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Emissions from potential Patagonian dust sources and associated biological response in the Atlantic sector of the Southern Ocean

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Abstract

The effect of Patagonian dust over primary producers in the Southern Ocean has long been disputed. Here we present new remote sensing evidence in favour of dust mediated biological response and postulate a hypothesis to explain the spatial relation observed. A new remote sensing definition of dust source areas based on the Normalized Difference Vegetation Index (NDVI) and Absorbing Aerosol Index (AAI) correlation is presented and interannual variation in AAI is evaluated within the source regions as a proxy for dust activity. Correlation of this data with annual chlorophyll concentration, phytoplankton biomass, and diatom dominance reveals a spatially coherent latitudinal band of positive correlation concentrated between the Polar Front and the Subtropical Front. This pattern is restricted to western areas in the biomass correlation and extends toward Africa for the chlorophyll and diatom correlation. This region is equivalent to the area of the Subantarctic Mode Water formation, characterized by a ratio $\mathrm{Si:N} \ll 1$ in late summer, an unfavourable condition for diatom development, especially under iron limitation. Therefore, due to Si–Fe co-limitation, the positive correlation could be the consequence of an enhanced sensibility of this area to external iron addition for diatom growth. For the Argentinean shelf-break, is not clear whether direct dust input and/or wind stress driving water masses upwelling could be responsible for the positive correlation.

1 Introduction

The last three decades saw an emerging discussion on the role of micronutrients, particularly iron, as a limiting factor for marine biological production (e.g., Martin and Fitzwater, 1988; de Baar et al., 1995; Boyd et al., 2007; Westberry et al., 2013). Iron (Fe) is a co-factor of metaloenzimes on major biochemical pathways, from respiratory electron transfer reactions to chlorophyll synthesis (Geider and La Roche, 1994; Morel et al., 2003). Although it is the fourth most abundant element on the Earth's crust

(Rudnick and Gao, 2003), at the current oxidizing conditions of the atmosphere and upper ocean, it is present primarily as Fe^{3+}, which is largely insoluble in seawater (Liu and Millero, 2002). As a result, the large amounts of eroded iron added to coastal waters are removed by physical, chemical and biological processes before reaching the open ocean.

In the Southern Ocean, where Ekman divergence drives strong upwelling of deep water masses rich in dissolved macronutrients (Orsi et al., 1995; Sigman et al., 1999), observational (e.g., Pollard et al., 2009) and experimental evidences (e.g., Martin et al., 2013) have shown that additions of iron alone can modify ecosystem functioning (Moore et al., 2013), enhancing primary production, with potential consequences to the carbon cycle (Smetacek et al., 2012).

Natural direct input of iron to these waters occurs through diffusion and mixing of dissolved iron from seabed and direct aeolian deposition of mineral dust into the surface (e.g., Moore and Braucher, 2008). In the Atlantic sector of the Southern Ocean, a region over the influence of Patagonia (Li et al., 2008), models suggest that dust can be as important as oceanic sources even at the expected modern low dust flux (Fung et al., 2000; Moore and Braucher, 2008). This is a unique region of the Southern Ocean in which geological evidence points to a coupled variation of dust flux and biological production over the last 1 My (Maher et al., 2010).

However, evidences are not consistent and the relative contribution of these sources, and their impact on the ecosystem, has been a matter of intense debate over the last decade (Fung et al., 2000; Erickson et al., 2003; Cassar et al., 2007; Meskhidze et al., 2007; Johnson et al., 2011). Much of this debate is based on modelling studies, which, despite their relevance, are subject to large errors. For example, dust iron solubility is a parameter notoriously difficult to simulate, as it is dependent on its mineralogy (Journet et al., 2008), physicochemical reactions during transport (e.g., Baker and Croot, 2010), plankton diversity (e.g., Rubin et al., 2011) and chemical condition of the ocean (Bressac and Guieu, 2013). But even the dust emission and flux are largely uncertain, and modelled South American dust emission can vary by $10^3\,\mathrm{Tg\,yr^{-1}}$ between models (Huneeus et al., 2011).

Here we present a remote sensing approach to study if and where the interannual variation on dust emission from Patagonia exerts observable signal on the phytoplankton in the Atlantic sector of the Southern Ocean.

2 Methods

2.1 Source areas and dust activity

Dust and other iron containing aerosols show a characteristic absorption in the blue-ultraviolet (UV) region of the electromagnetic radiation, which increases toward more energetic wavelengths (Patterson, 1981). Therefore, the difference in the observed and modelled clear sky spectral contrast in two UV bands can be used efficiently for their identification (Herman et al., 1997). The resulting parameter, the Absorbing Aerosol Index (AAI), is regarded as a qualitative proxy (Torres et al., 2002), since beside the dust load, the microphysical properties of the aerosol and the altitude of the aerosol layer also have significant influence on its absolute value (Torres et al., 1998; De Graaf et al., 2005). However, for temporal monitoring over source regions, microphysical properties and mean altitude should present a much lower variability than dust optical thickness, allowing a quantitative use of the index. Such approach have already been verified and employed with success in other studies (e.g., Chiapello et al., 1999).

We use the scientific AAI product (version 5.1) from the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) sensor on-board the Envisat platform (Tilstra et al., 2012), to calculate interannual variation from 2003 to 2010. We exclude 2011 from the calculations due to the intense Puyehue (Chile) eruption initiated in June, which covered a vast area with thick ash deposits (Gaitán et al., 2011), prone to remobilization by wind erosion (Haller and Frumento, 2012).

To define the dust source areas within meridional South America we relied on the negative correlation of the AAI with a vegetation proxy, employed as an integrative parameter of two time varying surface properties related to dust emission (Jobbágy et al., 2002; Cropp et al., 2013): (i) the soil moisture content, which influences particle cohesion; and (ii) the abundance and structure of vegetation, which influences the transmittance of the kinetic energy from the wind to the surface (Tegen and Fung, 1994; Mahowald et al., 2005). Together, these parameters regulate the threshold wind velocity needed to initiate the dust emission over a specified region. An analysis highlighting areas where AAI increase is related to vegetation decrease could reveal areas of dust emission, provided that areas of biomass burning are excluded.

We used the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) annual Normalized Difference Vegetation Index (NDVI) data set (Feldman and McClain, 2010) as a vegetation proxy. The NDVI uses the normalized difference of the surface radiance in the red (absorbed by chlorophyll) and in the infrared spectrum (scattered by the foliar structure) to indicate vegetation abundance and structure (Brown et al., 2006). The choice of any specific NDVI data set should have little impact on the source areas definition, as arid zones are the regions with greater coherence between sensors (Brown et al., 2006) and we note that Behrenfeld et al. (2001) reported high coherence of this data set with the legacy Advanced Very High Resolution Radiometer (AVHRR) NDVI.

To promote spatial constraint, we used the spearman's ρ threshold of -0.9 below which a pixel is identified as a source region. This is the minimum negative coefficient needed to attain statistical significance at the 0.05 level with all eight years of data (2003–2010). The statistical significance is not an objective method to define source areas because a greater sample size would include areas with small correlation, but it is a convenient threshold for this first order approach. To reduce the influence of biomass burning, we further applied the constraint of a mean annual NDVI below 0.4. The results found here (see Sect. 3.1), are markedly in agreement with other estimates of source areas in Patagonia.

2.2 Phytoplankton response

The simplest and most commonly used parameter to remotely access phytoplankton responses to environmental variability is the chlorophyll *a* (Chl *a*) concentration (Cropp et al., 2005), an universal pigment in the light harvesting process of photosynthesis (Ritchie, 2006). The fast and pronounced Chl *a* increase is a known effect following relief of iron limitation on phytoplankton (de Baar et al., 2005), that is related to physiological acclimation and biomass increase (Sunda and Huntsman, 1997; Westberry et al., 2013). Recently, Westberry et al. (2013) used a series of remotely sensed proxies of phytoplankton response to revisit natural and purposed iron fertilization studies in the last decade. In line with previous studies, their results showed that although Chl *a* concentration cannot be used reliable to estimate carbon stock changes, it is a sensitive parameter to iron addition. It could therefore be used as a proxy to investigate phytoplankton response to dust derived iron inputs to the Southern Ocean.

