Deep-Sea Research I 104 (2015) 9–25

Contents lists available at ScienceDirect

Deep-Sea Research I

journal homepage: www.elsevier.com/locate/dsri

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*

ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form
21 May 2015
Accepted 22 May 2015
Available online 9 June 2015

Keywords:
chlorophyll
shelf sediments
upwelling
ocean fronts
sea surface height
dust
glacial-interglacial cycles

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

* 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).

http://dx.doi.org/10.1016/j.dsr.2015.05.007
0967-0637/

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 be more stable.

The wide spatial coverage and high temporal resolution of satellite data offer several major advantages over in-situ measurements. Recent studies have used satellite chlorophyll data to infer and map the mean annual level of iron utilisation in the Southern Ocean, and also the degree of iron stress (Boyd et al., 2012a; Browning et al., 2014). Here, we exploit the assumed response of chlorophyll growth to iron supply (Coale et al., 1996; Cooper et al., 1996; Boyd et al., 2007; Klunder et al. .2011), to infer potential source regions of iron in the Southern Ocean from satellite chlorophyll data. The data we use and the limitations of our method are discussed in Section 2. In Section 3, we explore the relationship between satellite chlorophyll concentrations and ocean depth, to improve our understanding of the spatial distribution of the shelf sediment iron flux. From our analyses, we conclude that large shelf sediment iron fluxes only exist near coastal margins. Next, in Section 4, we explore the relationship between satellite chlorophyll concentrations and ocean fronts, to investigate the mechanisms of iron supply at ocean fronts. It is concluded that upwelling does not stimulate mean annual chlorophyll blooms at fronts in the open ocean, and is therefore unlikely to deliver iron to the ocean surface from the deep ocean. Instead, chlorophyll blooms at ocean fronts are primarily due to the horizontal advection of iron downstream from source regions around continental and island coastlines. In Section 5 we describe chlorophyll concentrations near the Antarctic Coastline. Finally, in Section 6, we discuss the relevance of our results to the glacial iron hypothesis. We suggest that an increased importance of coastal iron sources, due to lower sea levels, may be an important contributor to enhanced export production in the Sub-Antarctic Zone during glacial intervals.

2. Data and methods

Chlorophyll is a green pigment found in plants and algae that is used in photosynthesis. There are two types of chlorophyll, chlorophyll-a and chlorophyll-b. Chlorophyll-a is the primary photosynthetic pigment for phytoplankton (Yoder and Kennelly, 2003). In this study we use chlorophyll-a concentrations derived from ocean colour data, measured with the NASA Sea-viewing Wide Field-of-view-Sensor (SeaWiFS). The data we use are the 9 km resolution annual mean chlorophyll-a concentration between 1999 and 2009. These data are available from the NASA Ocean Colour website (http://oceandata.sci.gsfc.nasa.gov/SeaWiFS/Mapped/Annual/9km/chlor/). Since large areas of the Southern Ocean are iron limited, we assume that chlorophyll blooms develop at the location of major iron sources for the ocean surface (Boyd et al., 2004), and identify likely source regions of iron as local maxima in chlorophyll concentrations.

To assess the likely level of iron limitation in different regions of the Southern Ocean, we look at mean annual surface concentrations of macronutrients (nitrates, phosphates and silicates) from the World Ocean Atlas (Fig. 1).

To investigate the relationship between the shelf sediment iron flux and ocean depth, we compare the distribution of chlorophyll blooms to bathymetric data (Smith and Sandwell, 1997). Our initial analyses indicate that chlorophyll concentrations are more dependent on proximity to coastline than ocean depth. To investigate this further, we plot chlorophyll concentration vs ocean depth, and chlorophyll concentration vs distance from coastline. The distances from coastline were calculated by the NASA Goddard Space Flight Centre, and are available on their website (http://oos.soest.hawaii.edu/pacioos/metadata/dist2coast_1deg_ocean.html).

To improve our understanding of the role of horizontal advection for transporting iron to remote regions of the Southern Ocean, we deduce surface currents from the sea surface height

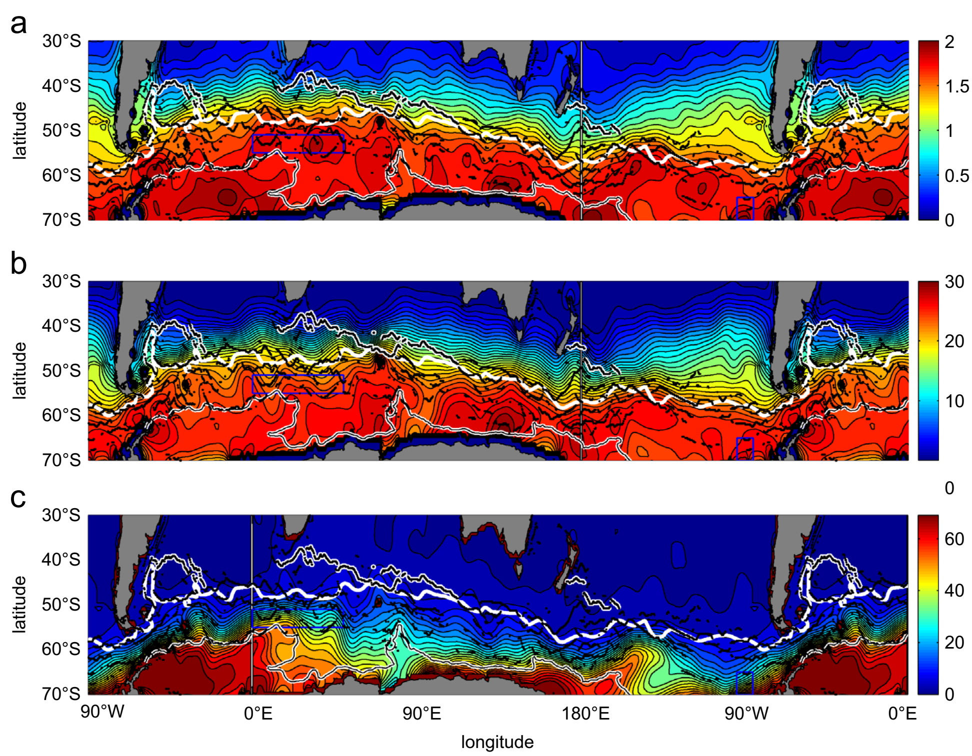

Fig. 1. Surface (a) phosphate (b) nitrate and (c) silicate concentrations (mmol m^{-3}), from the World Ocean Atlas 2009 (corresponding to samples taken from 0 to 9 m). Blue boxes indicate areas shown in Fig. 5. Black dots show the mean annual location of sea surface height fronts (Graham and De Boer, 2013). From North to South, the white lines are: the Dynamical Subtropical Front (*Graham and De Boer,* 2013), the Sub-Antarctic Front (Orsi et al., 1995), and the Antarctic gyre boundaries – approximated by the 0 °C isotherm at 200 m depth using HiGEM model output.

field and compare these to chlorophyll concentrations. The horizontal ocean circulation in the upper level of the Southern Ocean is approximately parallel to sea surface height contours (Sokolov and Rintoul, 2007a). More tightly packed sea surface height contours are indicative of faster velocities. The sea surface height dataset used here is the AVISO Up-To-Date Delay Time Merged Global Mean Absolute Dynamic Topography product. We average the data between 1999 and 2009, to be consistent with the chlorophyll data. The resolution of these data is $1/3°$ latitude $\times$ $1/3°$ longitude.

To further assess the role of the ocean circulation in transporting iron away from source regions upon the continental shelves, we calculate forward trajectories of virtual particles released from the South American and New Zealand coastlines. The particle tracking code we use is the Connectivity Modelling System v1.1 (Paris et al., 2013). The particles are released every seven days from 1999 to 2009, at the ocean surface, on a regular $0.5°$ latitude $\times$ $0.5°$ longitude grid. The virtual particles are advected forward in time using weekly averaged surface velocities derived from the AVISO sea surface height data (1999–2009), for a period of 90 days. The 90 days tracking interval is consistent with an estimated residence time for particulate iron derived from dust, in Sub-Antarctic waters east of New Zealand, which is on the order of 100 days (Frew et al., 2006). In order to account for some of the sub-mesoscale diffusion not captured in the AVISO data, an additional random-walk diffusivity of 100 m^2/s is added to the velocity fields (Van Sebille et al., 2015).

To assess whether chlorophyll concentrations are enhanced in frontal regions, we compare chlorophyll concentrations to the mean annual positions of ocean fronts for the period 1999-2009. The fronts we use correspond to the mean location of strong currents as identified by local maxima in sea surface height gradients (Graham and De Boer, 2013).

To determine whether chlorophyll concentrations are enhanced in response to topographically-induced upwelling of iron, where fronts pass over mid-ocean ridges, we compare the location of chlorophyll blooms to vertical velocities from the UK Met Office's High Resolution Global Environment Model (HiGEM) (Roberts et al., 2009; Shaffrey et al., 2009). We take a 30 year average of the mean annual upwelling velocities (years 71–100, from a 100 year control simulation), and average these over the top 650 m of the ocean. A recent very-high resolution ($1/80°$) regional modelling study from the Kerguelen Plateau indicates that the magnitude of the vertical velocities from HiGEM ($1/3°$) are likely to be underestimated (Rosso et al., 2014). Nonetheless, data-model inter-comparisons have shown that HiGEM captures the location of fronts well in the Southern Ocean (Graham et al., 2012; De Boer et al., 2013). We are therefore confident that the spatial pattern of topographically induced upwelling at fronts is reasonable. We also compare mean annual chlorophyll concentrations to mixed layer depths from the HiGEM model output.

2.1. Limitations of methods

We make the assumption in this study that surface waters in the Southern Ocean are iron limited. Thus, we assume that any chlorophyll bloom in the Southern Ocean is a direct response to an input of iron to the ocean surface. However, this assumption is only partly true, because productivity may be co-limited by factors other than iron in certain areas of the Southern Ocean.

Silicate concentrations decrease rapidly north of the Polar Front (Fig. 1c). Low silicate concentrations north of the Polar Front may limit productivity, and in particular the growth of diatoms, which are important contributors to net productivity as well as nutrient and carbon cycling in the Southern Ocean (Tripathy et al., 2015). North of the Sub-Antarctic Front, concentrations of all three macronutrients (nitrate, phosphate and silicate) decrease rapidly and may become limiting (Fig. 1). This means that, in theory, chlorophyll blooms in the Sub-Antarctic Zone may develop in response to an input of macro-nutrients, rather than iron. However, chlorophyll blooms in the Sub-Antarctic Zone still require a source of iron. Furthermore, several studies have demonstrated iron limitation in the Sub-Antarctic Zone, between the Subtropical and Sub-Antarctic Fronts, and shown that the addition of iron to these waters increases productivity and chlorophyll concentrations (Bowie et al., 2009; Mongin et al., 2011; Boyd et al., 2012b). In the subtropical gyres, north of the Subtropical Front, concentrations of all three macro-nutrients are very low (Fig. 1). Phosphate, rather than iron, is the main limiting nutrient in the subtropical gyres.

South of the Sub-Antarctic Front, iron is the limiting nutrient at the ocean surface (Martin, 1990). However, light can also limit productivity over large areas of the Southern Ocean. This may, for example, be due to long nights during winter months, or extensive sea-ice cover close to Antarctica. By using mean annual chlorophyll data, these seasonal effects of light limitation should be averaged out. However, deep mixed layers within the Antarctic Circumpolar Current and mode water formation areas may extend below the euphotic zone and thus lead to light limitation. Light limitation might help to explain why mean annual chlorophyll concentrations in the Southern Ocean are higher in regions where model mixed layer depths are shallower, and we would expect light levels in the surface layer to be higher (Fig. 2).

Subsurface chlorophyll maxima exist in certain regions of the Southern Ocean (Parslow et al., 2001; Bowie et al., 2011; Tripathy et al., 2015). Thus, an input of iron may in theory trigger a chlorophyll bloom below the surface that cannot be detected by satellites. Subsurface chlorophyll maxima are most commonly observed in stratified waters with shallow mixed layers (Ardyna et al., 2013; Cullen, 2015). These features typically occur in summer months, after spring blooms have exhausted nutrients at the surface. Studies from the Arctic Ocean have shown that using mean annual satellite chlorophyll data, as we do here, averages out the seasonal effects of subsurface chlorophyll blooms (Ardyna et al., 2013). Annual averaging also reduces biases due to problems such as cloud cover and sea ice (Geibert et al., 2010). We find that mean annual satellite measured chlorophyll concentrations are generally higher in regions of the Southern Ocean where mixed layer depths are shallow and subsurface chlorophyll blooms, obscured from satellite view, are most likely to exist (Fig. 2).

In most of the open ocean the Inherent Optical Properties of the water are dominated by phytoplankton. These regions are defined as Case I or blue waters. In contrast, the Inherent Optical Properties of many coastal regions and inland waters are influenced by dissolved organic matter and inorganic mineral particles, as well as by phytoplankton (Matsushita et al., 2012). These waters are known as Case II or green waters. As a result of these differences, separate algorithms are used to calculate chlorophyll concentrations from ocean colour data in Case I and Case II waters (Morel and Prieur, 1977; Matsushita et al., 2012). This factor should be taken into consideration when interpreting our results.

It should also be noted that different plankton functional types (e.g. coccolithophores and diatoms) have different nutrient requirements (Hashioka et al., 2013). This means that different types of phytoplankton will require different quantities of iron to produce the same amount of carbon (Boyd et al., 2012a). Therefore chlorophyll concentrations should not be interpreted as a direct indication of biomass or the magnitude of an iron source.

