue et al., 2009, 2012, 2014b; Boyd et al., 2012a; Biller et al., 2013). For example, an iron flux of 865 μmol $m^{-}2$ day^{-1} was measured from sediments on the Peruvian shelf (Noffke et al., 2012). Pore waters in anoxic shelf sediments are heavily enriched in dissolved iron (mainly the reduced Fe(II) species), due to the microbial reduction of particulate Fe(III) oxides and silicates within the sediments (Homoky et al., 2012; Raiswell and Canfield, 2012). The diffusive outflow of sediment pore waters, and the strong gradient in dissolved iron concentrations between enriched pore waters and bottom waters, results in a large flux of dissolved iron from anoxic shelf sediments to the overlying waters. Large fluxes of iron from the sea floor have been measured on several continental and island shelves (Johnson et al., 1999; Elrod et al., 2004; Blain et al., 2007; De Jong et al., 2012; Homoky et al., 2012; Biller et al., 2013; Conway and John, 2014).

The magnitude of the iron flux from shelf sediments to the overlying waters is controlled mainly by the redox state of the sediments (Chase et al., 2007; Raiswell and Canfield, 2012). Anoxic conditions in sediments are generated foremost by the microbial decomposition of organic matter. The oxygen status of sediments, and hence the iron flux from the sediments, therefore depends on the supply of fresh organic matter to the sediments (Raiswell and Canfield, 2012). Note that this is a positive feedback. We would expect to find large iron fluxes in regions of high productivity, because of the enhanced input of organic matter to the sediments below. Equally, we would expect productivity to be higher in regions where there are large iron fluxes. This feedback loop means that we need to consider export production as an initial condition to accurately parameterise the shelf sediment iron flux in biogeochemical models, and thus require an a priori knowledge of productivity (Moore and Braucher, 2008).

Many biogeochemical models parameterise the shelf sediment iron source as an inverse function of water depth, such that there are large iron fluxes through the sea floor in regions where the water depth is shallower than 1000 m (Moore et al., 2004; Aumont and Bopp, 2006; Lancelot et al., 2009; Tagliabue et al., 2014b; Wadley et al., 2014). These parameterisation schemes are supported by a reported strong inverse correlation between observed chlorophyll concentrations and water depth, in the Southern Ocean (Comiso et al., 1993; Sullivan et al., 1993; Moore and Abbott, 2000; Tyrrell et al., 2005). This inverse correlation indicates that productivity, and thus likely export production and iron fluxes, are greater in shallow waters. It is important to note that multiple overlapping iron sources may exist in near shore regions, including among others shelf sediments, surface runoff, glacial meltwater streams, and dust inputs (Boyd and Ellwood, 2010).

Fronts in the Southern Ocean have long been associated with regions of high productivity (Moore et al., 1999). It is becoming increasingly apparent that fronts, or ocean currents, can transport iron thousands of kilometres into the open ocean from iron sources upon continental shelves (De Baar et al., 1995; Planquette et al., 2007; Boyd and Ellwood, 2010; Boyd et al., 2012a; De Jong et al., 2012; Whitehouse et al., 2012; Measures et al., 2013; Klunder et al., 2014). However, high productivity at fronts in the open ocean is commonly attributed to the upwelling of nutrient enriched deep waters, rather than the horizontal advection of iron (Read et al., 2000; Measures and Vink, 2001; Moore and Abbott, 2002; Romero et al., 2006; Sokolov and Rintoul, 2007b; Boyd and Ellwood, 2010; Boyd et al., 2012a; Rosso et al., 2014). The strong currents associated with ocean fronts generate intense upwelling where these fronts cross over rough bottom topography and mid ocean ridges (Sokolov and Rintoul, 2007b; Rosso et al., 2014). This upwelling is believed to be strong enough to deliver large quantities of dissolved iron to the ocean surface, from deep sources such as hydrothermal vents (Sokolov and Rintoul, 2007b; Klunder et al., 2011; Rosso et al., 2014). Recent studies have also highlighted the important role of eddies that are shed from ocean fronts in re-stratifying the water column, as these eddies are able to shoal the nutricline and relieve light limitation (Mahadevan et al., 2012; Swart et al., 2014).

Many gaps remain in our understanding of the iron cycle. Understanding the large scale and long term spatial patterns of iron sources and supply mechanisms in the Southern Ocean poses a huge challenge. The number of in-situ iron measurements available from over the Global Ocean is rapidly increasing, thanks to the efforts made by research programs such as GEOTRACES (Klunder et al., 2011, 2014; Tagliabue et al., 2012). However, obtaining iron measurements from the Southern Ocean remains a difficult, expensive and time consuming task. Therefore, until recently, in-situ iron measurements from the Southern Ocean have been somewhat limited. The challenge of understanding the large-scale sources and supply mechanisms of iron is further complicated by the vast size of the Southern Ocean and eddying circulation. The residence time of iron in surface waters is thought to be relatively short, on the order of only weeks to months and newly available iron in surface waters may be quickly utilised by biota, or scavenged from the water column (Gerringa et al., 2012; Van der Merwe et al., 2015). It is also widely recognised that many supply mechanisms of iron are highly episodic (Boyd et al., 2004). Consequently, in-situ measurements of dissolved iron from surface waters may not be indicative of the mean state (Croot et al., 2004; Bergquist and Boyle, 2006; Boyd and Ellwood, 2010; Chever et al., 2010; Ellwood et al., 2014; Van der Merwe et al., 2015). However, iron concentrations in deeper waters (200–6000 m) are thought to