But for the dust fertilization hypothesis, leached iron additions should have an impact on the carbon stock, due to a delay in predators to cope with increased production (Irigoien, 2005) and the increase in abundance of larger, grazer-protected species. Therefore, we also evaluate changes in remotely sensed phytoplankton carbon (C_{phyto}) (Behrenfeld et al., 2005; Westberry et al., 2008, 2013) used as a biomass proxy for primary producers. C_{phyto} is derived from single band particulate backscattering (b_{bp}) at 443 nm, based on its modelled relationship with remotely sensed reflectance ($R_{rs}(443)$).

Diatoms are the primary group to respond to iron fertilization, but growth response is not restricted to this group (Boyd et al., 2007). To evaluate which groups could be responding to dust in this area, we also employed the relative annual frequency of broad groups from the PHYSAT algorithm (Alvain et al., 2005, 2008). The PHYSAT algorithm uses 5 bands in the blue-green range of the visible electromagnetic spectrum to derive pixel dominance of 5 phytoplankton groups (Nanoeucariotes, Prochlorococcus, Synechococcus, Diatoms and Phaecystis-like) on a daily basis. Changes in the relative annual dominance frequency of these groups could be related to dust variability.

Dust over the ocean or suspended in the seawater can interfere in carbon and pigment readings by changing single band reflectance and the blue to green reflectance ratio used to calculate phytoplankton carbon stock and Chl *a* from space-born sensors (O'Reilly et al., 2000; Moulin et al., 2001; Claustre et al., 2002). This could prevent the use of Chl *a* and C_{phyto} as proxies for dust mediated biological response. However, this effect should be minimal in waters where optical properties are dominated by biological constituents. The mineral artefact effect is proportional to the relative concentrations of dust and organisms/pigments (Claustre et al., 2002; Wozniak and Stramski, 2004), being more relevant on oligotrophic areas and/or areas with high dust load in the atmosphere or in the seawater. Over the Atlantic sector of the Southern Ocean, dust load and flux are expected to be small (Gaiero et al., 2003; Li et al., 2008) and the deep mixed layer in the region would decrease the concentration of the dust deposited in the seawater (Claustre et al., 2002; De Boyer Montégut et al., 2004). Phytoplankton biomass and pigment concentration however, are moderate to high throughout the year (Allison et al., 2010). Combined, these properties minimize the noise added by dust variation, suggesting a negligible effect of dust on biological proxy estimation in this region (e.g., Johnson et al., 2011).

Level 3 SeaWiFS annual Chl *a* and GSM b_{bp} (443) data (Feldman and McClain, 2010) from 2003 to 2010 were obtained, processed (C_{phyto}) and aggregated to 1°x1° spatial resolution. Level 3 monthly relative frequencies from PHYSAT were aggregated to annual frequencies and to 1°x1° spatial resolution. These data sets were then correlated with the AAI time series over the source areas in Patagonia.

All analyses were carried out in R software (R Core Team, 2013) with aid of packages "raster" (Hijmans and Etten, 2013), "rgdal" (Bivand et al., 2013a) and "sp" (Pebesma and Bivand, 2005; Bivand et al., 2013b).

3 Results and discussion

3.1 Source areas and interannual variation on dust emission

Four possible source areas were identified in Patagonia and Tierra del Fuego Island (Fig. 1). The major areas (i.e., Areas 1 and 2, Fig. 1) are located in northern and central Patagonia, on a sparsely vegetated region (Paruelo et al., 1998) punctuated by a disperse group of ephemeral rivers and lakes that provide wind erodible material (Prospero et al., 2002; Gaiero et al., 2003). Visual examination of the Moderate Resolution Imaging Spectroradiometer (MODIS) true colour composites (not shown) suggests that only a few point sources within these areas are major contributors to dust emission. The majority of the point sources are minor contributors, collectively compounding a diffuse brow haze over the southwest coast of the Atlantic Ocean, and only rarely presenting major emission events.

The major areas identified here are very similar to those published by Prospero et al. (2002), which used AAI data in a different classification scheme, and are closely related to the areas identified by the more recent remote sensing survey of Ginoux et al. (2012). Areas 1 and 2 also correspond to areas identified by the model of Johnson et al. (2010) as the major source areas in Patagonia. Modelled source areas identified by Li et al. (2010) are somewhat similar, but their southern area is centred around 50° S, over the San Julian Great Depression, which showed only weak correlation in this study (Fig. 1).

The area in north-eastern Tierra del Fuego (Area 3, Fig. 1) has been previously described by Arche and Vilas (1986, 2001) and recently proposed by Gassó et al. (2010) as the source for mineral dust arriving at the Concordia Station (75.1° S, 123.35° E), Antarctica. Although small, it is the southernmost recognized dust source in the Southern Hemisphere. This site is located surrounding the San Sebastián bay, and is composed of seasonal dry lakes with strong wind erosion patterns (Arche and Vilas, 1986, 2001). Dust plumes from this site can be easily identified in MODIS true colour composites as elongated brown shades, due to the combination of strong westerlies south of the Andes and aggregated deflation areas.

The area in western Tierra del Fuego (Area 4, Fig. 1), however, probably represents a miss identification by the procedure employed, as this site does not hold characteristics needed for dust emission. The islands surrounding the Beagle Channel represent a mixture of exposed rocks, forests and ice caps, without significant sedimentary sites. Therefore, this site is excluded from further processing.

As the simple arithmetic mean is sensitive to even a single extreme event, we computed the 10 % trimmed mean AAI over the source regions. As expected due to area relations, AAI time series over these regions (Fig. 2) show dominance from areas 1 and 2. As dust emission could not be confirmed for area 4, time series used for further processing included only areas 1, 2 and 3. We note that this choice should exert minimal influence due to the close similarity between the time series.

3.2 Source activity and phytoplankton proxies correlation

The correlation of the mean AAI time series and Chl *a* show a clear zonal pattern of positive correlation over the Atlantic sector of the Southern Ocean downwind of Patagonia (Fig. 3a and b). This zonal area of positive correlation is bounded by the limits of the Antarctic Circumpolar Current Southern Boundary (ACC-SB) and the Subtropical Front (STF) at the north, but generally restricted at the north of the Polar Front (PF; Fig. 3a), as defined by Orsi et al. (1995). Although the zonal pattern is also visible in the C_{phyto} and AAI correlation (Fig. 3c and d), it is less clear and restricted to western areas closest to source, but with the same zonal relations.

The correlation presented is an indirect analysis of dust interaction with the Southern Ocean biological system, as the dust transport and deposition could not be evaluated. The patterns of spatial transport depend heavily on the relative position of source areas and high/low pressure zones (Johnson et al., 2011), while deposition also depends on the variable wet removal of dust particles from the atmosphere (Jickells et al., 2005). Nevertheless, spatial patterns of annual dust deposition are highly coherent among models in this region, processed for different years or periods (e.g., Mahowald et al., 2005). Together with the result showed here, this suggests that on an annual scale, spatial variations in atmospheric dust transport and deposition could be less important than dust source area activity.

Notwithstanding the indirect analysis, the resulting zonal pattern is suggestive as it bears resemblance with the Southern Ocean meridional zonation in physical, chemical and biological features (Deacon, 1982; Pollard et al., 2002). The general pattern in the Chl *a* correlation and its relation to the PF are also coherent with the results of Erickson et al. (2003), who used spatially resolved modelled dust deposition and monthly anomaly in Chl *a* data between 2000–2001.