Despite the limitations of satellite data, the high spatial resolution can provide many advantages over in-situ measurements (Boyd et al., 2012a; Browning et al., 2014; Carranza and Gille, 2014; Gille et al., 2014). Satellite data offer a unique opportunity to identify large-scale patterns in the ocean, and can be used as a tool

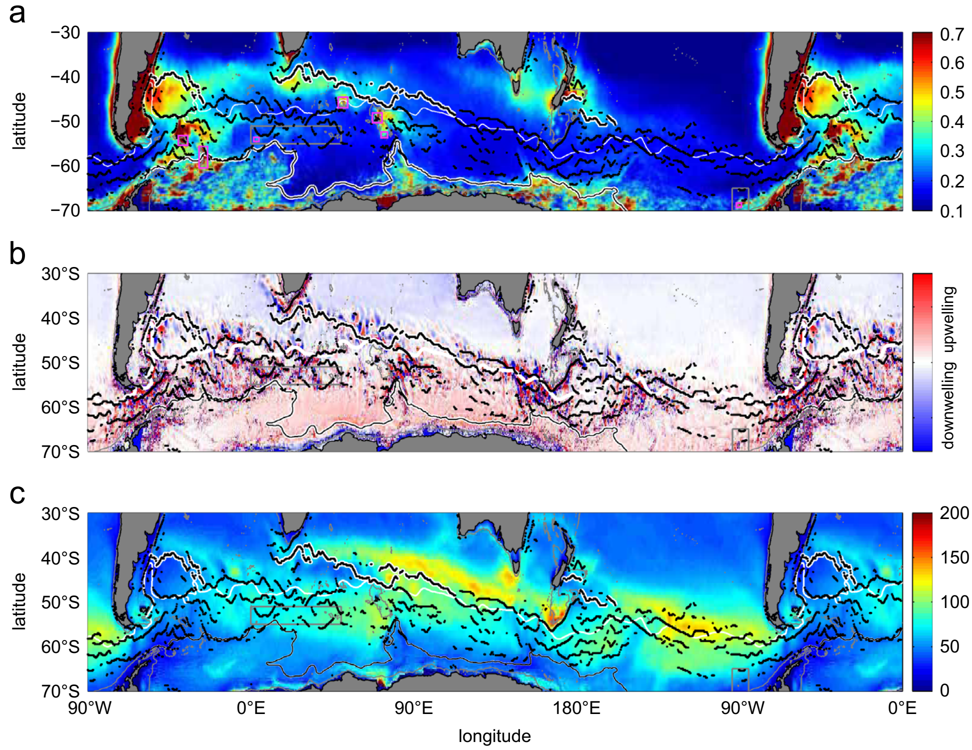

Fig. 2. Mean annual near surface chlorophyll-a concentrations for the years 1999–2009 (mg m^{-3}, colour scale). The Location of sea surface height fronts, indicative of strong currents, are shown by the black dots (Graham and De Boer, 2013). From North to South, the white lines are: the Dynamical Subtropical Front (Graham and De Boer, 2013), the Sub-Antarctic Front (Orsi et al., 1995), and the Antarctic Gyre Boundaries – approximated by the 0 °C isotherm at 200 m depth using HiGEM model output. Grey contours are the 1000 m isobaths. Pink boxes highlight the location of some islands south of the Sub-Antarctic Front. Grey boxes indicate the areas shown in Fig. 5. DP=Drake Passage, CP=Campbell Plateau. Mean annual upwelling velocity averaged over years 71–100 of a control simulation with HiGEM. Velocities are averaged between the surface and 650 m depth. Mean annual mixed layer depths (m) averaged over years 71–100 of a control simulation with HiGEM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to guide future in-situ measurements (d'Ovidio et al., 2015).

3. Chlorophyll concentrations over shallow topography

3.1. Enhanced chlorophyll concentrations in coastal regions

Mean annual chlorophyll concentrations are elevated over continental shelves compared with open ocean locations (Figs. 2a and 3b). The widest continental shelf bordering the Southern Ocean is the South American Shelf, and we shall focus initially on this area. Satellite derived chlorophyll concentrations are not uniformly high over the South American Shelf, but elevated around coastal margins (Fig. 3a). In particular, chlorophyll concentrations are very high around major river outlets such as the Rio de la Plata. Chlorophyll blooms can be seen extending north eastwards from the South American coastline towards the edge of the continental shelf.

In most instances, chlorophyll concentrations decrease with distance from the coastline. However, the ocean circulation clearly plays an important role. For example, a long and intense chlorophyll bloom extends northwards from the Falkland Islands (Fig. 3a). This bloom is comprised of coccolithopores and is the highest reflectance region, as seen by satellites, in the Great Calcite Belt of the Southern Ocean (Balch et al., 2014). The bloom closely follows the sea surface height contours, which indicate the direction of the ocean circulation. The presence of the Falkland bloom has previously been attributed to shelf break upwelling (Saraceno et al., 2005). However, similar blooms are absent in comparable dynamic settings, such as the south-eastern edge of the Campbell Plateau (Fig. 4b). The Falkland bloom is also absent south (upstream) of the Falkland Islands, while immediately north of the Falkland Islands the bloom is in fact not located on the shelf break but rather slightly to the west of it (Fig. 3a). In-situ measurements have also shown that the bloom is most intense immediately northeast (upstream) of the Falkland Islands (Balch et al., 2014).

Chlorophyll concentrations are low over areas of continental shelf that are isolated from any land mass. For example, east of the southern tip of South America and south of the Falkland Islands, there is a large plateau (60°W, 54°S). This plateau is separated from the main continental shelf by a small channel with a depth of ~400 m (Fig. 3b). At the centre of the plateau, the ocean depth is as little as 5 m, which is shallower than the main continental shelf connecting South America and the Falkland Islands. Chlorophyll concentrations are enhanced locally at the centre of the plateau where the water depths are shallowest (Fig. 3b). However, there is a sharp contrast between the very high chlorophyll concentrations on the main continental shelf and the low concentrations on this shallow plateau (Fig. 3b).

Prominent chlorophyll blooms are observed downstream of many islands in the Southern Ocean (Fig. 2a). Large chlorophyll blooms even develop downstream of very small islands, with narrow shelves, such as Peter 1 and Bouvet Island (Fig. 5). These islands have land areas of 154 and 49 km^2 respectively. There are several seamounts in close proximity to Peter 1 and Bouvet Island, some of which extend to within 5 m of the ocean surface (Fig. 5). These bathymetric features have similar or larger shallow areas ($<$ 1000 m) compared with the shelves surrounding the islands. However, mean annual chlorophyll concentrations are not visibly enhanced over or downstream of these seamounts (Fig. 5).

To summarise, we observe that mean annual satellite

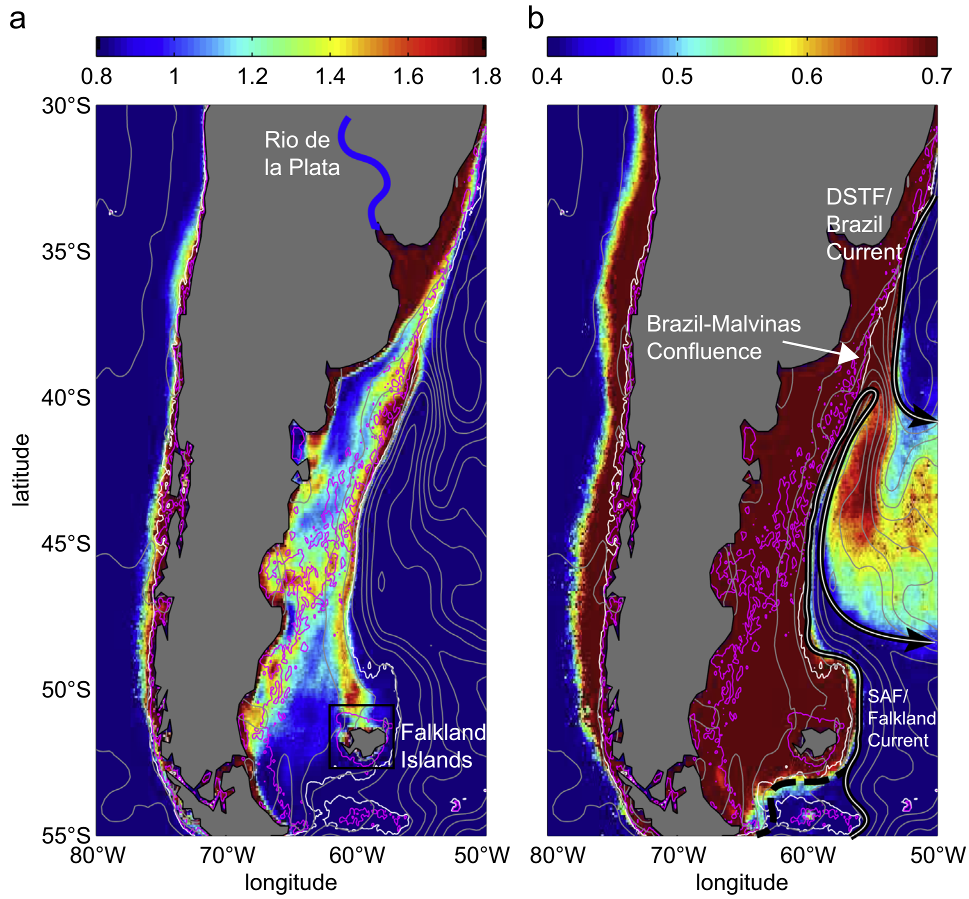

Fig. 3. Mean annual chlorophyll concentrations for years 1999–2009 (mg m^{-3}, colour scale). Grey contours are the sea surface height field for 1999-2009. White contours are the 400 m isobaths, and pink contours the 120 m isobaths. Panels (a) and (b) show the same data but with different colour scales for the chlorophyll concentrations. Black arrows illustrate the path of the western boundary currents, Sub-Antarctic Front and Dynamical Subtropical Front in (b). The location of the Rio de la Plata estuary is shown by the blue line in (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

chlorophyll concentrations are enhanced around coastal areas of both continental land-masses and islands. Similar chlorophyll blooms are not observed over, or downstream of, submerged seamounts and plateaus in close proximity to these features.

3.2. *Depth dependence vs proximity to land*

Several studies have reported a strong inverse correlation between chlorophyll concentrations and ocean depth in the Southern Ocean (Comiso et al., 1993; Sullivan et al., 1993; Moore and Abbott, 2000; Tyrrell et al., 2005). Here, we argue that high mean annual chlorophyll concentrations are more closely tied to coastal regions than areas of shallow bathymetry ($<$ 1000 m).

In the following analyses we exclude waters south of 60°S and north of 42°S (Fig. 6a). Chlorophyll concentrations south of 60°S are likely to be strongly influenced by sea ice cover and thus light limitation, while areas north of 42°S are limited by nitrate and phosphate (Fig. 1).

We first wish to consider all continental and island shelves in the Southern Ocean. Here, we take the chlorophyll concentrations from all points that are within 500 km of a coastline, and have a water depth shallower than 1000 m (Fig. 6a, pink lines indicate the 500 km radii from a coastline, and the 1000 m and 2000 m isobaths are shown in white). When chlorophyll is plotted as a function of distance from coastline, we can see that all extremely high chlorophyll concentrations (>3 mg m^{-3}) occur within 20 km of a coastline (Fig. 6b). Some of these chlorophyll values may be spurious, due to suspended non-organic particulate matter in the water column (Tyrrell et al., 2005). Chlorophyll concentrations between 2 and 3 mg m^{-3} are only found within 50 km of a coastline (Fig. 6b). Mean annual chlorophyll concentrations between 1 and 2 mg m^{-3} can be found anywhere up to 450 km from a coastline (Fig. 6b). On continental shelves, there is little evidence of any decrease in chlorophyll concentrations between 50 km to 450 km from a coastline. The high chlorophyll concentrations (>1 mg m^{-3}) within this range are primarily found within the Falkland Bloom, on the eastern edge of the South American Shelf (Fig. 6a).

When chlorophyll concentrations from continental and island shelves are plotted as a function of ocean depth, there is considerably more scatter compared with when chlorophyll is plotted as a function of distance from a coastline (Fig. 6b, c). Extremely high chlorophyll concentrations (>3 mg m^{-3}) are found in water depths up to 600 m, and mean annual chlorophyll concentrations >2 mg m^{-3} are found in depths up to 1000 m (Fig. 6c). There is a large cluster of chlorophyll concentrations between 1 and 2 mg m^{-3} in depths shallower than 200 m, corresponding largely to the high chlorophyll concentrations on the South American Shelf (Fig. 6a and c). These analyses demonstrate that mean annual satellite chlorophyll concentrations >2 mg m^{-3} in the Southern Ocean are more constrained by proximity to a coastline ($<$ 50 km from a coast), than by water depth (Fig. 6b, c).

We next investigate whether there is evidence of enhanced chlorophyll concentrations over areas of shallow bathymetry in the open ocean. Here, we consider chlorophyll concentrations in the 'open ocean', which we define as points located more than

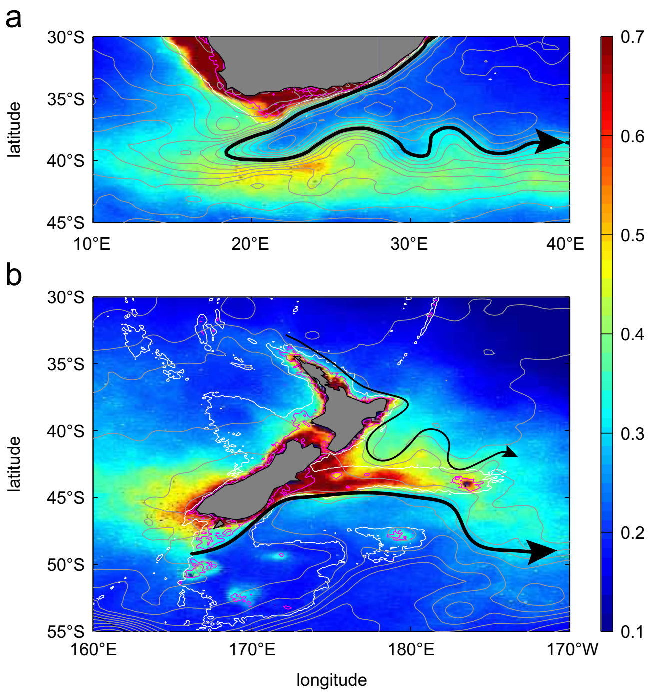

Fig. 4. Mean annual chlorophyll concentration for 1999–2009 (mg m^{-3}, colour scale). Grey contours are the sea surface height field for 1999–2009. White contours are the 1000 m isobaths, and pink the 200 m isobaths. Black arrows illustrate the path of the western boundary currents and Dynamical Subtropical Front: (a) South Africa and (b) New Zealand and the Campbell Plateau.

500 km from any coastline, and we define shallow bathymetry as water depths shallower than 2000 m (Fig. 6a, pink lines indicate the 500 km radii from a coastline, and the 1000 m and 2000 m isobaths are shown in white). We plot chlorophyll concentration both as a function of ocean depth and distance from coastline (Fig. 6d, e). The highest mean annual chlorophyll concentration at locations that are shallower than 2000 m but more than 500 km from a coastline is <0.8 mg m^{-3} (Fig. 6d). In contrast, mean annual chlorophyll concentrations exceed 10 mg m^{-3} on coastal shelves (Fig. 6b). Over submerged, shallow shelves of less than 200 m, mean annual chlorophyll concentrations do not exceed 0.27 mg m^{-3} (Fig. 6e). Chlorophyll concentrations >0.4 mg m^{-3} are only observed in regions where waters are deeper than 1200 m (Fig. 6e). In summary, we find no evidence that mean annual satellite chlorophyll concentrations in the Southern Ocean are enhanced over shallow bathymetric features (<1000 m) that are located more than 500 km from a coastline.

3.3. Implications for the shelf sediment iron flux

In many biogeochemical model parameterisations, the shelf sediment iron source is assumed to be large over all areas with bathymetry shallower than 1000 m (Moore et al., 2004; Aumont and Bopp, 2006; Lancelot et al., 2009; Boyd et al., 2012a; Borrione et al., 2014). If there were a large iron flux from these sediments, one would expect chlorophyll concentrations to be enhanced over all areas of shallow bathymetry, assuming the surface waters above are iron limited.

Our analyses show that annual mean satellite chlorophyll concentrations are not enhanced over any areas of shallow bathymetry located more than 500 km from a coastline in the Southern Ocean. Moreover, very high mean annual chlorophyll concentrations are only observed within 50 km of a coastline. Our interpretation of these results is that sediment layers on areas of shallow bathymetry that are isolated from coastal margins are unlikely to act as a large source of iron to the ocean. The shelf sediment iron flux is most likely to be located around coastal margins, rather than spread evenly across continental shelves.

It is possible that shelf sediments on isolated bathymetric features are acting as a source of iron to the ocean, but the iron is more rapidly dispersed compared with coastal regions. Therefore the iron does not reach the surface to imprint on the chlorophyll signal. However, this scenario seems unlikely given the fact that there was no evidence of enhanced chlorophyll concentrations over any isolated bathymetric features (Fig. 6).

We speculate that the reason for large iron fluxes in coastal regions may be that these shelves receive a large flux of terrestrial organic matter and continentally weathered material, from processes such as riverine transport, coastal erosion, and glacial debris (e.g. Chase et al., 2007). The high sedimentation rates along coastal margins, and input of terrestrial organic matter, may favour the establishment of anoxic conditions in these sediments, which would promote the reduction of iron oxide within the sediments and the release of dissolved iron to the overlying bottom waters (Raiswell and Canfield, 2012). In contrast, subsurface seamounts and other shallow bathymetric features in the open ocean are likely to have lower sedimentation rates and sediment scouring from ocean currents, as well as a lack of terrestrial organic material. These conditions are less favourable to promote anoxia in sediment layers.

While we believe that the most likely source of the coastal iron signal is a diffusive flux of dissolved iron from shelf sediments, the potential contribution from other sources of bioavailable iron to coastal regions must not be overlooked (Boyd and Ellwood, 2010). For example, sediment re-suspension on continental and island shelves may be a large source of particulate iron (Homoky et al.,

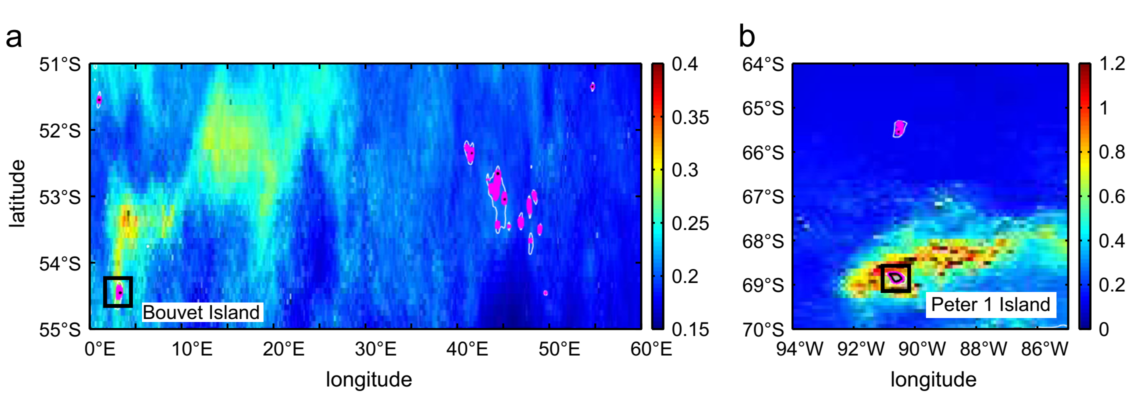

Fig. 5. Mean annual chlorophyll concentrations (mg m^{-3}, colour scale, note different scale between figures). White contours are the 1000 m isobaths. Pink contours are the 150 m isobaths, and black the 50 m isobaths. (a) Bouvet Island and (b) Peter 1 Island. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

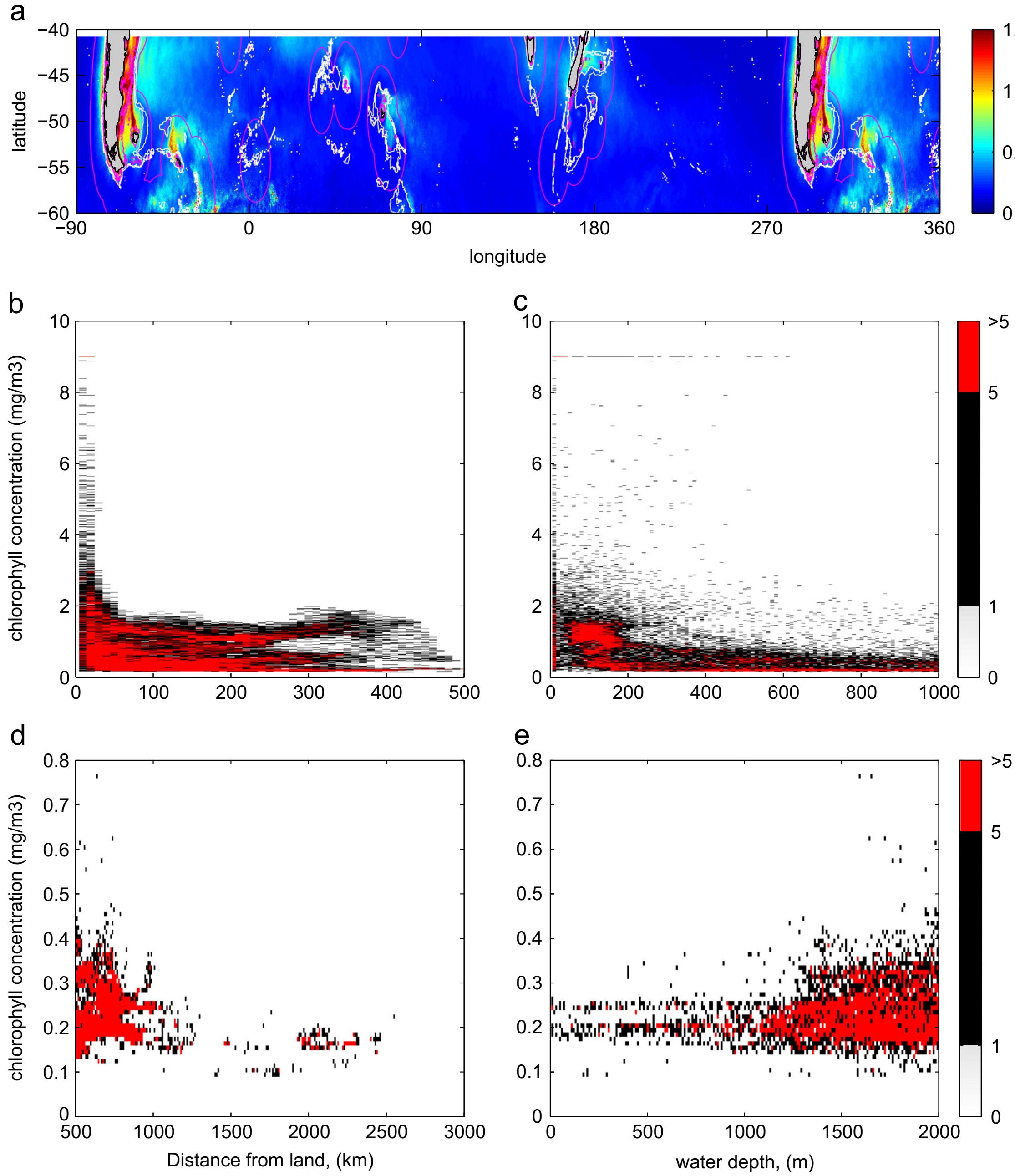

Fig. 6. Mean annual surface chlorophyll concentrations for the period 1999–2009 (mg m^{-3}, colour scale). White contours show the 1000 m and 2000 m isobaths. Pink circles show the 500 km radii from the nearest coastline, and pink contours show the 120 m isobaths. Chlorophyll concentrations plotted as a function of distance from coastline for all regions shallower than 1000 m and within 500 km of a coastline. Colours refer to the number of grid points satisfying criteria. Upper limit of chlorophyll concentrations was set to 9 mg m^{-3}. Chlorophyll concentrations plotted as a function of ocean depth for all regions shallower than 1000 m and within 500 km of a coastline (i.e. the same area as in (b). Chlorophyll concentrations plotted as a function of distance from coastline for all regions shallower than 2000 m and more than 500 km from a coastline. Chlorophyll concentrations plotted as a function of ocean depth for all regions shallower than 2000 m and more than 500 km from a coastline (i.e. the same area as in (d)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2013; Conway and John, 2014; Van der Merwe et al., 2015). Fluxes of iron from icebergs and sub-glacial melt water streams are likely to be important around Antarctica and glaciated islands in the Southern Ocean (Raiswell et al., 2008; Geibert et al., 2010; Gerringa et al., 2012; Death et al., 2013; Planquette et al., 2013). The outflow of rivers and boreal streams passing through peat land have been shown to be an important source of iron to the Arctic Ocean (*Kl*under et al., 2012; Krachler et al., 2012; Neubauer et al., 2013; Köhler et al., 2014), and may therefore be important around the Falkland Islands and high latitudes (south of 50°S) of South America (Fig. 4a). There is also thought to be a large flux of iron from ground-water discharge along the South American coastline (Windom et al., 2006). It is possible that multiple sources of iron influence different regions in the Southern Ocean, and the relative importance of these sources may change over the annual cycle (Boyd and Ellwood, 2010; Van der Merwe et al., 2015). When prescribing iron fluxes in biogeochemical models, and calculating iron budgets, care needs to be taken not to doubly account for these sources.

With the satellite data used in this study, we cannot confirm whether the largest iron fluxes are truly located in close proximity to coastal margins, or what the exact source(s) of these iron fluxes may be. To test these hypothesis, in-situ measurements are required to investigate how the shelf sediment iron flux varies over large continental shelves, like that of South America. To date, most in-situ measurements of the shelf sediment iron flux have focused on relatively narrow areas of continental shelf neighbouring coastlines, such as the Californian Shelf and a number of island shelves in the Southern Ocean (Johnson et al., 1999; Elrod et al., 2004; Chase et al., 2007; Planquette et al., 2007; Blain et al., 2008; Noffke et al., 2012; Homoky et al., 2013). Furthermore, new measurements are required to investigate whether large iron fluxes exist on isolated seamounts and submerged plateaus.

Following the results from our analyses, we recommend that depth dependent parameterisations for the shelf sediment iron flux, currently used in most biogeochemical models (e.g. Wadley et al., 2014), should be replaced by a large iron flux neighbouring coastal regions. This flux may be prescribed up to a fixed distance from the coastline, or alternatively between the coastline and specific isobaths. In support of this method, a recent high resolution modelling study by Borrione et al. (2014) was able to accurately simulate the chlorophyll bloom downstream of South Georgia by prescribing a shelf sediment iron flux between the coast and 5 m isobaths, rather than the more common criteria of all areas shallower than 1000 m.

We do not anticipate that the new shelf sediment iron parameterisation will have a major effect on modern-day simulations, compared with models using depth dependent parameterisations, because the largest expanses of shallow water (< 1000 m) in the ocean are located around coastal margins on continental shelves (Fig. 6a). Therefore, the location of the major shelf iron sources will not change. The main conclusions drawn from studies using depth dependent parameterisation schemes are thus likely to remain valid (Moore and Braucher, 2008; Tagliabue et al., 2009, 2014a; Wadley et al., 2014). However, depth dependent parameterisation schemes would likely result in spurious chlorophyll blooms developing downstream of isolated subsurface features, such as the Campbell Plateau and the seamounts nearby Peter 1 and Bouvet Island (Figs. 4 and 5). We anticipate that the most significant changes when using this new iron parameterisation scheme would be for simulations of past or future climates where sea level and/or the configurations of continental shelves are different from today (see Section 6).

4. The role of local upwelling vs horizontal advection of iron

4.1. Chlorophyll concentrations at fronts in the Southern Ocean.

We define ocean fronts here as strong narrow currents or jets (Graham and De Boer, 2013). Fronts act as barriers to mixing in the ocean (Naveira-Garabato et al., 2011), which means that water parcels and their associated nutrients, such as iron, cannot easily cross from one side of a front to another (Naveira Garabato et al., 2002). The locations of fronts are indicated by the black dots in Figs. 1 and 2, and black lines in Figs. 3, 4 and 7.

Mean annual chlorophyll concentrations are not visibly enhanced along fronts in remote regions of the Southern Ocean, such as the southeast Pacific (Fig. 2a). Chlorophyll concentrations are only elevated near ocean fronts where the upstream front has passed near an island or continental slope (Figs. 2a and 7). Chlorophyll concentrations are elevated along sea surface height contours passing around islands, and decrease gradually towards the east downstream of these islands (Fig. 7). High chlorophyll concentrations are found in the areas between islands and nearby ocean fronts. Close to islands, there are strong gradients in chlorophyll concentrations across fronts (Fig. 7). Chlorophyll concentrations are enhanced on the side of the fronts facing islands, and comparatively weaker on the opposite side of fronts. Further downstream of islands, chlorophyll concentrations peak near the core of ocean fronts (Fig. 7).