As areas of enhanced Chl *a* are related to greater availability of iron on a first order basis (Sokolov and Rintoul, 2007), climatological distribution of Chl *a* could be used as indirect assessment of nutritional status. Also, Chl *a* absolute value is one important component of the artefact effect magnitude (Wozniak and Stramski, 2004). It is therefore valuable to analyse the relation between the climatological values of Chl *a* (1997–2010) and the correlation index. This analysis shows lack of relation (Fig. 4), suggesting small to null system scale effect of nutritional (availability of trace metals) or artefact aspects (dust interference on the Chl *a* signal) on the correlation. We also note that no clear longitudinal gradient in correlation strength along the zonal pattern is observed in Fig. 3a and b, which suggests also a lack of relation on dust flux and correlation indices, as observed by Erickson et al. (2003). As will be discussed later, this could result from a great sensitivity to even small additions of trace metals and the long range transport of dust particles suspended in the surface waters.

The similarity of the diatom annual relative dominance and dust source activity correlation pattern (Fig. 5a) with those of Chl *a* and C_{phyto}, and its association with the meridional zone between the STF and the PF suggests a determinant role of large scale circulation and biogeochemical features related to diatom ecology. This is expected, as diatoms are the primary group limited by trace metals and Si availability in the Southern Ocean (Hutchins et al., 2001; Leblanc et al., 2005).

Under prevailing limiting iron conditions of the Southern Ocean, the Si : NO_3 consumption ratio can reach ∼ 3 : 1, 2–3 times higher than in iron replete systems (e.g., Hutchins and Bruland, 1998). The higher consumption ratio results in the preferential removal of Si relative to other macronutrients from the surface waters (Hutchins and Bruland, 1998; Takeda, 1998). With the advance of the growing season, shallow and more stratified waters north of the PF in the Atlantic sector prevent sufficient resupply of Si from deeper waters (Sarmiento et al., 2004). Also, as water masses are advected northerly through the Ekman transport from the upwelling site near continental Antarctica to the PF (Sigman et al., 1999), Si is removed by the same process, resulting in advected waters with deficiency in Si relative to other macronutrients (Hutchins and Bruland, 1998). Therefore, in contrast with waters south of the PF, this region suffers a seasonal depletion of silicate in summer, reaching the limiting values for diatom growth of < 5 µM (Coale et al., 2004; De La Rocha and Passow, 2004), an Si : N < 0.5 : 1 (Garcia et al., 2010). The effect of such conditions is clear on late summer, when communities in this region are typically dominated by non-diatom groups as both revealed by fraction of biomass basis (Laubscher et al., 1993) or pigment concentration (Alvain et al., 2008).

Upon iron addition, however, despite low Si availability, diatom assembly Chl *a* and biomass can increase several fold (Hutchins et al., 2001; Leblanc et al., 2005). The result is a reduced Si : Diatom biomass and a community Si : NO_3 consumption that can drop below unity, to average values of ∼ 0.5 : 1, reducing the remaining Si to submicromolar levels (Takeda, 1998; Coale et al., 2003; Leblanc et al., 2005). It is noteworthy that controls in waters very deficient in Si (< 0.6 µM) have Si : NO_3 consumption ratio even smaller than Fe amended treatments (Hutchins et al., 2001; Leblanc et al., 2005). While Si is mainly consumed by diatoms, NO_3 can be consumed by other taxa, and the very low consumption ratio in the controls is due to a relatively low diatom growth compared with non-diatoms groups.

The mechanism behind the Fe effect in the Si : Diatom biomass and Si : NO_3 consumption ratio is not yet clear and could involve synergic interactions of physiological (growth rate), morphological (silification and/or volume) and taxonomical changes in the diatom assembly (e.g., Marchetti and Cassar, 2009). Nevertheless, these effects are consistent and can be observed even with small additions of 0.2–0.5 nM Fe to these waters (Coale et al., 2003; Leblanc et al., 2005). Therefore, a possible dust fertilization effect could extend the growing season for diatoms, which would reduce the relative annual dominance of successional groups like Synechoccocus (Alvain et al., 2008), as can be observed in Fig. 5b.

Dust dissolution could supply other trace metals to the surface layer, but their effects on diatoms ecology are not yet clear. Under Si limitation, Zinc (Zn) additions can increase the affinity of the Si uptake system, as measured by the lower half saturation constant for Si uptake (De La Rocha et al., 2000), providing competitive advantage at least for some species (Leblanc et al., 2005). But community experiments are variable in the effect of this element on diatom growth and $\mathrm{Si:NO_3}$ consumption ratios (Coale et al., 2003; Crawford et al., 2003; Leblanc et al., 2005). Nevertheless, it is interesting that Zn concentrations are very low on the area of high correlation (Wyatt et al., 2014) and that Croot et al. (2011) noted that Zn removal occurred slightly after Si removal in meridional transects in the Atlantic sector of the Southern Ocean.

But the plausibility of the dust fertilization hypothesis can be accessed for the iron effect alone. Assuming the average iron composition and solubility of Patagonian dust (Gaiero et al., 2003), it would be required a dust flux of $0.4\,\mathrm{g\,m^{-2}}$ to add 0.5 nM Fe to a 50 m mixed layer depth, a value one order of magnitude lower than that estimated for singular dust events in Patagonia (Johnson et al., 2011).

Therefore, on an annual basis, increased addition of “background” dust or increased frequency and intensity of dust events could provide measurable biological response within the gradient of iron deficiency to iron replete systems on low Si waters at least for Chl *a*. Higher iron additions would be needed for biomass increase and the exponential decay on atmospheric flux of mineral particles with distance from source could explain the response restricted to western areas. Thus, the combined constraints of at least Fe and Si on diatom growth possibly condition this region to be highly sensitive to dust derived iron additions, explaining the spatial patterns. Direct effect of silicate addition from dissolution of dust in seawater is unlikely (Boyd et al., 2010), as soluble Si represents up to 1 % of aluminum-silicate mass (Tegen and Kohfeld, 2006), only two fold higher than iron in Patagonian dust (Gaiero et al., 2003), but with 10^3 greater biological demand.

Examination of true colour composites reveals that thick Patagonian dust plumes disperse being no longer visible after a few hundred kilometres from coast and therefore direct aeolian input of biologically significant amounts of trace metals would be difficult on far off sites. However, due to the integrity and dynamism of the fronts structure (Sokolov and Rintoul, 2007) and possible long residence time of dust in the mixed layer (Boyd et al., 2010), dust deposited on the western region could be transported to distant sites, as has already been suggested for Argentinean shelf sediments (de Baar et al., 1995). Also, oceanic communities limited by micronutrients are efficient recyclers of iron. In such communities, dust derived organically bounded iron can be transported hundreds of kilometres from the addition location, as is observed downstream from islands (Sokolov and Rintoul, 2007). This longitudinal transport by ocean currents would also help to explain the observed zonal pattern, not entirely coincident with modelled dust deposition patterns.

Finally, Fig. 3 also shows a strong positive relation at the blooming region along the Argentinean shelf-break. This region potentially receives micronutrients from upwelling, shelf water and direct dust deposition (Garcia et al., 2008). Shelf water micronutrients originate from a mixed contribution of which, apart from ground water discharge, aeolian dust can contribute to a minimum of ∼ 40 % (Gaiero et al., 2003). This indicates that interannual dust variation could influence an important fraction of the micronutrients delivered to this region. Although the correlation could be an artefact of wind influence on both upwelling and dust emission (Meskhidze et al., 2007) due to the close proximity of the sites, it need not be the case as dust variation can be related to wind-independent soil moisture and vegetation variation. As direct correlation on wind speed and Chl *a* anomalies are positive for this region (Kahru et al., 2010), effects of these sources cannot be easily separated without models or field campaign, but we note that the two processes can occur simultaneously and need not be exclusive.