Topographically induced upwelling occurs throughout the water column where ocean fronts pass over mid ocean ridges and seamounts (Sokolov and Rintoul, 2007b). The largest vertical velocities associated with topographically induced upwelling in the model output from HiGEM are located at Drake Passage (60°W),

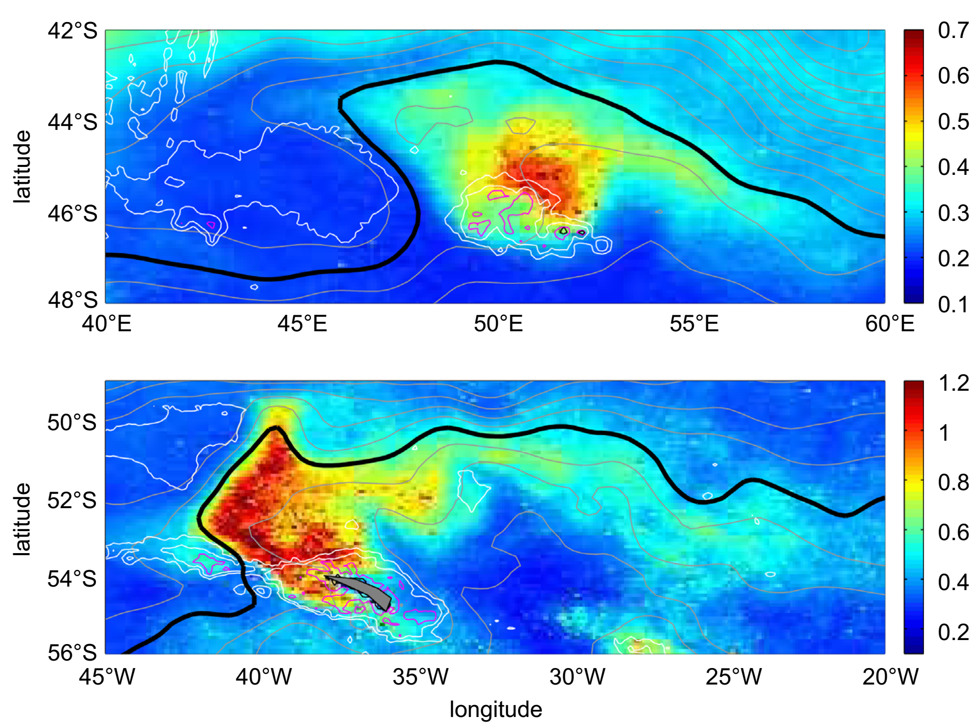

Fig. 7. Mean annual chlorophyll concentration for 1999–2009 (mg m^{-3}, colour scale, note the different scales). Grey contours are the sea surface height field for 1999–2009. Black sea surface height contours approximate the location of ocean fronts (which are related to strong currents) in these regions. White contours are the 2000 m and 1000 m isobaths. Pink contours are the 100 m isobaths, and black the 0 m isobaths. (a) The Crozet Islands and (b) South Georgia.

and around the southern edge of the Campbell Plateau (170°E) (Fig. 2b). Mean annual chlorophyll concentrations are very low in these regions (Fig. 2a, b). Thus, there is little evidence to suggest that mean annual chlorophyll concentrations are enhanced as a result of topographically induced upwelling at fronts, in remote and deep regions of the Southern Ocean.

Western boundary currents run parallel to the edge of continental shelves on the western side of each sector of the Southern Ocean (i.e. along the eastern coastlines of continents). These currents can extend to more than 2000 m depth in the ocean (*Graham and De Boer,* 2013). Sharp gradients in chlorophyll concentrations exist across these boundary currents (Figs. 3b and 4). There is no boundary current running parallel to the shelf break on the west coast of South America. Here, high chlorophyll concentrations extend several hundred kilometres off the continental shelf and into the open ocean (Fig. 3b). As with fronts passing around islands in the open ocean, chlorophyll concentrations are consistently enhanced on the side of boundary currents facing the continental coastlines, and are comparatively weaker on the open ocean side (Figs. 3b and 4).

The western boundary currents in the Atlantic, Indian and Pacific Sectors of the Southern Ocean detach from the continental shelves at approximately 40°S, and turn eastwards into the open ocean (Fig. 2). In the Tasman Sea, the East Australian Current detaches early at approximately 31°S. The eastward extensions of these currents are called the Dynamical Subtropical Front (Graham and De Boer, 2013). Large mean annual chlorophyll blooms extend eastwards into the Southern Ocean along the Dynamical Subtropical Front (Figs. 2–4). Chlorophyll concentrations are enhanced on the side of the Dynamical Subtropical Front that was previously facing the continental coastline, and are comparatively weaker on the opposite side of the front (Figs. 3b and 4). These areas of enhanced chlorophyll concentrations are confined to a relatively narrow range of sea surface height, and chlorophyll concentrations decrease gradually with increasing distance from the continental coastlines (Figs. 3b and 4).

In the Atlantic Sector of the Southern Ocean, two western boundary currents flow along the eastern South American continental shelf (Fig. 3b). Flowing northward along the shelf break from the southern tip of South America is the Falkland Current, or Sub-Antarctic Front, and to the north there is the southward flowing Brazil Current. These two currents meet at the Brazil-Malvinas Confluence (~40°S), and turn eastwards into the Southern Ocean. The chlorophyll bloom in the South Atlantic Sub-Antarctic Zone originates exactly from this narrow choke point (Fig. 3b). Chlorophyll concentrations are enhanced along sea surface height contours extending off the shelf. The bloom fills the entire Sub-Antarctic Zone between the Dynamical Subtropical Front to the north and Sub-Antarctic Front to the south (Figs. 2a and 3b). Chlorophyll concentrations decrease rapidly across both these fronts.

Care should be taken when interpreting these results. In particular, consideration should be given to the fact that separate algorithms are likely used for deriving the chlorophyll concentrations in coastal and open water areas (Matsushita et al., 2012). Therefore the magnitude of gradients in chlorophyll concentrations across continental shelf breaks should be treated with caution. Nonetheless, the close correspondence of chlorophyll concentrations and the sea surface height field, from two independent data sets, indicates that the patterns we see are likely to be real. In-situ measurements from the South American Shelf also confirm the existence of phytoplankton blooms in the regions with high chlorophyll concentrations seen with satellite data (Balch et al., 2014).

These qualitative analyses show that the synoptic scale mean annual satellite chlorophyll concentrations in the Southern Ocean can be explained to a larger extent by horizontal advection along ocean fronts, than topographically induced upwelling at fronts.

4.2. Where do shelf waters go?

It has been shown that particulate and dissolved iron from continental shelves is entrained into western boundary currents and advected into the Sub-Antarctic Zone along the Dynamical Subtropical Front (*Bowie et al., 2009; Boyd et al., 2012b; Rijkenberg et al.,* 2014). To further investigate this mechanism, we calculate the trajectories of virtual particles released at the ocean surface from the eastern coastline of South America, and the New Zealand coastline. (Recall, in Section 3 we inferred that the largest iron sources on continental shelves are likely to be located along coastal margins.) These virtual particles are advected forward in time for 90 days, using weekly surface velocities calculated from AVISO sea surface height data. The trajectories of these virtual particles should indicate the regions of the ocean that one might expect to be subjected to natural iron fertilisation, from shelf sediment iron advected by western boundary currents and their extensions. If surface waters in these areas are iron limited, one would expect to observe higher chlorophyll concentrations along the paths of the virtual particles.

The trajectories of the virtual particles released along these coastlines show some strong similarities with the mean annual chlorophyll concentrations around the Campbell Plateau and South America (Fig. 8). For example, the highest chlorophyll concentrations and densities of trajectories are in coastal regions. On the Campbell Plateau, chlorophyll concentrations are enhanced along the southern edge of Chatham Rise, and there is a high density of virtual particles here (Fig. 8a, b). Similarly, the virtual particles follow the large meander of the current north of Chatham Rise, and chlorophyll concentrations are enhanced here, too. On the South American Shelf there is a high density of trajectories north of the Falkland Islands, which is reminiscent of the Falkland chlorophyll bloom (Fig. 8c, d). However, unlike the Falkland Bloom, the virtual particle trajectories do not extend far enough north from the Falkland Island to reach the Brazil-Malvinas Confluence. As a result, the virtual particles are not advected into the Sub-Antarctic Zone along the Sub-Antarctic Front. Therefore the plume of virtual particles in the South Atlantic Sub-Antarctic Zone is displaced north of the chlorophyll bloom (Fig. 8c, d). This may be either because we were tracking the virtual particles for too short a time period, or because the satellite sea surface height data used to advect the virtual particles is too coarse, and not well resolved on the continental shelf (i.e. the currents are too broad and velocities too slow). It is also possible that the large input of organic matter into the sediments beneath the Falkland Bloom generates anoxic conditions in the sediments. This would result in a flux of dissolved iron from the sediments and stimulate more productivity, thus triggering a positive feedback, which we do not account for here.

One important caveat of these analyses is that we are using surface velocities from satellite altimetry. We do not use three dimensional velocity fields, and so do not explicitly consider the possible uplift of sediments from the lower continental shelf. However, our earlier analyses of the satellite chlorophyll data in Section 3 indicated that this contribution was likely small.

The results from these analyses provide support for the hypothesis that chlorophyll blooms in the Sub-Antarctic Zone are stimulated by the horizontal advection of iron rich shelf waters, along western boundary currents and the Dynamical Subtropical Front (Bowie et al., 2009; Boyd et al., 2012b; Rijkenberg et al., 2014).

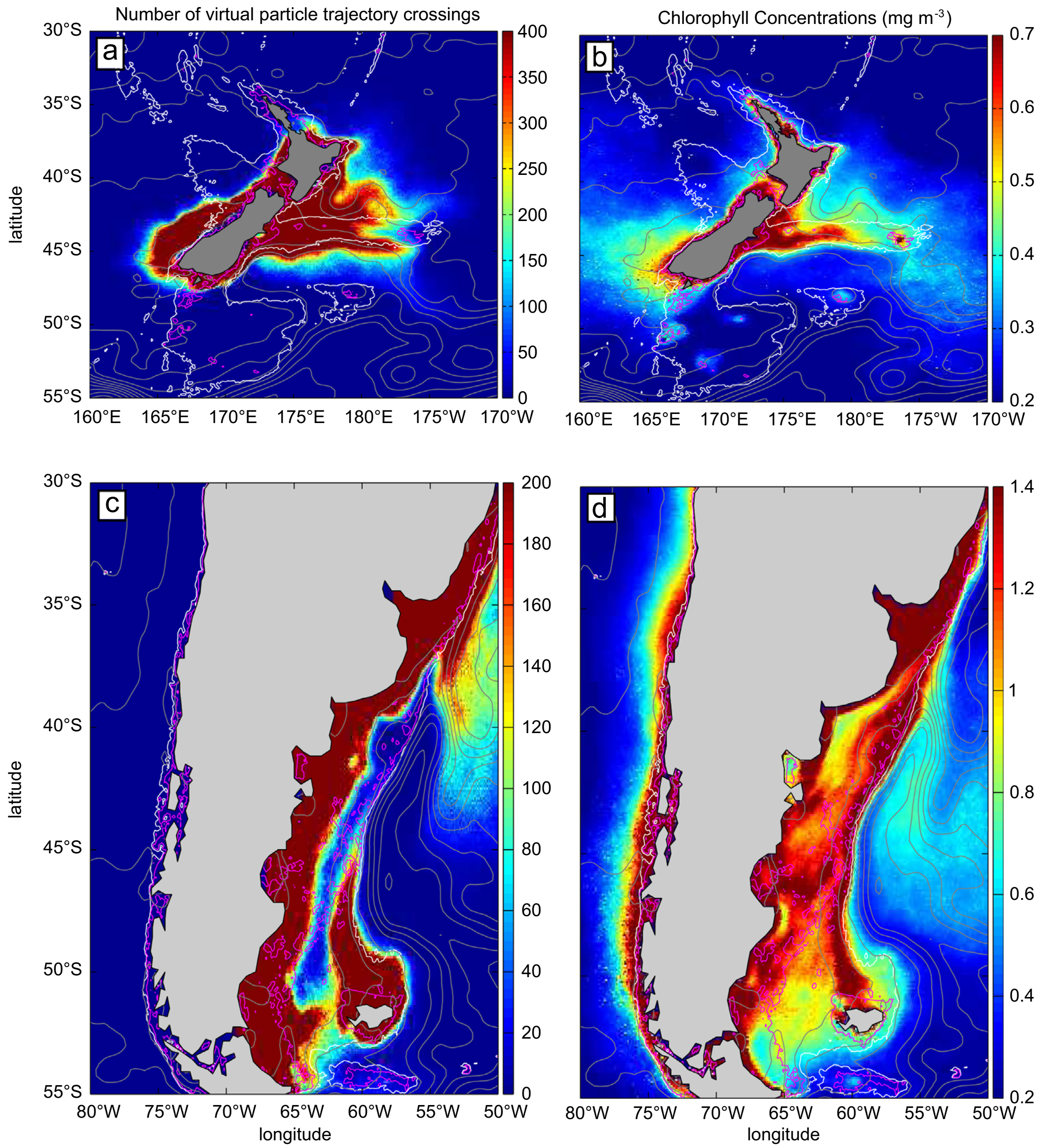

Fig. 8. (a) The number of virtual trajectories crossing each grid point, for virtual particles released from the New Zealand coastline. (b) Mean annual chlorophyll concentrations around New Zealand for 1999–2009 (mg m^{-3}). (C) The number of virtual trajectories crossing each grid point, for virtual particles released from the eastern South American coastline. (d) Mean annual chlorophyll concentrations around South America for 1999–2009 (mg m^{-3}). Grey contours show the mean annual sea surface height field for the period 1999–2009. White contours show the 1000 m isobaths. Pink contours are the 120 m isobaths.

4.3. *The role of ocean fronts in iron supply to the Southern Ocean*

The results from our analyses indicate that the primary mechanism of iron supply at ocean fronts is through the horizontal advection of iron from sources associated with coastal regions, rather than the upwelling of iron from deep sources, such as hydrothermal vents. In particular, we hypothesise that western boundary currents entrain iron from the continental shelf and advect this iron into the Sub-Antarctic Zone along the Dynamical Subtropical Front. In support of this hypothesis, in-situ iron measurements from the Atlantic, North Pacific and Tasman Sea reveal high concentrations of iron on the pole-ward edge of the western boundary current extensions, corresponding to the Brazil Current, North Atlantic Current, Kuroshio Current and the East Australia Current (Lam et al., 2006; Nishioka et al., 2007, 2011; Bowie et al., 2009; Rijkenberg et al., 2014; Schlosser et al., in preparation). Similarly, large fluxes of iron downstream of the Kerguelen and Crozet Islands have been attributed to the lateral advection of shelf sediment iron by ocean fronts (Blain et al., 2007, 2008; Planquette et al., 2007; Chever et al., 2010; Sanial et al., 2014; Van der Merwe et al., 2015). The source of this iron is thought to be from sediment re-suspension as fronts traverse continental and island shelves, as well as continentally weathered material entering coastal regions through surface runoff (Van der Merwe et al., 2015). Likewise, many studies from the Weddell Sea and downstream of the Antarctic Peninsula have revealed large horizontal fluxes of iron off the Antarctic shelf and shelves of the surrounding islands (Ardelan et al., 2010; Boyd et al., 2012a; De Jong et al., 2012; Whitehouse et al., 2012; Frants et al., 2013; Measures et al., 2013; Klunder et al., 2014). In particular, an exponential decrease in iron concentrations within the upper 200 m of the ocean was measured 3000 km downstream from the Antarctic Peninsula (De Jong et al., 2012). Thus, there is strong observational evidence that western boundary currents and ocean fronts are crucial mechanisms for advecting iron long distances into the open ocean, from coastal shelf regions.