It is more difficult to understand the negative correlation surrounding the areas of positive correlation. Air masses leaving the principal source regions in Patagonia potentially cover all Atlantic sector of the Southern Ocean (Li et al., 2010), from the Drake Passage to Southern Africa, but are generally directed to southeast. Therefore negative (or positive) areas north of ~ 40° S may have no relation with coupled dust and biological variability. South of 60° S, sea ice dynamics and influence on biological communities would result in a lack of relation or at least a small positive correlation due to dust accumulation on sea ice and subsequent release in the same integration period (calendar year). However, areas south of ~ 60° S are also generally negative, and the mechanism behind this behaviour is not yet understood.

4 Conclusions

The effect of Patagonian dust on the productivity of Atlantic sector of Southern Ocean has generally been regarded as negligible. Unfortunately, no research team has reported a dust storm from Patagonia over the ocean, so that the magnitude of dust flux in those conditions and its associated biological response are still unknown. Therefore, until observational or experimental data are available, we have to rely only on indirect studies based on modelling and remote sensing. The present study is an attempt to contribute with further indirect evidences.

Here we presented patterns of dust source activity correlation with three remotely sensed proxies for biological response (chlorophyll *a*, phytoplankton carbon concentration and diatom relative dominance). The results showed a coherent spatial structure within the meridional zonation of the Southern Ocean, extending from South America to Africa. The correlation is interpreted in terms of dust supply of trace metals to surface waters, and represents new evidence that trace metal dissolution from dust deposition has an observable biological effect even at modern flux. The sensibility of the area north of the Polar Front is attributed to diatom co-limitation by silicate and iron, although synergic effects of other micronutrient supplied by dust could also contribute.

The possibility that Patagonian dust could help to modulate the productivity in the Atlantic sector of the Southern Ocean even at the modern low flux is important in face of the current climate change and land-use effects on dust source emission in Patagonia.

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References

Allison, D. B., Stramski, D., and Mitchell, B. G.: Seasonal and interannual variability of particulate organic carbon within the Southern Ocean from satellite ocean color observations, J. Geophys. Res., 115, C06002, doi:10.1029/2009JC005347, 2010.

Alvain, S., Moulin, C., Dandonneau, Y., and Bréon, F.-M.: Remote sensing of phytoplankton groups in case 1 waters from global SeaWiFS imagery, Deep-Sea Res. Pt. I, 52, 1989–2004, doi:10.1016/j.dsr.2005.06.015, 2005.

Alvain, S., Moulin, C., Dandonneau, Y., and Loisel, H.: Seasonal distribution and succession of dominant phytoplankton groups in the global ocean: a satellite view, Global Biogeochem. Cy., 22, GB3001, doi:10.1029/2007GB003154, 2008.

Arche, A. and Vilas, F.: Depósitos eólicos de grano fino en la Bahía de San Sebastián, Tierra del Fuego, Argentina, Acta Geològica Hispànica, 21–22, 261–266, 1986.

Arche, A. and Vilas, F.: Fine-grained aeolian sediments in San Sebastián Bay, Tierra del Fuego, Argentina, J. Iber. Geol., 27, 159–173, 2001.

Baker, A. R. and Croot, P. L.: Atmospheric and marine controls on aerosol iron solubility in seawater, Mar. Chem., 120, 4–13, doi:10.1016/j.marchem.2008.09.003, 2010.

Behrenfeld, M. J., Randerson, J. T., McClain, C. R., Feldman, G. C., Los, S. O., Tucker, C. J., Falkowski, P. G., Field, C. B., Frouin, R., Esaias, W. E., Kolber, D. D., and Pollack, N. H.: Biospheric primary production during an ENSO transition., Science, 291, 2594–2597, doi:10.1126/science.1055071, 2001.

Behrenfeld, M. J., Boss, E., Siegel, D. A., and Shea, D. M.: Carbon-based ocean productivity and phytoplankton physiology from space, Global Biogeochem. Cy., 19, GB1006, doi:10.1029/2004GB002299, 2005.

Bivand, R., Keitt, T., and Rowlingson, B.: rgdal: Bindings for the Geospatial Data Abstraction Library, available at: http://cran.r-project.org/package=rgdal, 2013a.

Bivand, R. S., Pebesma, E., and Gómez-Rubio, V.: Applied Spatial Data Analysis with R, 2nd edn., Springer New York, New York, NY, 2013b.

Boyd, P. W., Jickells, T., Law, C. S., Blain, S., Boyle, E. A., Buesseler, K. O., Coale, K. H., Cullen, J. J., de Baar, H. J. W., Follows, M., Harvey, M., Lancelot, C., Levasseur, M., Owens, N. P. J., Pollard, R., Rivkin, R. B., Sarmiento, J., Schoemann, V., Smetacek, V., Takeda, S., Tsuda, A., Turner, S., and Watson, A. J.: Mesoscale iron enrichment experiments 1993–2005: synthesis and future directions, Science, 315, 612–7, doi:10.1126/science.1131669, 2007.

Boyd, P. W., Mackie, D. S., and Hunter, K. A.: Aerosol iron deposition to the surface ocean – modes of iron supply and biological responses, Mar. Chem., 120, 128–143, doi:10.1016/j.marchem.2009.01.008, 2010.

Bressac, M. and Guieu, C.: Post-depositional processes: what really happens to new atmospheric iron in the ocean's surface?, Global Biogeochem. Cy., 27, 859–870, doi:10.1002/gbc.20076, 2013.

Brown, M. E., Pinzón, J. E., Didan, K., Morisette, J. T., Tucker, C. J., and Pinzon, J. E.: Evaluation of the consistency of long-term NDVI time series derived from AVHRR,SPOT-vegetation, SeaWiFS, MODIS, and Landsat ETM+ sensors, IEEE T. Geosci. Remote, 44, 1787–1793, doi:10.1109/TGRS.2005.860205, 2006.

Cassar, N., Bender, M. L., Barnett, B. A., Fan, S., Moxim, W. J., Levy, H., and Tilbrook, B.: The Southern Ocean biological response to aeolian iron deposition., Science, 317, 1067–70, doi:10.1126/science.1144602, 2007.

Chiapello, I., Prospero, J. M., Herman, J. R., and Hsu, N. C.: Detection of mineral dust over the North Atlantic Ocean and Africa with the Nimbus 7 TOMS, J. Geophys. Res., 104, 9277–9291, doi:10.1029/1998JD200083, 1999.

Claustre, H., Morel, A., Hooker, S. B., Babin, M., Antoine, D., Oubelkheir, K., Bricaud, A., Leblanc, K., Quéguiner, B., and Maritorena, S.: Is desert dust making oligotrophic waters greener?, Geophys. Res. Lett., 29, 1469, doi:10.1029/2001GL014056, 2002.

Cleveland, W. S.: Robust Locally Weighted Regression and Smoothing Scatterplots, J. Am. Stat. Assoc., 74, 829–836, doi:10.1080/01621459.1979.10481038, 1979.

Coale, K. H., Wang, X., Tanner, S. J., and Johnson, K. S.: Phytoplankton growth and biological response to iron and zinc addition in the Ross Sea and Antarctic Circumpolar Current along 170° W, Deep-Sea Res. Pt. II, 50, 635–653, doi:10.1016/S0967-0645(02)00588-X, 2003.

Coale, K. H., Peloquin, J., Hall, J., Safi, K., Smith Jr., W. O., Wright, S. W., and van den Enden, R.: Southern Ocean iron enrichment experiment: carbon cycling in high- and low-Si waters, Science, 304, 408–14, doi:10.1126/science.1089778, 2004.