While our results suggest that upwelling at fronts in the open Southern Ocean does not deliver iron to the surface from deep sources, such as hydrothermal vents, processes such as deep winter mixing, Ekman pumping, wind driven mixing, and upwelling at ocean fronts, are likely to be crucial for the seasonal and intra-seasonal timing of chlorophyll blooms (Swart et al., 2012, 2014; Carranza and Gille, 2014; Gille et al., 2014; Tagliabue et al., 2014a). These processes are likely to be important for relieving light limitation, and may also deliver iron to the ocean from intermediate depths (Swart et al., 2012, 2014; Carranza and Gille, 2014; Gille et al., 2014; Tagliabue et al., 2014a). However, it is important to note that the distribution of the sub-surface iron reservoir at intermediate depths (i.e. below the ferocline) is unlikely to be spatially uniform. Instead, the spatial distribution of iron at depth is most likely controlled by the horizontal advection of iron from coastal source regions (Van der Merwe et al., 2015).

With the satellite data used in this study, we cannot determine the form of iron transported by ocean fronts. One of the major unanswered questions from this study is how iron can remain in the upper ocean and sustain productivity across entire sectors of the Southern Ocean. It is unclear whether this is due to intense biological recycling of dissolved iron from shelf sediments, long range transport of particulate iron, or some other process. Further in-situ iron measurements are required to explore these processes further. Data collected during the GEOTRACES and KEOPS-II programs should help to answer these questions (Conway and John, 2014; Rijkenberg et al., 2014; Van der Merwe et al., 2015; Schlosser et al., in preparation).

5. Chlorophyll concentrations near the Antarctic coastline

Mean annual satellite chlorophyll concentrations are generally higher within the gyre systems adjacent to the Antarctic coastline compared with the open ocean (Fig. 2a, gyre boundary is approximated with the southernmost black and white line). The largest of these gyres are the Ross and Weddell Gyres. A striking feature of these chlorophyll blooms is how well the ocean gyres constrain their extent. Chlorophyll concentrations within the gyres are extremely patchy, with small localised areas of very high concentrations and patches of low concentrations (Fig. 2a). The patches of high chlorophyll concentrations may be related to the opening of polynyas in the sea ice and relieving of light limitation (Sullivan et al., 1993; Moore and Abbott, 2000; Swart et al., 2012; Planquette et al., 2013). High chlorophyll concentrations are observed in places along the Antarctic coastline and upon the Antarctic shelf. However, the common pattern that chlorophyll concentrations gradually decrease with distance from the coast, as is observed further north, is absent here.

The primary sources of iron in polar regions are thought to be subglacial meltwater streams, shelf sediments, melting icebergs, wind driven upwelling, brine rejection, and the seasonal melting of sea ice (Raiswell et al., 2008; Boyd et al., 2012a; Gerringa et al., 2012; Death et al., 2013; Planquette et al., 2013; Gille et al., 2014; Schallenberg et al., 2015). However, the areas characterised by seasonal sea-ice cover in the Southern Ocean are much larger than the gyre circulations, and therefore the spring ice-melt alone cannot explain the shape of these regions of high chlorophyll concentrations. These cyclonic gyres are also known to be areas of upwelling, which may supply iron to the ocean surface from depth. Nonetheless, wind driven upwelling is strong across much of the Southern Ocean, south of 50°S, and thus upwelling of iron is also unable to explain why the high mean annual chlorophyll concentrations are found exclusively within the gyre circulations (Fig. 1).

We speculate that iron supplied along the Antarctic Coastline from glacial meltwater streams, shelf sediments, and melting icebergs, enters the ocean gyres. This iron is then frozen into sea ice that forms over the gyres, or close to the Antarctic coastline (Schallenberg et al., 2015). During the spring sea-ice melt, light limitation is relieved, stratification at the surface increases, and iron is released back into the ocean from the sea ice, leading to the rapid development of chlorophyll blooms (Schallenberg et al., 2015). Sea-ice that forms outside of the gyre boundaries may be less enriched in iron, due to the low iron concentrations of surface waters where the ice forms. However, in-situ measurements are required to test these hypotheses.

6. Relevance to the glacial iron hypothesis

Sediment records show that export production increased in the Sub-Antarctic Zone during glacial intervals (Kohfeld et al., 2005, 2013). Coincident with the increase in export production, ice-core records from Antarctica show that dust fluxes were more than twenty times greater than today during glacial intervals, and atmospheric carbon dioxide concentrations decreased (Petit et al., 1990). There is, thus, strong paleo-climatic evidence to show that (1) dust fluxes to the Southern Ocean increased during glacial intervals; (2) Coincident with the timing of these enhanced dust fluxes, export production in the Sub-Antarctic Zone increased; and (3) atmospheric carbon dioxide concentrations decreased as export production increased. These records have led many studies to conclude that enhanced export production in the Sub-Antarctic Zone during glacial intervals was driven by an increased supply of iron from dust, and that this acted to lower atmospheric carbon dioxide concentrations through a strengthened biological pump (Martin, 1990; Petit et al., 1990; Kumar et al., 1995; Moore et al., 2000; Kohfeld and Ridgwell, 2009; Ziegler et al., 2013; Anderson et al., 2014; Lamy et al., 2014; Martinez-Garcia et al., 2014).

Recent observations and modelling studies have shown that productivity in the modern day Southern Ocean is relatively insensitive to iron supplied by dust (Boyd et al., 2004, 2010; Mackie et al., 2008; Wagener et al., 2008; Tagliabue et al., 2014b). For example, a modelling study by Tagliabue et al. (2014b) showed that export production decreased by approximately 1% when all dust sources of iron were removed. This reduction in iron supply caused atmospheric carbon dioxide concentrations to increase by ~2 ppm. In contrast, when sedimentary iron sources were removed, export production decreased by approximately 7%, and atmospheric carbon dioxide increased by ~14.5 ppm (Tagliabue et al., 2014b). Moreover, the results from our study indicate that chlorophyll blooms in the modern day Sub-Antarctic Zone are supported by an advective supply of iron from continental shelves, along the Dynamical Subtropical Front, rather than continental dust sources (Figs. 3 and 4). Given these findings, we argue that the possibility ought to be considered that glacial export production anomalies in the Southern Ocean could have been driven in part by changes to the supply of shelf sediment iron, rather than simply an increase in dust.

At the Last Glacial Maximum, sea levels were approximately 120 m lower than today (Peltier and Fairbanks, 2006). With the present day topographic data used in our study, we calculate that a uniform drop in sea level of 120 m would reduce the area of continental shelves between the depths of 0 and 1000 m by approximately 50% (Fig. 6, 120 m isobaths is shown in pink). For

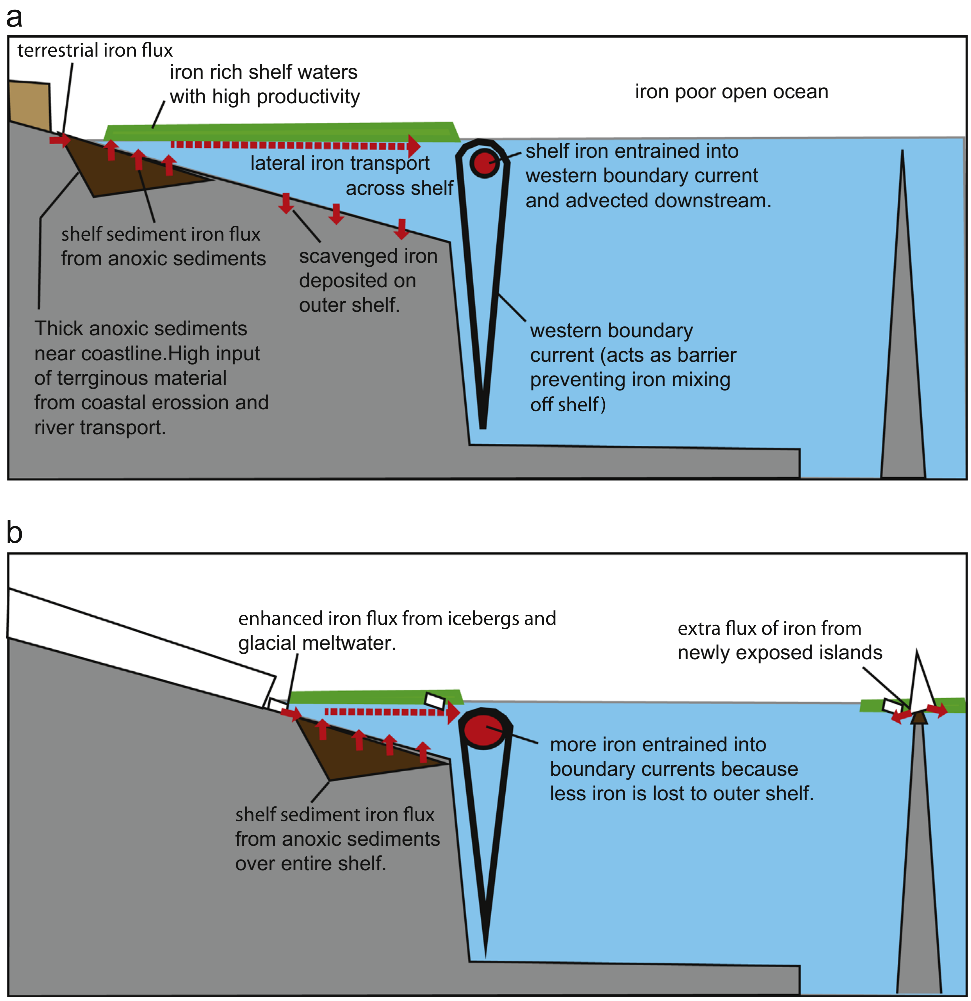

Fig. 9. Schematic of how a change in sea level might affect iron transport. Solid red arrows indicate iron sources and sinks. Dashed arrows indicate transport. Dark brown colouring indicates anoxic sediments. Green shows high chlorophyll concentrations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

many biogeochemical models, this would result in a ~50% decrease in the magnitude of the shelf sediment flux of dissolved iron (Moore et al., 2004; Aumont and Bopp, 2006; Lancelot et al., 2009). The findings from Tagliabue et al. (2014b) suggest that such a change in the shelf sediment iron flux would lead to a substantial reduction in export production and increase atmospheric carbon dioxide concentrations. However, various records show the opposite, in that export production increased in the Sub-Antarctic Zone and atmospheric carbon dioxide decreased (Ziegler et al., 2013; Anderson et al., 2014; Lamy et al., 2014; Martinez-Garcia et al., 2014).

The chlorophyll data analysed in our study, and a recent modelling study by Borrione et al. (2014), indicate that the largest shelf sediment iron fluxes are concentrated around coastal margins, rather than spread evenly over all shallow bathymetry (< 1000 m). If the major source regions of iron are located along coastal margins, it is possible that there is more potential to loose iron through scavenging on the outer regions of large shelves, such as South America, before reaching the open ocean (Fig. 9). If true, this would mean that the drop in sea level during glacial intervals would not have caused a sharp decrease in the magnitude of the shelf sediment iron flux. Instead, the reduction in sea level would have shifted coastal regions with the largest iron fluxes closer to the edge of the continental shelves and western boundary currents (Fig. 3, pink lines indicate 120 m isobaths). This may have increased the efficiency at which iron was entrained into western boundary currents that run parallel to the shelf breaks (Fig. 9). These boundary currents would therefore transport more iron to the Sub-Antarctic Zone, and potentially increase productivity there. This mechanism would be more consistent with suggestions that sediment transport by ocean currents, rather than dust, are substantial contributors to the increased lithogenic fraction recorded in ocean sediment cores from the Agulhas Region and Antarctic Peninsula during glacial periods (Diekmann et al., 2000; Latimer and Filippelli, 2001; Diekmann and Kuhn, 2002; Latimer et al., 2006; Noble et al., 2012).

In addition to changes in the iron fluxes upon continental shelves, the ~120 m drop in sea level during glacial intervals would have exposed a number of presently submerged seamounts and plateaus in the Southern Ocean (Fig. 6, pink contours indicate the 120 m isobaths, and pink circles indicate the 500 km radii from present day coastlines). This may have generated more coastal iron sources in the open ocean (Van der Merwe et al., 2015), and therefore also enhancing the availability of iron during glacial periods (Fig. 9).

The hypothesis that we present above is purely speculative at this stage. Future modelling studies and in-situ observations are required to test its validity. It is likely that these mechanism of reduced distance between coastlines and shelf breaks and increased number of island iron sources due to sea level drop were acting together with several other processes, such as changes in dust, upwelling, iceberg calving etc., to increase iron supply in the

Sub-Antarctic Zone. Changes in upwelling over the Southern Ocean are known to have a strong control on net atmosphere-ocean carbon dioxide fluxes, because upwelling delivers carbon rich deep waters and macronutrients to the surface (Toggweiler et al., 2006; Lauderdale et al., 2013; Völker and Köhler, 2013). However, upwelling in the Southern Ocean is determined mainly by the wind field, and changes to the Southern Hemisphere wind fields during glacial intervals remain elusive, and are strongly debated (Kohfeld et al., 2013; Sime et al., 2013). In our hypothesis, we do not take into account how coastal sedimentation processes, and iron fluxes, may have changed in response to local changes in environment and climate, or how changes in sea ice or the hydrography of the Southern Ocean may have affected productivity. Moreover, the relationship between productivity and export production is poorly understood (Salter et al., 2014). While an increase in iron supply would increase productivity in the Sub-Antarctic Zone, it is not known what effect this would have on export production and atmospheric CO_2.

7. Summary

In this study, we use a combination of mean annual satellite chlorophyll and sea surface height data and high resolution model output to infer the likely spatial distribution of iron sources in the Southern Ocean, and the mechanisms of iron supply at ocean fronts. We make the assumption that surface waters in the Southern Ocean are iron limited, and therefore chlorophyll concentrations are enhanced in regions where there are fluxes of iron to the ocean surface.

Large chlorophyll blooms are observed along coastal margins of continents, and downstream of small islands in the Southern Ocean. All mean annual chlorophyll concentrations >2 mg m^{-3} in the Southern Ocean occur within 50 km of a coastline. Chlorophyll concentrations are not visibly enhanced over any isolated seamounts or plateaus that are located more than 500 km from a coastline. These results indicate that major source regions of shelf sediment iron are located along coastal margins. Sediments on shallow bathymetric features in the open ocean are unlikely to act as a large iron source. We therefore recommend that depth dependent shelf sediment iron parameterisations, which are used in many biogeochemical models, should be replaced by a fixed flux through the seafloor in grid cells neighboring coastlines, or alternatively between the coastline and specific isobaths much shallower than 1000 m.

Chlorophyll concentrations are enhanced at ocean fronts downstream of continental and island land masses. However, there is no evidence of mean annual chlorophyll blooms developing at open ocean fronts in regions of intense topographically induced upwelling, as indicated by a high resolution model. These upwelling regions include locations such as Drake Passage and the south-eastern Campbell Plateau. This result suggests that upwelling at fronts in the open ocean does not deliver iron to the ocean surface, from deep sources such as hydrothermal vents. Instead high productivity at ocean fronts is primarily due to the horizontal advection of iron from coastal regions. Nonetheless, deep winter mixing, wind driven mixing, and upwelling, are likely to be important for regulating the seasonal and intra-seasonal timing of blooms through changes in light intensity, and may deliver iron to the surface from intermediate depths.