Crawford, D. W., Lipsen, M. S., Purdie, D. A., Lohan, M. C., Statham, P. J., Whitney, F. A., Putland, J. N., Johnson, W. K., Sutherland, N., Peterson, T. D., Harrison, P. J., and Wong, C.-S.: Influence of zinc and iron enrichments on phytoplankton growth in the northeastern subarctic Pacific, Limnol. Oceanogr., 48, 1583–1600, doi:10.4319/lo.2003.48.4.1583, 2003.

Croot, P. L., Baars, O., and Streu, P.: The distribution of dissolved zinc in the Atlantic sector of the Southern Ocean, Deep-Sea Res. Pt. II, 58, 2707–2719, doi:10.1016/j.dsr2.2010.10.041, 2011.

Cropp, R. A., Gabric, A. J., McTainsh, G. H., Braddock, R. D., and Tindale, N. W.: Coupling between ocean biota and atmospheric aerosols: dust, dimethylsulphide, or artifact?, Global Biogeochem. Cy., 19, GB4002, doi:10.1029/2004GB002436, 2005.

Cropp, R. A., Gabric, A. J., Levasseur, M., McTainsh, G. H., Bowie, A. R., Hassler, C. S., Law, C. S., McGowan, H., Tindale, N. W., and Viscarra Rossel, R.: The likelihood of observing dust-stimulated phytoplankton growth in waters proximal to the Australian continent, J. Marine Syst., 117–118, 43–52, doi:10.1016/j.jmarsys.2013.02.013, 2013.

De Baar, H. J. W., de Jong, J. T. M., Bakker, D. C. E., Löscher, B. M., Veth, C., Bathmann, U., and Smetacek, V.: Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean, Nature, 373, 412–415, doi:10.1038/373412a0, 1995.

De Baar, H. J. W., Boyd, P. W., Coale, K. H., Landry, M. R., Tsuda, A., Assmy, P., Bakker, D. C. E., Bozec, Y., Barber, R. T., Brzezinski, M. A., Buesseler, K. O., Boyé, M., Croot, P. L., Gervais, F., Gorbunov, M. Y., Harrison, P. J., Hiscock, W. T., Laan, P., Lancelot, C., Law, C. S., Levasseur, M., Marchetti, A., Millero, F. J., Nishioka, J., Nojiri, Y., van Oijen, T., Riebesell, U., Rijkenberg, M. J. A., Saito, H., Takeda, S., Timmermans, K. R., Veldhuis, M. J. W., Waite, A. M., and Wong, C.-S.: Synthesis of iron fertilization experiments: from the Iron Age in the Age of Enlightenment, J. Geophys. Res., 110, C09S16, doi:10.1029/2004JC002601, 2005.

De Boyer Montégut, C., Madec, G., Fischer, A. S., Lazar, A., and Iudicone, D.: Mixed layer depth over the global ocean: an examination of profile data and a profile-based climatology, J. Geophys. Res., 109, C12003, doi:10.1029/2004JC002378, 2004.

De Graaf, M., Stammes, P., Torres, O., and Koelemeijer, R. B. A.: Absorbing Aerosol Index: sensitivity analysis, application to GOME and comparison with TOMS, J. Geophys. Res., 110, D01201, doi:10.1029/2004JD005178, 2005.

De La Rocha, C. L., Hutchins, D. A., Brzezinski, M. A., and Zhang, Y.: Effects of iron and zinc deficiency on elemental composition and silica production by diatoms, Mar. Ecol.-Prog. Ser., 195, 71–79, 2000.

De La Rocha, C. L. and Passow, U.: Recovery of *Thalassiosira weissflogii* from nitrogen and silicon starvation, Limnol. Oceanogr., 49, 245–255, doi:10.4319/lo.2004.49.1.0245, 2004.

Deacon, G. E. R.: Physical and biological zonation in the Southern Ocean, Deep-Sea Res. Pt. I, 29, 1–15, doi:10.1016/0198-0149(82)90058-9, 1982.

Erickson, D. J., Hernandez, J. L., Ginoux, P., Gregg, W. W., McClain, C., and Christian, J.: Atmospheric iron delivery and surface ocean biological activity in the Southern Ocean and Patagonian region, Geophys. Res. Lett., 30, 1–4, doi:10.1029/2003GL017241, 2003.

Feldman, G. C. and McClain, C. R.: Ocean Color Web, SeaWiFS Reprocessing 2010.0, edited by: Kuring, N. and Bailey, S. W., available at: http://oceancolor.gsfc.nasa.gov/, 2010.

Fung, I. Y., Meyn, S. K., Tegen, I., Doney, S. C., John, J. G., and Bishop, J. K. B.: Iron supply and demand in the upper ocean, Global Biogeochem. Cy., 14, 281–295, doi:10.1029/1999GB900059, 2000.

Gaiero, D. M., Probst, J.-L., Depetris, P. J., Bidart, S. M., and Leleyter, L.: Iron and other transition metals in Patagonian riverborne and windborne materials: geochemical control and transport to the southern South Atlantic Ocean, Geochim. Cosmochim. Ac., 67, 3603–3623, doi:10.1016/S0016-7037(03)00211-4, 2003.

Gaitán, J. J., Ayesa, J. A., Umaña, F., Raffo, F., and Bran, D. B.: Cartografía del área afectada por cenizas volcánicas en las provincias de Río Negro y Neuquén, in: XIX Congreso Latinoamericano de la ciencia del suelo, XXIII Congreso Aregntino de la ciencia del suelo, 2011.

Garcia, H. E., Locarnini, R. A., Boyer, T. P., Antonov, J. I., Zweng, M. M., Baranova, O. K., and Johnson, D. R.: World Ocean Atlas 2009, Volume 4: Nutrients (Phosphate, Nitrate, and Silicate), edited by: Levitus, S., US Government Printing Office, Washington DC, 2010.

Garcia, V. M. T., Garcia, C. A. E., Mata, M., Pollery, R., Piola, A., Signorini, S. R., Mcclain, C., and Iglesiasrodriguez, M.: Environmental factors controlling the phytoplankton blooms at the Patagonia shelf-break in spring, Deep-Sea Res. Pt. I, 55, 1150–1166, doi:10.1016/j.dsr.2008.04.011, 2008.

Gassó, S., Stein, A., Marino, F., Castellano, E., Udisti, R., and Ceratto, J.: A combined observational and modeling approach to study modern dust transport from the Patagonia desert to East Antarctica, Atmos. Chem. Phys., 10, 8287–8303, doi:10.5194/acp-10-8287-2010, 2010.

Geider, R. J. and La Roche, J.: The role of iron in phytoplankton photosynthesis, and the potential for iron-limitation of primary productivity in the sea, Photosynth. Res., 39, 275–301, doi:10.1007/BF00014588, 1994.

Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C., and Zhao, M.: Global scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS deep blue aerosol products, Rev. Geophys., 50, RG3005, doi:10.1029/2012RG000388, 2012.

Haller, M. J. and Frumento, O. A.: Estimating remobilization rate of ash deposited during the Puyehue (Southern Andes) eruption in 2011, in: Abstracts for the October 2012 Meeting on Volcanism in the American Southwest, Flagstaff, Arizona, edited by: Lowenstern, J. B., 1 pp., United States Geological Survey, 2012.

Harris, U. and Orsi, A. H.: Locations of the various fronts in the Southern Ocean, available at: https://data.aad.gov.au/aadc/metadata/metadata_redirect.cfm?md=/AMD/AU/southern_ocean_fronts, 2008.

Herman, J. R., Bhartia, P. K., Torres, O., Hsu, C., Seftor, C., and Celarier, E.: Global distribution of UV-absorbing aerosols from Nimbus 7/TOMS data, J. Geophys. Res., 102, 16911–16922, doi:10.1029/96JD03680, 1997.

Hijmans, R. J. and van Etten, J.: raster: geographic data analysis and modeling, [online] available at: http://cran.r-project.org/package=raster, 2013.