Large mean annual chlorophyll blooms are observed in the Sub-Antarctic Zone of the Atlantic, Indian and Pacific Sectors of the Southern Ocean. These blooms develop where the western boundary currents detach from the continental shelves and turn eastwards into the Southern Ocean. Chlorophyll concentrations are enhanced along contours of sea surface height that extend off the continental shelf, and decrease gradually with increasing distance from the shelf. Forward trajectories of virtual particles released from the South American and New Zealand coastlines show that coastal waters are advected along the Dynamical Subtropical Front into these regions of high chlorophyll concentrations. These analyses provide support for the hypothesis that western boundary currents are an important mechanism for transporting coastal waters, enriched with shelf sediment iron, into the Sub-Antarctic Zone.

Chlorophyll concentrations are enhanced within the cyclonic gyres adjacent to Antarctica, corresponding to the Ross and Weddell Gyres. Wind driven upwelling and the spring ice melt are thought to be important supply mechanisms of iron for this region. However, the areas characterised by wind driven upwelling and seasonal sea ice are much broader than the small and irregular areas of high chlorophyll concentrations here.

We speculate that the reduction in sea level during glacial intervals may have reduced the distance between iron sources along continental coastlines and western boundary currents. This might have increased the efficiency at which iron was entrained into western boundary currents and transported into the Sub-Antarctic Zone along the Dynamical Subtropical Front. Moreover, additional 'coastal iron' sources may have been created as the drop in sea level exposed presently submerged seamounts as islands. These mechanisms of increased iron supply should be considered further, alongside dust, to help explain enhanced export production in the Sub-Antarctic Zone during glacial intervals.

Acknowledgements

We would like to thank Philip Boyd and two anonymous reviewers for their comments that have helped to improve this manuscript. RMG was funded by a Ph.D. studentship from the Department of Geological Sciences at Stockholm University. EvS was supported by the Australian Research Council via Grant DE130101336. The open access publication fees of this article were covered by a grant from the Bolin Centre for Climate Research. The HiGEM model output was kindly provided by David Stevens. HiGEM was developed from the UK Met Office Hadley Centre model by the UK High-Resolution Modelling (HiGEM) Project and the UK Japan Climate Collaboration (UJCC). HiGEM is supported by a NERC High Resolution Climate Modelling Grant (R8/H12/123). UJCC was supported by the Foreign and Commonwealth Office Global Opportunites Fund, and jointly funded by NERC and the DECC/Defra Met Office Hadley Centre Climate Programme (GA01101). The work of Professor Pier Luigi Vidale and Dr. Malcom Roberts in leading the effort in Japan is particularly valued.

References

Anderson, R.F., et al., 2014. Biological response to millennial variability of dust and nutrient supply in the Subantarctic South Atlantic Ocean Biological response to millennial variability of dust and nutrient supply in the Subantarctic South Atlantic Ocean. Philis. Trans. R. Soc. 372, 20130054.

Ardelan, M.V., Holm-Hansen, O., Hewes, C.D., Reiss, C.S., Silva, N.S., Dulaiova, H., Steinnes, E., Sakshaug, E., 2010. Natural iron enrichment around the Antarctic Peninsula in the Southern Ocean. Biogeosciences 6 (1995), 7481–7515. http://dx.doi.org/10.5194/bgd-6-7481-2009.

Ardyna, M., Babin, M., Gosselin, M., Devred, E., Bélanger, S., Matsuoka, A., Tremblay, J.-É., 2013. Parameterization of vertical chlorophyll *a* in the Arctic Ocean: impact of the subsurface chlorophyll maximum on regional, seasonal, and annual primary production estimates. Biogeosciences 10 (6), 4383–4404. http://dx.doi.org/10.5194/bg-10-4383-2013.

Assmy, P., et al., 2013. Thick-shelled, grazer-protected diatoms decouple ocean carbon and silicon cycles in the iron-limited Antarctic Circumpolar Current. Proc. Natl. Acad. Sci. USA 110 (51), 20633–20638. http://dx.doi.org/10.1073/pnas.1309345110.

Aumont, O., Bopp, L., 2006. Globalizing results from ocean in situ iron fertilization studies. Global Biogeochem. Cycles 20 (2). http://dx.doi.org/10.1029/2005GB002591.
De Baar, H., De Jong, J., Bakker, D., 1995. Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean. Nature 373, 412–415.
De Baar, H.J.W., et al., 2005. Synthesis of iron fertilization experiments: from the iron age in the age of enlightenment. J. Geophys. Res. C Ocean 110, 1–24. http://dx.doi.org/10.1029/2004JC002601.
Bakker, D.C.E., Bozec, Y., Nightingale, P.D., Goldson, L., Messias, M.-J., de Baar, H.J.W., Liddicoat, M., Skjelvan, I., Strass, V., Watson, A.J., 2005. Iron and mixing affect biological carbon uptake in SOIREE and EisenEx, two Southern Ocean iron fertilisation experiments. Deep Sea Res. Part I: Oceanogr. Res. Pap. 52 (6), 1001–1019. http://dx.doi.org/10.1016/j.dsr.2004.11.015.
Balch, W.M., Drapeau, D.T., Bowler, B.C., Lyczskowski, E.R., Lubelczyk, L.C., Painter, S. C., Poulton, A.J., 2014. Surface biological, chemical, and optical properties of the Patagonian Shelf coccolithophore bloom, the brightest waters of the Great Calcite Belt. Limnol. Oceanogr. 59 (5), 1715–1732. http://dx.doi.org/10.4319/lo.2014.59.5.1715.
Bergquist, B.A., Boyle, E.A., 2006. Dissolved iron in the tropical and subtropical Atlantic Ocean. Glob. Biogeochem. Cycles 20 (1). http://dx.doi.org/10.1029/2005GB002505.
Biller, D.V., Coale, T.H., Till, R.C., Smith, G.J., Bruland, K.W., 2013. Coastal iron and nitrate distributions during the spring and summer upwelling season in the central California Current upwelling regime. Cont. Shelf Res. 66, 58–72. http://dx.doi.org/10.1016/j.csr.2013.07.003.
Blain, S., et al., 2007. Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. Nature 446 (7139), 1070–1074. http://dx.doi.org/10.1038/nature05700.
Blain, S., Sarthou, G., Laan, P., 2008. Distribution of dissolved iron during the natural iron-fertilization experiment KEOPS (Kerguelen Plateau, Southern Ocean). Deep Sea Res. Part II Top. Stud. Oceanogr. 55 (5–7), 594–605. http://dx.doi.org/10.1016/j.dsr2.2007.12.028.
Borrione, I., Aumont, O., Nielsdóttir, M.C., Schlitzer, R., 2014. Sedimentary and atmospheric sources of iron around South Georgia, Southern Ocean: a modelling perspective. Biogeosciences 11 (7), 1981–2001. http://dx.doi.org/10.5194/bg-11-1981-2014.
Bowie, A.R., Lannuzel, D., Remenyi, T. a, Wagener, T., Lam, P.J., Boyd, P.W., Guieu, C., Townsend, A.T., Trull, T.W., 2009. Biogeochemical iron budgets of the Southern Ocean south of Australia: decoupling of iron and nutrient cycles in the subantarctic zone by the summertime supply. Glob. Biogeochem. Cycles 23, 1–14. http://dx.doi.org/10.1029/2009GB003500.
Bowie, A.R., Brian Griffiths, F., Dehairs, F., Trull, T.W., 2011. Oceanography of the subantarctic and Polar Frontal Zones south of Australia during summer: setting for the SAZ-sense study. Deep Sea Res. Part II Top. Stud. Oceanogr 58 (21–22), 2059–2070. http://dx.doi.org/10.1016/j.dsr2.2011.05.033.
Boyd, P.W., Ellwood, M.J., 2010. The biogeochemical cycle of iron in the ocean. Nat. Geosci. 3 (10), 675–682. http://dx.doi.org/10.1038/ngeo964.
Boyd, P.W., et al., 2000. A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. Nature 407 (6805), 695–702. http://dx.doi.org/10.1038/35037500.
Boyd, P.W., McTainsh, G., Sherlock, V., Richardson, K., Nichol, S., Ellwood, M., Frew, R., 2004. Episodic enhancement of phytoplankton stocks in New Zealand subantarctic waters: contribution of atmospheric and oceanic iron supply. Glob. Biogeochem. Cycles 18(1), 10.1029/2002GB002020.
Boyd, P.W., et al., 2007. Mesoscale iron enrichment experiments 1993-2005: synthesis and future directions. Science 315 (February), 612–617. http://dx.doi.org/10.1126/science.1131669.
Boyd, P.W., Mackie, D.S., Hunter, K. a, 2010. Aerosol iron deposition to the surface ocean — modes of iron supply and biological responses. Mar. Chem 120 (1–4), 128–143. http://dx.doi.org/10.1016/j.marchem.2009.01.008.
Boyd, P.W., Arrigo, K.R., Strzepek, R., Van Dijken, G.L., 2012a. Mapping phytoplankton iron utilization: insights into Southern Ocean supply mechanisms. J. Geophys. Res. Ocean 117 (June), 1–18. http://dx.doi.org/10.1029/2011JC007726.
Boyd, P.W., et al., 2012b. Microbial control of diatom bloom dynamics in the open ocean. Geophys. Res. Lett. 39, 2–7. http://dx.doi.org/10.1029/2012GL053448.
Browning, T., Bouman, H., Moore, C., 2014. Satellite-detected fluorescence: decoupling nonphotochemical quenching from iron stress signals in the South Atlantic and Southern Ocean. Glob. Biogeochem. 28, 510–524. http://dx.doi.org/10.1002/2013GB004773.
Carranza, M.M., Gille, S.T., 2014. Southern Ocean wind-driven entrainment enhances satellite chlorophyll-a through the summer. J. Geophys. Res. Ocean . http://dx.doi.org/10.1002/2014JC010203.
Chase, Z., Strutton, P.G., Hales, B., 2007. Iron links river runoff and shelf width to phytoplankton biomass along the U.S. West Coast. Geophys. Res. Lett. 34 (4), L04607. http://dx.doi.org/10.1029/2006GL028069.
Chever, F., Sarthou, G., Bucciarelli, E., Blain, S., Bowie, A.R., 2010. An iron budget during the natural iron fertilisation experiment KEOPS (Kerguelen Islands, Southern Ocean). Biogeosciences 7 (2), 455–468. http://dx.doi.org/10.5194/bg-7-455-2010.
Chisholm, S.W., Morel, F.M.M., 1991. What controls phyoplankton production in nutrient rich areas of the open sea? Limnol. Oceanogr. 36, 8.
Coale, K.H., et al., 1996. A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. Nature 383 (6600), 495–501. http://dx.doi.org/10.1038/383495a0.
Comiso, J., McClain, C., Sullivan, C., Ryan, J., Leonard, C., 1993. Coastal Zone Color Scanner pigment concentrations in the Southern Ocean and relationships to geophysical surface features. J. Geophys. Res. 98 (92), 2419–2451. http://dx.doi.org/10.1029/92JC02505.
Conway, T.M., John, S.G., 2014. Quantification of dissolved iron sources to the North Atlantic Ocean. Nature 511 (7508), 212–215. http://dx.doi.org/10.1038/nature13482.
Cooper, D., Watson, A., Nightingale, P., 1996. Large decrease in ocean-surface CO_2 fugacity in response to in situ iron fertilization. Nature 383, 511–513. http://dx.doi.org/10.1038/383511a0.
Croot, P.L., Streu, P., Baker, A.R., 2004. Short residence time for iron in surface seawater impacted by atmospheric dry deposition from Saharan dust events. Geophys. Res. Lett. 31(23), 10.1029/2004GL020153.
Cullen, J.J., 2015. Subsurface chlorophyll maximum layers: enduring enigma or mystery solved? Ann. Rev. Mar. Sci 7, 207–239. http://dx.doi.org/10.1146/annurev-marine-010213-135111.
d'Ovidio, F., Della Penna, A., Trull, T.W., Nencioli, F., Pujol, I., Rio, M.H., Park, Y.-H., Cotté, C., Zhou, M., Blain, S., 2015. The biogeochemical structuring role of horizontal stirring: Lagrangian perspectives on iron delivery downstream of the Kerguelen plateau. Biogeosci. Discuss 12, 779–814. http://dx.doi.org/10.5194/bgd-12-779-2015.
De Boer, A.M., Graham, R.M., Thomas, M.D., Kohfeld, K.E., 2013. The control of the Southern Hemisphere Westerlies on the position of the Subtropical Front. J. Geophys. Res. Ocean 118 (10), 5669–5675. http://dx.doi.org/10.1002/jgrc.20407.
Death, R., Wadham, J.L., Monteiro, F., Le Brocq, A.M., Tranter, M., Ridgwell, A., Dutkiewicz, S., Raiswell, R., 2013. Antarctic ice sheet fertilises the Southern Ocean. Biogeosci. Discuss 10 (7), 12551–12570. http://dx.doi.org/10.5194/bgd-10-12551-2013.
Diekmann, B., Kuhn, G., 2002. Sedimentary record of the mid-Pleistocene climate transition in the southeastern South Atlantic (ODP Site 1090). Palaeogeogr. Palaeoclimatol., 182.
Diekmann, B., Kuhn, G., Rachold, V., Abelmanna, A., Brathauera, U., Fütterera, D.K., Gersondea, R., Grobea, H., 2000. Terrigenous sediment supply in the Scotia Sea (Southern Ocean): response to Late Quaternary ice dynamics in Patagonia and on the Antarctic Peninsula. Palaeogeogr. Palaeoclimatol. Palaeoecol. 162, 357–387. http://dx.doi.org/10.1016/S0031-0182(00)00138-3.
Ellwood, M.J., Nodder, S.D., King, A.L., Hutchins, D. a, Wilhelm, S.W., Boyd, P.W., 2014. Pelagic iron cycling during the subtropical spring bloom, east of New Zealand. Mar. Chem. 160, 18–33. http://dx.doi.org/10.1016/j.marchem.2014.01.004.
Elrod, V.A., Berelson, W.M., Coale, K.H., Johnson, K.S., 2004. The flux of iron from continental shelf sediments: a missing source for global budgets. Geophys. Res. Lett. 31 (12), L12307. http://dx.doi.org/10.1029/2004GL020216.
Frants, M., Gille, S.T., Hatta, M., Hiscock, W.T., Kahru, M., Measures, C.I., Greg Mitchell, B., Zhou, M., 2013. Analysis of horizontal and vertical processes contributing to natural iron supply in the mixed layer in southern Drake Passage. Deep-Sea Res. Part II Top. Stud. Oceanogr. 90, 68–76. http://dx.doi.org/10.1016/j.dsr2.2012.06.001.
Frew, R.D., Hutchins, D. a, Nodder, S., Sanudo-Wilhelmy, S., Tovar-Sanchez, A., Leblanc, K., Hare, C.E., Boyd, P.W., 2006. Particulate iron dynamics during Fe cycle in subantarctic waters southeast of New Zealand. Global Biogeochem. Cycles 20, 1–15. http://dx.doi.org/10.1029/2005GB002558.
Geibert, W., et al., 2010. High productivity in an ice melting hot spot at the eastern boundary of the Weddell Gyre. Glob. Biogeochem. Cycles 24(3), 10.1029/2009GB003657.
Gerringa, L., Alderkamp, A.-C., Laan, P., Thuróczy, C.-E., de Baar, H., Mills, M., van, D. G.L., van, H.H., 2012. Iron from melting glaciers fuels the phytoplankton blooms in Amundsen Sea (Southern Ocean); iron biogeochemistry. Deep-Sea Res. Part II 76, 16–31. http://dx.doi.org/10.1016/j.dsr2.2012.03.007.
Gille, S.T., Carranza, M.M., Cambra, R., Morrow, R., 2014. Wind-induced upwelling in the Kerguelen Plateau Region. Biogeosci. Discuss 11, 8373–8397. http://dx.doi.org/10.5194/bgd-11-8373-2014.
Gledhill, M., Buck, K.N., 2012. The organic complexation of iron in the marine environment: a review. Front. Microbiol. 3 (February), 1–17. http://dx.doi.org/10.3389/fmicb.2012.00069.
Graham, R.M., De Boer, A.M., 2013. The dynamical subtropical front. J. Geophys. Res. Ocean. 118(May), doi:10.1002/jgrc.20408.
Graham, R.M., de Boer, A.M., Heywood, K.J., Chapman, M.R., Stevens, D.P., 2012. Southern Ocean fronts: controlled by wind or topography? J. Geophys. Res. 117 (C8), 1–14. http://dx.doi.org/10.1029/2012JC007887.
Grand, M.M., Measures, C.I., Hatta, M., Hiscock, W.T., Landing, W.M., Morton, P.L., Buck, C.S., Barrett, P.M., Resing, J.A., 2015. Dissolved Fe and Al in the upper 1000 m of the eastern Indian Ocean: a high-resolution transect from the Antarctic margin to the Bay of Bengal. Glob. Biogeochem. Cycles . http://dx.doi.org/10.1002/2014GB004920.
Hashioka, T., et al., 2013. Phytoplankton competition during the spring bloom in four plankton functional type models. Biogeosciences 10 (11), 6833–6850. http://dx.doi.org/10.5194/bg-10-6833-2013.
Homoky, W.B., Severmann, S., McManus, J., Berelson, W.M., Riedel, T.E., Statham, P. J., Mills, R. a, 2012. Dissolved oxygen and suspended particles regulate the benthic flux of iron from continental margins. Mar. Chem. 134–135, 59–70. http://dx.doi.org/10.1016/j.marchem.2012.03.003.
Homoky, W.B., John, S.G., Conway, T.M., Mills, R. a, 2013. Distinct iron isotopic signatures and supply from marine sediment dissolution. Nat. Commun. 4, 2143. http://dx.doi.org/10.1038/ncomms3143.
Johnson, K.S., Chavez, F.P., Friederich, G.E., 1999. Continental-shelf sediment as a primary source of iron for coastal phytoplankton. Nature 398, 697–700. http://dx.doi.org/10.1038/19511.

De Jong, J., Schoemann, V., Lannuzel, D., Croot, P., de Baar, H., Tison, J.-L., 2012. Natural iron fertilization of the Atlantic sector of the Southern Ocean by continental shelf sources of the Antarctic Peninsula. J. Geophys. Res. 117 (G1), G01029. http://dx.doi.org/10.1029/2011JG001679.

Klunder, M.B., Laan, P., Middag, R., De Baar, H.J.W., van Ooijen, J.C., 2011. Dissolved iron in the Southern Ocean (Atlantic sector). Deep-Sea Res. Part II: Top. Stud. Oceanogr., 58(25–26), 2678–2694. http://dx.doi.org/10.1016/j.dsr2.2010.10.042.

Klunder, M.B., Bauch, D., Laan, P., de Baar, H.J.W., van Heuven, S., Ober, S., 2012. Dissolved iron in the Arctic shelf seas and surface waters of the central Arctic Ocean: impact of Arctic river water and ice-melt. J. Geophys. Res. 117 (C1), C01027. http://dx.doi.org/10.1029/2011JC007133.

Klunder, M.B., Laan, P., De Baar, H.J.W., Middag, R., Neven, I., Van Ooijen, J., 2014. Dissolved Fe across the Weddell Sea and Drake Passage: impact of DFe on nutrient uptake. Biogeosciences 11, 651–669. http://dx.doi.org/10.5194/bg-11-651-2014.

Kohfeld, K.E., Ridgwell, A., 2009. Glacial–interglacial variability in atmospheric CO_2. Surf. Ocean-Low. Atmos. Process. Geophys. Res. Ser 187, 251–286. http://dx.doi.org/10.1029/2008GM000845.

Kohfeld, K.E., Le Quéré, C., Harrison, S.P., Anderson, R.F., 2005. Role of marine biology in glacial-interglacial CO_2 cycles. Science 308 (5718), 74–78. http://dx.doi.org/10.1126/science.1105375.

Kohfeld, K.E., Graham, R.M., de Boer, A.M., Sime, L.C., Wolff, E.W., Le Quéré, C., Bopp, L., 2013. Southern Hemisphere westerly wind changes during the Last Glacial maximum: paleo-data synthesis. Quat. Sci. Rev. 68, 76–95. http://dx.doi.org/10.1016/j.quascirev.2013.01.017.

Köhler, S.J., Lidman, F., Laudon, H., 2014. Landscape types and pH control organic matter mediated mobilization of Al, Fe, U and La in boreal catchments. Geochim. Cosmochim. Acta . http://dx.doi.org/10.1016/j.gca.2014.03.033.

Krachler, R., von der Kammer, F., Jirsa, F., Süphandag, A., Krachler, R.F., Plessl, C., Vogt, M., Keppler, B.K., Hofmann, T., 2012. Nanoscale lignin particles as sources of dissolved iron to the ocean. Global Biogeochem. Cycles 26 (3). http://dx.doi.org/10.1029/2012GB004294, n/a–n/a.

Kumar, N., Anderson, R., Mortlock, R., Froelich, P., Kubik, P., Dittrich-Hannen, B., Suter, M., 1995. Increased biological productivity and export production in the glacial Southern Ocean. Nature, 378.

Lam, P.J., Bishop, J.K.B., Henning, C.C., Marcus, M. a, Waychunas, G. a, Fung, I.Y., 2006. Wintertime phytoplankton bloom in the subarctic Pacific supported by continental margin iron. Glob. Biogeochem. Cycles 20 (1). http://dx.doi.org/10.1029/2005GB002557, n/a–n/a.

Lamy, F., Gersonde, R., Winckler, G., Esper, O., Jaeschke, A., Kuhn, G., Ullermann, J., Martinez-Garcia, A., Lambert, F., Kilian, R., 2014. Increased dust deposition in the Pacific Southern Ocean during glacial periods. Science 343 (6169), 403–407. http://dx.doi.org/10.1126/science.1245424.

Lancelot, C., de Montety, A., Goosse, H., Becquevort, S., Schoemann, V., Pasquer, B., Vancoppenolle, M., 2009. Spatial distribution of the iron supply to phytoplankton in the Southern Ocean: a model study. Biogeosciences 6 (12), 2861–2878. http://dx.doi.org/10.5194/bg-6-2861-2009.

Latimer, J., Filippelli, G., 2001. Terrigenous input and paleoproductivity in the Southern Ocean. Paleoceanography 16 (6), 627–643.

Latimer, J.C., Filippelli, G.M., Hendy, I.L., Gleason, J.D., Blum, J.D., 2006. Glacia–interglacial terrigenous provenance in the southeastern Atlantic Ocean: the importance of deep-water sources and surface currents. Geology 34 (7), 545. http://dx.doi.org/10.1130/G22252.1.

Lauderdale, J.M., Garabato, A.C.N., Oliver, K.I.C., Follows, M.J., Williams, R.G., 2013. Wind-driven changes in Southern Ocean residual circulation, ocean carbon reservoirs and atmospheric CO_2. Clim. Dyn. 41 (7–8), 2145–2164. http://dx.doi.org/10.1007/s00382-012-1650-3.

Law, C.S., et al., 2006. Patch evolution and the biogeochemical impact of entrainment during an iron fertilisation experiment in the sub-Arctic Pacific. Deep Sea Res. Part II Top. Stud. Oceanogr. 53(20–22), 2012–2033. http://dx.doi.org/10.1016/j.dsr2.2006.05.028.

Mackie, D.S., Boyd, P.W., McTainsh, G.H., Tindale, N.W., Westberry, T.K., Hunter, K. a, 2008. Biogeochemistry of iron in Australian dust: from eolian uplift to marine uptake. Geochem. Geophys. Geosyst. 9 (3). http://dx.doi.org/10.1029/2007GC001813, n/a–n/a.

Mahadevan, A., D'Asaro, E., Lee, C., Perry, M.J., 2012. Eddy-driven stratification initiates North Atlantic spring phytoplankton blooms. Science 337 (July), 54–58. http://dx.doi.org/10.1126/science.1218740.

Martin, J., 1990. Glacial–interglacial CO_2 change: the iron hypothesis. Paleoceanography 5 (1), 1–13.

Martinez-Garcia, A., Sigman, D.M., Ren, H., Anderson, R.F., Straub, M., Hodell, D.A., Jaccard, S.L., Eglinton, T.I., Haug, G.H., 2014. Iron Fertilization of the Subantarctic Ocean During the Last Ice Age. Science 343 (6177), 1347–1350. http://dx.doi.org/10.1126/science.1246848.

Matsushita, B., Yang, W., Chang, P., Yang, F., Fukushima, T., 2012. A simple method for distinguishing global Case-1 and Case-2 waters using SeaWiFS measurements. ISPRS J. Photogramm. Remote Sens. 69, 74–87. http://dx.doi.org/10.1016/j.isprsjprs.2012.02.008.

Measures, C.I., Vink, S., 2001. Dissolved Fe in the upper waters of the Pacific sector of the Southern Ocean. Deep Sea Research part II, 48, 3913–3941 http://dx.doi.org/10.1016/S0967-0645(01)00074-1.

Measures, C.I., Brown, M.T., Selph, K.E., Apprill, A., Zhou, M., Hatta, M., Hiscock, W.T., 2013. The influence of shelf processes in delivering dissolved iron to the HNLC waters of the Drake Passage Antartica. Deep Sea Res. Part II Top. Stud. Oceanogr 90, 77–88. http://dx.doi.org/10.1016/j.dsr2.2012.11.004.

Van der Merwe, P., et al., 2015. Sourcing the iron in the naturally-fertilised bloom around the Kerguelen Plateau: particulate trace metal dynamics. Biogeosci. Discuss, 739–755. http://dx.doi.org/10.5194/bg-12-739-2015.

Mongin, M., Matear, R., Chamberlain, M., 2011. Seasonal and spatial variability of remotely sensed chlorophyll and physical fields in the SAZ-sense region. Deep Sea Res. Part II Top. Stud. Oceanogr 58 (21–22), 2082–2093. http://dx.doi.org/10.1016/j.dsr2.2011.06.002.

Moore, J., Abbott, M., 2000. Phytoplankton chlorophyll distributions and primary production in the Southern Ocean. J. Geophys. Res. 105 (C12).

Moore, J., Braucher, O., 2008. Sedimentary and mineral dust sources of dissolved iron to the world ocean. Biogeosciences 5 (1994), 631–656. http://dx.doi.org/10.5194/bg-5-631-2008.

Moore, J.K., Abbott, M.R., 2002. Surface chlorophyll concentrations in relation to the Antarctic Polar front: seasonal and spatial patterns from satellite observations. J. Mar. Syst 37 (1–3), 69–86. http://dx.doi.org/10.1016/S0924-7963(02)00196-3.

Moore, J.K., Abbott, M.R., Richman, J.G., Smith, W.O., Cowles, T.J., Coale, K.H., Gardner, W.D., Barber, R.T., 1999. SeaWiFS satellite ocean color data from the Southern Ocean. Geophys. Res. Lett. 26 (10), 1465–1468. http://dx.doi.org/10.1029/1999GL900242.

Moore, J.K., Abbott, M.R., Richman, G., Nelson, D.M., 2000. The Southern Ocean at the last glacial maximum- A strong sink for atmospheric carbon dioxide of this expanded SIZ throughout the Southern. Glob. Biogeochem. Cycles 14 (1), 455–475.

Moore, J.K., Doney, S.C., Lindsay, K., 2004. Upper ocean ecosystem dynamics and iron cycling in a global three-dimensional model. Glob. Biogeochem. Cycles 18 (4). http://dx.doi.org/10.1029/2004GB002220, n/a–n/a.

Morel, A., Prieur, L., 1977. Analysis of variations in ocean color. Limnol. Oceanogr. 22 (4), 709–722. http://dx.doi.org/10.4319/lo.1977.22.4.0709.

Naveira Garabato, A.C., Strass, V.H., Kattner, G., 2002. Fluxes of nutrients in a three-dimensional meander structure of the Antarctic Polar Front. Deep Sea Res. Part II Top. Stud. Oceanogr. 49 (1), 3771–3792. http://dx.doi.org/10.1016/S0967-0645(02)00110-8.

Naveira-Garabato, A., Ferrari, R., Polzin, K., 2011. Eddy stirring in the Southern Ocean. J. Geophys. 116 (C9), 1–29. http://dx.doi.org/10.1029/2010JC006818.

Neubauer, E., Köhler, S.J., von der Kammer, F., Laudon, H., Hofmann, T., 2013. Effect of pH and stream order on iron and arsenic speciation in boreal catchments. Environ. Sci. Technol. 47 (13), 7120–7128. http://dx.doi.org/10.1021/es401193j.

Nishioka, J., et al., 2007. Iron supply to the western subarctic Pacific: importance of iron export from the Sea of Okhotsk. J. Geophys. Res. Ocean, *112*. http://dx.doi.org/10.1029/2006JC004055.

Nishioka, J., Ono, T., Saito, H., Sakaoka, K., Yoshimura, T., 2011. Oceanic iron supply mechanisms which support the spring diatom bloom in the Oyashio region, western subarctic Pacific. J. Geophys. Res. Ocean 116 (December 2010). http://dx.doi.org/10.1029/2010JC006321.