Huneeus, N., Schulz, M., Balkanski, Y., Griesfeller, J., Prospero, J., Kinne, S., Bauer, S., Boucher, O., Chin, M., Dentener, F., Diehl, T., Easter, R., Fillmore, D., Ghan, S., Ginoux, P., Grini, A., Horowitz, L., Koch, D., Krol, M. C., Landing, W., Liu, X., Mahowald, N., Miller, R., Morcrette, J.-J., Myhre, G., Penner, J., Perlwitz, J., Stier, P., Takemura, T., and Zender, C. S.:

Global dust model intercomparison in AeroCom phase I, Atmos. Chem. Phys., 11, 7781–7816, doi:10.5194/acp-11-7781-2011, 2011.

Hutchins, D. A. and Bruland, K. W.: Iron-limited diatom growth and Si : N uptake ratios in a coastal upwelling regime, Nature, 393, 561–564, doi:10.1038/31203, 1998.

Hutchins, D. A., Sedwick, P. N., DiTullio, G. R., Boyd, P. W., Quéguiner, B., Griffiths, F. B., and Crossley, A. C.: Control of phytoplankton growth by iron and silicic acid availability in the subantarctic Southern Ocean: experimental results from the SAZ Project, J. Geophys. Res., 106, 31559, doi:10.1029/2000JC000333, 2001.

Irigoien, X.: Phytoplankton blooms: a “loophole” in microzooplankton grazing impact?, J. Plankton Res., 27, 313–321, doi:10.1093/plankt/fbi011, 2005.

Jickells, T. D., An, Z.-S., Andersen, K. K., Baker, A. R., Bergametti, G., Brooks, N., Cao, J. J., Boyd, P. W., Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., LaRoche, J., Liss, P. S., Mahowald, N. M., Prospero, J. M., Ridgwell, A. J., Tegen, I., and Torres, R.: Global iron connections between desert dust, ocean biogeochemistry, and climate, Science, 308, 67–71, doi:10.1126/science.1105959, 2005.

Jobbágy, E. G., Sala, O. E., and Paruelo, J. M.: Patterns and controls of primary production in the Patagonian steppe: a remote sensing appoach, Ecology, 83, 307–319, doi:10.1890/0012-9658(2002)083[0307:PACOPP]2.0.CO;2, 2002.

Johnson, M. S., Meskhidze, N., Solmon, F., Gassó, S., Chuang, P. Y., Gaiero, D. M., Yantosca, R. M., Wu, S., Wang, Y., and Carouge, C.: Modeling dust and soluble iron deposition to the South Atlantic Ocean, J. Geophys. Res., 115, 1–13, doi:10.1029/2009JD013311, 2010.

Johnson, M. S., Meskhidze, N., Kiliyanpilakkil, V. P., and Gassó, S.: Understanding the transport of Patagonian dust and its influence on marine biological activity in the South Atlantic Ocean, Atmos. Chem. Phys., 11, 2487–2502, doi:10.5194/acp-11-2487-2011, 2011.

Journet, E., Desboeufs, K. V, Caquineau, S., and Colin, J.-L.: Mineralogy as a critical factor of dust iron solubility, Geophys. Res. Lett., 35, L07805, doi:10.1029/2007GL031589, 2008.

Kahru, M., Gille, S. T., Murtugudde, R., Strutton, P. G., Manzano-Sarabia, M., Wang, H., and Mitchell, B. G.: Global correlations between winds and ocean chlorophyll, J. Geophys. Res., 115, C12040, doi:10.1029/2010JC006500, 2010.

Laubscher, R. K., Perissinotto, R., and McQuaid, C. D.: Phytoplankton production and biomass at frontal zones in the Atlantic sector of the Southern Ocean, Polar Biol., 13, 471–481, doi:10.1007/BF00233138, 1993.

Leblanc, K., Hare, C. E., Boyd, P. W., Bruland, K. W., Sohst, B., Pickmere, S., Lohan, M. C., Buck, K. N., Ellwood, M. J., and Hutchins, D. A.: Fe and Zn effects on the Si cycle and diatom community structure in two contrasting high and low-silicate HNLC areas, Deep-Sea Res. Pt. I, 52, 1842–1864, doi:10.1016/j.dsr.2005.06.005, 2005.

Li, F., Ginoux, P., and Ramaswamy, V.: Distribution, transport, and deposition of mineral dust in the Southern Ocean and Antarctica: contribution of major sources, J. Geophys. Res., 113, D10207, doi:10.1029/2007JD009190, 2008.

Li, F., Ginoux, P., and Ramaswamy, V.: Transport of Patagonian dust to Antarctica, J. Geophys. Res., 115, 1–9, doi:10.1029/2009JD012356, 2010.

Liu, X. and Millero, F. J.: The solubility of iron in seawater, Mar. Chem., 77, 43–54, doi:10.1016/S0304-4203(01)00074-3, 2002.

Maher, B. A., Prospero, J. M., Mackie, D., Gaiero, D. M., Hesse, P. P., and Balkanski, Y.: Global connections between aeolian dust, climate and ocean biogeochemistry at the present day and at the last glacial maximum, Earth-Sci. Rev., 99, 61–97, doi:10.1016/j.earscirev.2009.12.001, 2010.

Mahowald, N. M., Baker, A. R., Bergametti, G., Brooks, N., Duce, R. A., Jickells, T. D., Kubilay, N., Prospero, J. M., and Tegen, I.: Atmospheric global dust cycle and iron inputs to the ocean, Global Biogeochem. Cy., 19, GB4025, doi:10.1029/2004GB002402, 2005.

Marchetti, A. and Cassar, N.: Diatom elemental and morphological changes in response to iron limitation: a brief review with potential paleoceanographic applications, Geobiology, 7, 419–31, doi:10.1111/j.1472-4669.2009.00207.x, 2009.

Martin, J. H. and Fitzwater, S. E.: Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic, Nature, 331, 341–343, doi:10.1038/331341a0, 1988.

Martin, P., van der Loeff, M. R., Cassar, N., Vandromme, P., d'Ovidio, F., Stemmann, L., Rengarajan, R., Soares, M., González, H. E., Ebersbach, F., Lampitt, R. S., Sanders, R., Barnett, B. A., Smetacek, V., and Naqvi, S. W. A.: Iron fertilization enhanced net community production but not downward particle flux during the Southern Ocean iron fertilization experiment LOHAFEX, Global Biogeochem. Cy., 27, 871–881, doi:10.1002/gbc.20077, 2013.

Meskhidze, N., Nenes, A., Chameides, W. L., Luo, C., and Mahowald, N. M.: Atlantic Southern Ocean productivity: fertilization from above or below?, Global Biogeochem. Cy., 21, 1–9, doi:10.1029/2006GB002711, 2007.

Moore, C. M., Mills, M. M., Arrigo, K. R., Berman-Frank, I., Bopp, L., Boyd, P. W., Galbraith, E. D., Geider, R. J., Guieu, C., Jaccard, S. L., Jickells, T. D., La Roche, J., Lenton, T. M., Mahowald, N. M., Marañón, E., Marinov, I., Moore, J. K., Nakatsuka, T., Oschlies, A., Saito, M. A., Thingstad, T. F., Tsuda, A., and Ulloa, O.: Processes and patterns of oceanic nutrient limitation, Nat. Geosci., 6, 701–710, doi:10.1038/ngeo1765, 2013.

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

Morel, F. M. M., Milligan, A. J., and Saito, M. A.: Marine bioinorganic chemistry: the role of trace metals in the oceanic cycles of major nutrients, in: Treatise on Geochemistry, vol. 6, edited by: Turekian, K. K. and Holland, H. D., Elsevier, Oxford, 113–143, 2003.