Noble, T.L., Piotrowski, A.M., Robinson, L.F., McManus, J.F., Hillenbrand, C.-D., Bory, A.J.-M., 2012. Greater supply of Patagonian-sourced detritus and transport by the ACC to the Atlantic sector of the Southern Ocean during the last glacial period. Earth Planet. Sci. Lett. 317–318, 374–385. http://dx.doi.org/10.1016/j.epsl.2011.10.007.

Nodwell, L.M., Price, N.M., 2001. Direct use of inorganic colloidal iron by marine mixotrophic phytoplankton. Limnol. Oceanogr. 46 (4), 765–777. http://dx.doi.org/10.4319/lo.2001.46.4.0765.

Noffke, A., Hensen, C., Sommer, S., Scholz, F., Bohlen, L., Mosch, T., Graco, M., Wallmann, K., 2012. Benthic iron and phosphorus fluxes across the Peruvian oxygen minimum zone. Limnol. Oceanogr. 57 (3), 851–867. http://dx.doi.org/10.4319/lo.2012.57.3.0851.

Orsi, A., Whitworth, T., Nowlin, W.D.J., 1995. On the meridional extent and fronts of the Antarctic circumpolar current. Deep Sea Res. Part I Oceanogr 42 (5), 641–673. http://dx.doi.org/10.1016/0967-0637(95)00021-W.

Paris, C.B., Helgers, J., van Sebille, E., Srinivasan, A., 2013. Connectivity modeling system: a probabilistic modeling tool for the multi-scale tracking of biotic and abiotic variability in the ocean. Environ. Model. Softw 42, 47–54. http://dx.doi.org/10.1016/j.envsoft.2012.12.006.

Parslow, J.S., Boyd, P.W., Rintoul, R., Brian, F., 2001. A persistent subsurface chlorophyll maximum in the Interpolar Frontal Zone south of Australia: seasonal progression and implications for phytoplankton-light-nutrient interactions. J. Geophys. Res., 106.

Peltier, W.R., Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quat. Sci. Rev. 25 (23–24), 3322–3337. http://dx.doi.org/10.1016/j.quascirev.2006.04.010.

Petit, J., Mourner, L., Jouzel, J., Korotkevich, Y., Kotlyakov, V., Lorius, C., 1990. Palaeoclimatological and chronological implications of the Vostok core dust record. Nature 343, 56–58. http://dx.doi.org/10.1038/343056a0.

Planquette, H., et al., 2007. Dissolved iron in the vicinity of the Crozet Islands, Southern Ocean. Deep Sea Res. Part II Top. Stud. Oceanogr. 54 (18–20), 1999–2019. http://dx.doi.org/10.1016/j.dsr2.2007.06.019.

Planquette, H., Sherrell, R.M., Stammerjohn, S., Field, M.P., 2013. Particulate iron delivery to the water column of the Amundsen Sea, Antarctica. Mar. Chem. 153, 15–30. http://dx.doi.org/10.1016/j.marchem.2013.04.006.

Pollard, R., Sanders, R., Lucas, M., Statham, P., 2007. The Crozet natural iron bloom and export experiment (CROZEX). Deep Sea Res. Part II Top. Stud. Oceanogr. 54 (18–20), 1905–1914. http://dx.doi.org/10.1016/j.dsr2.2007.07.023.

Pollard, R.T., et al., 2009. Southern Ocean deep-water carbon export enhanced by natural iron fertilization. Nature 457 (7229), 577–580. http://dx.doi.org/10.1038/nature07716.

Raiswell, R., Canfield, D., 2012. The iron biogeochemical cycle past and present. Geochem. Perspect. 1, 1.

Raiswell, R., Benning, L.G., Tranter, M., Tulaczyk, S., 2008. Bioavailable iron in the Southern Ocean: the significance of the iceberg conveyor belt. Geochem. Trans. 9, 7. http://dx.doi.org/10.1186/1467-4866-9-7.

Read, J., Lucas, M., Holley, S., Pollard, R., 2000. Phytoplankton, nutrients and hydrography in the frontal zone between the Southwest Indian Subtropical gyre and the Southern Ocean. Deep Sea Res. Part I Oceanogr. Res. Pap 47 (12), 2341–2367. http://dx.doi.org/10.1016/S0967-0637(00)00021-2.

Rijkenberg, M.J. a, Middag, R., Laan, P., Gerringa, L.J. a, Van Aken, H.M., Schoemann, V., De Jong, J.T.M., De Baar, H.J.W., 2014. The distribution of dissolved iron in the West Atlantic Ocean. PLoS One 9 (6), 1–14. http://dx.doi.org/10.1371/journal.pone.0101323.

Roberts, M.J., et al., 2009. Impact of Resolution on the Tropical Pacific Circulation in a matrix of coupled models. J. Clim. 22 (10), 2541–2556. http://dx.doi.org/10.1175/2008JCLI2537.1.

Robinson, J., Popova, E.E., Yool, A., Srokosz, M., Lampitt, R.S., Blundell, J.R., 2014. How deep is deep enough? Ocean iron fertilization and carbon sequestration in the Southern Ocean. Geophys. Res. Lett. . http://dx.doi.org/10.1002/2013GL058799

Romero, S.I., Piola, A.R., Charo, M., Garcia, C. a E., 2006. Chlorophyll – a variability off Patagonia based on SeaWiFS data. J. Geophys. Res. 111 (C5), C05021. http://dx.doi.org/10.1029/2005JC003244.

Rosso, I., Hogg, A.M., Strutton, P.G., Kiss, A.E., Matear, R., Klocker, A., van Sebille, E., 2014. Vertical transport in the ocean due to sub-mesoscale structures: impacts in the Kerguelen region. Ocean Model. 80, 10–23. http://dx.doi.org/10.1016/j.ocemod.2014.05.001.

Salter, I., Schiebel, R., Ziveri, P., Movellan, A., Lampitt, R., Wol, G. a, 2014. Carbonate counter pump stimulated by natural iron fertilization in the Polar Frontal Zone. Nat. Geosci. 7 (December), 885–889. http://dx.doi.org/10.1038/NGEO2285.

Sanial, V., van Beek, P., Lansard, B., D'Ovidio, F., Kestenare, E., Souhaut, M., Zhou, M., Blain, S., 2014. Study of the phytoplankton plume dynamics off the Crozet Islands (Southern Ocean): a geochemical–physical coupled approach. J. Geophys. Res. Ocean 119, 1–11. http://dx.doi.org/10.1002/2013JC009305.

Saraceno, M., Provost, C., Piola, A.R., 2005. On the relationship between satellite-retrieved surface temperature fronts and chlorophyll a in the western South Atlantic. J. Geophys. Res. 110 (C11), C11016. http://dx.doi.org/10.1029/2004JC002736.

Schallenberg, C., van der Merwe, P., Chever, F., Cullen, J.T., Lannuzel, D., Bowie, A.R., 2015. Dissolved iron and iron(II) distributions beneath the pack ice in the east antarctic (120°E) during the winter/spring transition. Deep Sea Res. Part II Top. Stud. Oceanogr. (Ii) . http://dx.doi.org/10.1016/j.dsr2.2015.02.019.

Schlosser, C., Henderson, G., Graham, R.M., Klar, J. K., Pampin-Bora, J., Woodward, E. M. S., Chance, R., Moore, C.M., Achterberg, E.P. Iron fuels vast phytoplankton bloom along 40 South in the Atlantic Ocean, in preparation.

Van Sebille, E., Scussolini, P., Durgadoo, J.V., Peeters, F.J.C., Biastoch, A., Weijer, W., Turney, C., Paris, C.B., Zahn, R., 2015. Ocean currents generate large footprints in marine palaeoclimate proxies. Nat. Commun., 6(Ivm), 6521. http://dx.doi.org/10.1038/ncomms7521.

Shaffrey, L.C., et al., 2009. U.K. HiGEM: the new U.K. high-resolution global environment model—model description and basic evaluation. J. Clim. 22 (8), 1861–1896. http://dx.doi.org/10.1175/2008JCLI2508.1.

Shaked, Y., Lis, H., 2012. Disassembling iron availability to phytoplankton. Front. Microbiol 3 (April), 1–26. http://dx.doi.org/10.3389/fmicb.2012.00123.

Sime, L.C., Kohfeld, K.E., Le, C., Wolff, E.W., De Boer, A.M., Graham, R.M., Bopp, L., 2013. Author ' s personal copy Southern Hemisphere westerly wind changes during the Last Glacial Maximum : model-data comparison. Quarternary Sci. Rev 64, 104–120.

Smetacek, V., et al., 2012. Deep carbon export from a Southern Ocean iron-fertilized diatom bloom. Nature 487 (7407), 313–319. http://dx.doi.org/10.1038/nature11229.

Smith, W., Sandwell, D., 1997. Global sea floor topography from satellite altimetry and ship depth soundings. Science 2 (September), 209–215.

Sokolov, S., Rintoul, S.R., 2007a. Multiple jets of the Antarctic Circumpolar Current South of Australia. J. Phys. Oceanogr. 37 (5), 1394–1412. http://dx.doi.org/10.1175/JPO3111.1.

Sokolov, S., Rintoul, S.R., 2007b. On the relationship between fronts of the Antarctic Circumpolar Current and surface chlorophyll concentrations in the Southern Ocean. J. Geophys. Res. 112 (C7), 1–17. http://dx.doi.org/10.1029/2006JC004072.

Sullivan, C.W., Arrigo, K.R., McClain, C.R., Comiso, J.C., Firestone, J., 1993. Distributions of phytoplankton blooms in the southern ocean. Science 262 (5141), 1832. http://dx.doi.org/10.1126/science.262.5141.1832 –7.

Swart, S., Thomalla, S.J., Monteiro, P.M.S., Ansorge, I.J., 2012. Mesoscale features and phytoplankton biomass at the GoodHope line in the Southern Ocean during austral summer. African J. Mar. Sci. 34 (January 2013), 511–524. http://dx.doi.org/10.2989/1814232X.2012.749811.

Swart, S., Thomalla, S.J., Monteiro, P.M.S., 2014. The seasonal cycle of mixed layer dynamics and phytoplankton biomass in the Sub-Antarctic Zone: a high-resolution glider experiment. J. Mar. Syst. . http://dx.doi.org/10.1016/j.jmarsys.2014.06.002

Tagliabue, A., Mtshali, T., Aumont, O., Bowie, A.R., Klunder, M.B., Roychoudhury, A. N., Swart, S., 2012. A global compilation of dissolved iron measurements: focus on distributions and processes in the Southern Ocean. Biogeosciences 9 (6), 2333–2349. http://dx.doi.org/10.5194/bg-9-2333-2012.

Tagliabue, A., Bopp, L., Aumont, O., 2009. Evaluating the importance of atmospheric and sedimentary iron sources to Southern Ocean biogeochemistry. Geophys. Res. Lett. 36 (13), L13601. http://dx.doi.org/10.1029/2009GL038914.

Tagliabue, A., Sallee, J.B., Bowie, A.R., Levy, M., Swart, S., Boyd, P.W., 2014a. Surface water iron supplies in the Southern Ocean sustained by deep winter mixing. Nature Geoscience. 7. http://dx.doi.org/10.1038/NGEO2101.

Tagliabue, A., Aumont, O., Bopp, L., 2014b. The impact of different external sources of iron on the global carbon cycle. Geophys. Res. Lett. 41, 920–926. http://dx.doi.org/10.1002/2013GL059059.Received.

Toggweiler, J.R., Russell, J.L., Carson, S.R., 2006. Midlatitude westerlies, atmospheric CO_2, and climate change during the ice ages. Paleoceanography 21 (2), 1–15. http://dx.doi.org/10.1029/2005PA001154.

Tripathy, S.C., Pavithran, S., Sabu, P., Pillai, H.U.K., Dessai, D.R.G., Anilkumar, N., 2015. Deep chlorophyll maximum and primary productivity in Indian Ocean sector of the Southern Ocean: case study in the Subtropical and Polar Front during austral summer 2011. Deep Sea Res. Part II Top. Stud. Oceanogr., (Mld), 1–10. http://dx.doi.org/10.1016/j.dsr2.2015.01.004.

Tyrrell, T., Merico, A., Waniek, J.J., Wong, C.S., Metzl, N., Whitney, F., 2005. Effect of seafloor depth on phytoplankton blooms in high-nitrate, low-chlorophyll (HNLC) regions. J. Geophys. Res. 110 (G2), G02007. http://dx.doi.org/10.1029/2005JG000041.

Völker, C., Köhler, P., 2013. Responses of ocean circulation and carbon cycle to changes in the position of the Southern Hemisphere westerlies at Last Glacial Maximum. Paleoceanography 28 (4), 726–739. http://dx.doi.org/10.1002/2013PA002556.

Wadley, M.R., Jickells, T.D., Heywood, K.J., 2014. The role of iron sources and transport for Southern Ocean productivity. Deep Sea Res. Part I Oceanogr. Res. Pap. 87, 82–94. http://dx.doi.org/10.1016/j.dsr.2014.02.003.

Wagener, T., Guieu, C., Losno, R., Bonnet, S., Mahowald, N., 2008. Revisiting atmospheric dust export to the Southern Hemisphere ocean: biogeochemical implications. Glob. Biogeochem. Cycles 22 (2). http://dx.doi.org/10.1029/2007GB002984, n/a–n/a.

Watson, A.J., Naveira Garabato, A.C., 2006. The role of Southern Ocean mixing and upwelling in glacial–interglacial atmospheric CO_2 change. Tellus B 58 (1), 73–87. http://dx.doi.org/10.1111/j.1600-0889.2005.00167.x.

Whitehouse, M.J., Atkinson, A., Korb, R.E., Venables, H.J., Pond, D.W., Gordon, M., 2012. Substantial primary production in the land-remote region of the central and northern Scotia Sea. Deep Sea Res. Part II: Top. Stud. Oceanogr. 59–60, 47–56. http://dx.doi.org/10.1016/j.dsr2.2011.05.010.

Windom, H.L., Moore, W.S., Niencheski, L.F.H., Jahnke, R. a, 2006. Submarine groundwater discharge: a large, previously unrecognized source of dissolved iron to the South Atlantic Ocean. Mar. Chem 102 (3–4), 252–266. http://dx.doi.org/10.1016/j.marchem.2006.06.016.

Yoder, J.A., Kennelly, M.A., 2003. Seasonal and ENSO variability in global ocean phytoplankton chlorophyll derived from 4 years of SeaWiFS measurements. Glob. Biogeochem. Cycles 17 (4). http://dx.doi.org/10.1029/2002GB001942, n/a–n/a.

Ziegler, M., Diz, P., Hall, I.R., Zahn, R., 2013. Millennial-scale changes in atmospheric CO_2 levels linked to the Southern Ocean carbon isotope gradient and dust flux. Nat. Geosci. 6 (6), 457–461. http://dx.doi.org/10.1038/ngeo1782.