Moulin, C., Gordon, H. R., Chomko, R. M., Banzon, V. F., and Evans, R. H.: Atmospheric correction of ocean color imagery through thick layers of Saharan dust, Geophys. Res. Lett., 28, 5–8, doi:10.1029/2000GL011803, 2001.

O'Reilly, J. E., Maritorena, S., O'Brien, M. C., Siegel, D. A., Toole, D., Menzies, D., Smith, R. C., Mueller, J. L., Mitchell, B. G., Kahru, M., Chavez, F. P., Strutton, P., Cota, G. F., Hooker, S. B., McClain, C. R., Carder, K. L., Müller-Karger, F., Harding, L., Magnuson, A., Phinney, D., Moore, G. F., Aiken, J., Arrigo, K. R., Letelier, R., and Culver, M.: SeaWiFS postlaunch calibration and validation analyses, part 3, in: NASA Technical Memorandum 2000–206892, vol. 11, edited by: Hooker, S. B. and Firestone, E. R., NASA Goddard Space Flight Center, 49 pp., 2000.

Orsi, A. H., Whitworth, T., and Nowlin, W. D.: On the meridional extent and fronts of the Antarctic Circumpolar Current, Deep-Sea Res. Pt. I, 42, 641–673, doi:10.1016/0967-0637(95)00021-W, 1995.

Paruelo, J. M., Jobbágy, E. G., and Sala, O. E.: Biozones of Patagonia (Argentina), Ecol. Austral, 8, 145–153, 1998.

Patterson, E. M.: Optical properties of the crustal aerosol: relation to chemical and physical characteristics, J. Geophys. Res., 86, 3236–3246, doi:10.1029/JC086iC04p03236, 1981.

Pebesma, E. J. and Bivand, R. S.: Classes and methods for spatial data in R, R News, 5, 9–13, http://cran.r-project.org/doc/Rnews/, 2005.

Pollard, R. T., Lucas, M., and Read, J.: Physical controls on biogeochemical zonation in the Southern Ocean, Deep-Sea Res. Pt. II, 49, 3289–3305, doi:10.1016/S0967-0645(02)00084-X, 2002.

Pollard, R. T., Salter, I., Sanders, R. J., Lucas, M. I., Moore, C. M., Mills, R. A., Statham, P. J., Allen, J. T., Baker, A. R., Bakker, D. C. E., Charette, M. A., Fielding, S., Fones, G. R., French, M., Hickman, A. E., Holland, R. J., Hughes, J. A., Jickells, T. D., Lampitt, R. S., Morris, P. J., Nédélec, F. H., Nielsdóttir, M., Planquette, H., Popova, E. E., Poulton, A. J., Read, J. F., Seeyave, S., Smith, T., Stinchcombe, M., Taylor, S., Thomalla, S., Venables, H. J., Williamson, R., and Zubkov, M. V: Southern Ocean deep-water carbon export enhanced by natural iron fertilization., Nature, 457, 577–80, doi:10.1038/nature07716, 2009.

Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., and Gill, T. E.: Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, Rev. Geophys., 40, 1–31, doi:10.1029/2000RG000095, 2002.

R Core Team: R: A language and environment for statistical computing, available at: http://www.r-project.org/, 2013.

Ritchie, R. J.: Consistent sets of spectrophotometric chlorophyll equations for acetone, methanol and ethanol solvents, Photosynth. Res., 89, 27–41, doi:10.1007/s11120-006-9065-9, 2006.

Rubin, M., Berman-Frank, I., and Shaked, Y.: Dust- and mineral-iron utilization by the marine dinitrogen-fixer trichodesmium, Nat. Geosci., 4, 529–534, doi:10.1038/ngeo1181, 2011.

Rudnick, R. L. and Gao, S.: 3.01 – Composition of the continental crust, in: Treatise on Geochemistry, vol. 3, edited by: Holland, H. D. and Turekian, K. K., Pergamon, Oxford, 1–64, 2003.

Sarmiento, J. L., Gruber, N., Brzezinski, M. A., and Dunne, J. P.: High-latitude controls of thermocline nutrients and low latitude biological productivity, Nature, 427, 56–60, doi:10.1038/nature02127, 2004.

Sigman, D. M., Altabet, M. A., McCorkle, D. C., Francois, R., and Fischer, G.: The δ^{15}N of nitrate in the southern ocean: consumption of nitrate in surface waters, Global Biogeochem. Cy., 13, 1149–1166, doi:10.1029/1999GB900038, 1999.

Smetacek, V., Klaas, C., Strass, V. H., Assmy, P., Montresor, M., Cisewski, B., Savoye, N., Webb, A., D'Ovidio, F., Arrieta, J. M., Bathmann, U. V., Bellerby, R. G. J., Berg, G. M., Croot, P. L., Gonzalez, S., Henjes, J., Herndl, G. J., Hoffmann, L. J., Leach, H., Losch, M., Mills, M. M., Neill, C., Peeken, I., Röttgers, R., Sachs, O., Sauter, E., Schmidt, M. M., Schwarz, J., Terbrüggen, A., and Wolf-Gladrow, D.: Deep carbon export from a Southern Ocean iron-fertilized diatom bloom, Nature, 487, 313–319, doi:10.1038/nature11229, 2012.

Sokolov, S. and Rintoul, S. R.: On the relationship between fronts of the Antarctic Circumpolar Current and surface chlorophyll concentrations in the Southern Ocean, J. Geophys. Res., 112, C07030, doi:10.1029/2006JC004072, 2007.

Sunda, W. G. and Huntsman, S. A.: Interrelated influence of iron, light and cell size on marine phytoplankton growth, Nature, 2051, 389–392, doi:10.1038/37093, 1997.

Takeda, S.: Influence of iron availability on nutrient consumption ratio of diatoms in oceanic waters, Nature, 393, 774–777, doi:10.1038/31674, 1998.

Tegen, I. and Fung, I. Y.: Modeling of mineral dust in the atmosphere: sources, transport, and optical thickness, J. Geophys. Res., 99, 22897–22914, doi:10.1029/94JD01928, 1994.

Tegen, I. and Kohfeld, K. E.: Atmospheric transport of silicon, in: The Silicon Cycle?: Human Perturbations and Impacts on Aquatic Systems, edited by: Ittekkot, V., Unger, D., Humborg, C., and An, N. T., Island Press, 81–92, 2006.

Tilstra, L. G., De Graaf, M., Aben, I., and Stammes, P.: In-flight degradation correction of SCIAMACHY UV reflectances and absorbing aerosol index, J. Geophys. Res., 117, D06209, doi:10.1029/2011JD016957, 2012.

Torres, O., Bhartia, P. K., Herman, J. R., Ahmad, Z., and Gleason, J.: Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation: theoretical basis, J. Geophys. Res., 103, 17099–17110, doi:10.1029/98JD00900, 1998.

Torres, O., Herman, J. R., Bhartia, P. K., and Sinyuk, A.: Aerosol properties from EP-TOMS near UV observations, Adv. Space Res., 29, 1771–1780, doi:10.1016/S0273-1177(02)00109-6, 2002.

Westberry, T. K., Behrenfeld, M. J., Milligan, A. J., and Doney, S. C.: Retrospective satellite ocean color analysis of purposeful and natural ocean iron fertilization, Deep-Sea Res. Pt. I, 73, 1–16, doi:10.1016/j.dsr.2012.11.010, 2013.

Wozniak, S. B. and Stramski, D.: Modeling the Optical Properties of Mineral Particles Suspended in Seawater and their Influence on Ocean Reflectance and Chlorophyll Estimation from Remote Sensing Algorithms, Appl. Optics, 43, 3489, doi:10.1364/AO.43.003489, 2004.

Wyatt, N. J., Milne, A., Woodward, E. M. S., Rees, A. P., Browning, T. J., Bouman, H. A., Worsfold, P. J., and Lohan, M. C.: Biogeochemical cycling of dissolved zinc along the GEOTRACES South Atlantic transect GA10 at 40° S, Global Biogeochem. Cy., 28, 44–56, doi:10.1002/2013GB004637, 2014.

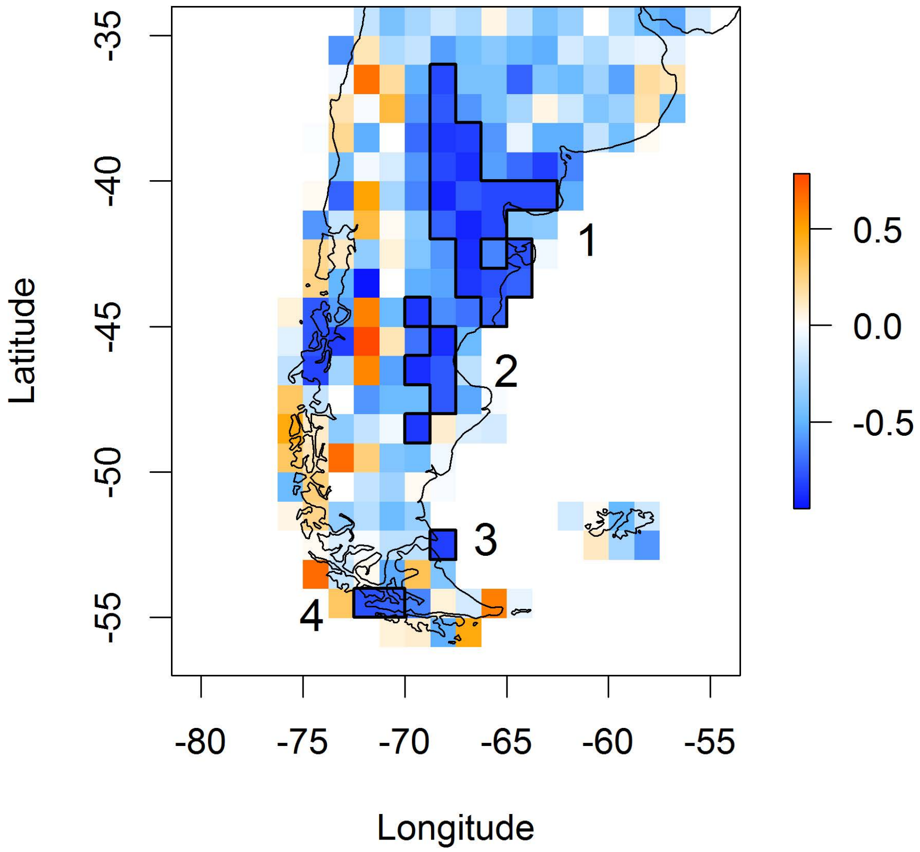

Figure 1. Final contour of identified "source areas" overlaid on the AAI × NDVI correlation map. Visually confirmed source areas are: (1) northern Patagonia, (2) central Patagonia, and (3) northeastern Tierra del Fuego; area 4, in western Tierra del Fuego, was not confirmed and is probably a miss identification (see text).

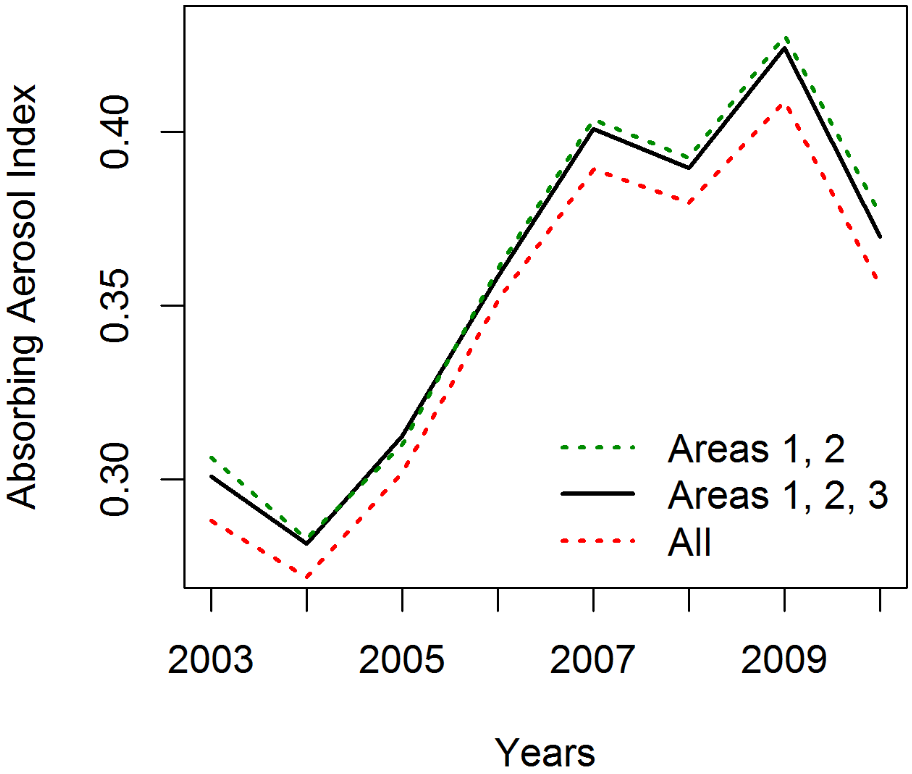

Figure 2. Mean SCIAMACHY AAI time series over source regions.

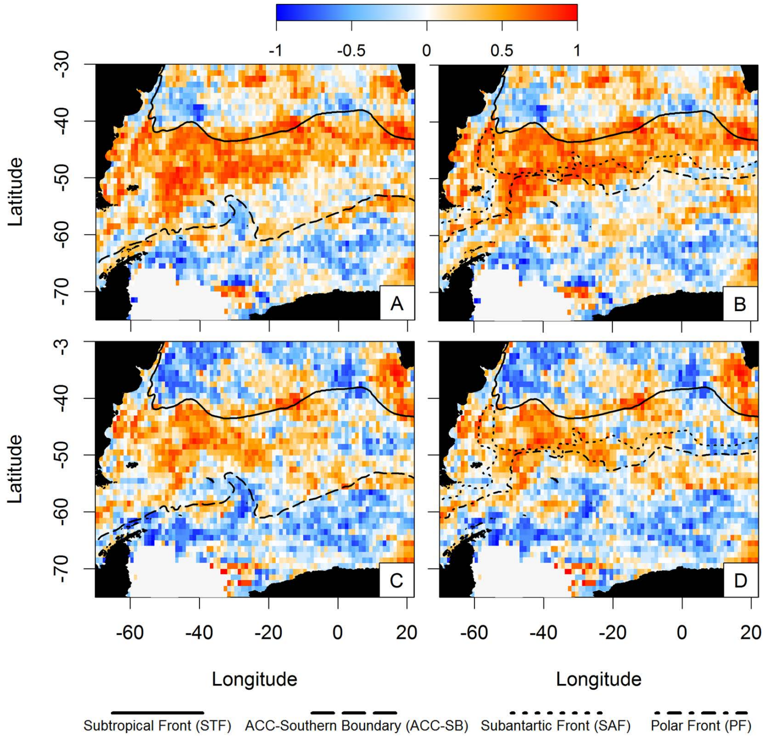

Figure 3. Correlation of mean AAI over source areas in Patagonia and Chl *a* **(A, B)** and C_{phyto} **(C, D)** over the Atlantic sector of the Southern Ocean. (**A** and **C**) show the ocean fronts delimiting the larger spatial extent of the correlations, while (**B** and **D**) superimpose ocean fronts delimiting areas with higher correlations. Grey corresponds to areas with < 4 years of phytoplankton data. The fronts positions were obtained from Harris and Orsi (2008).

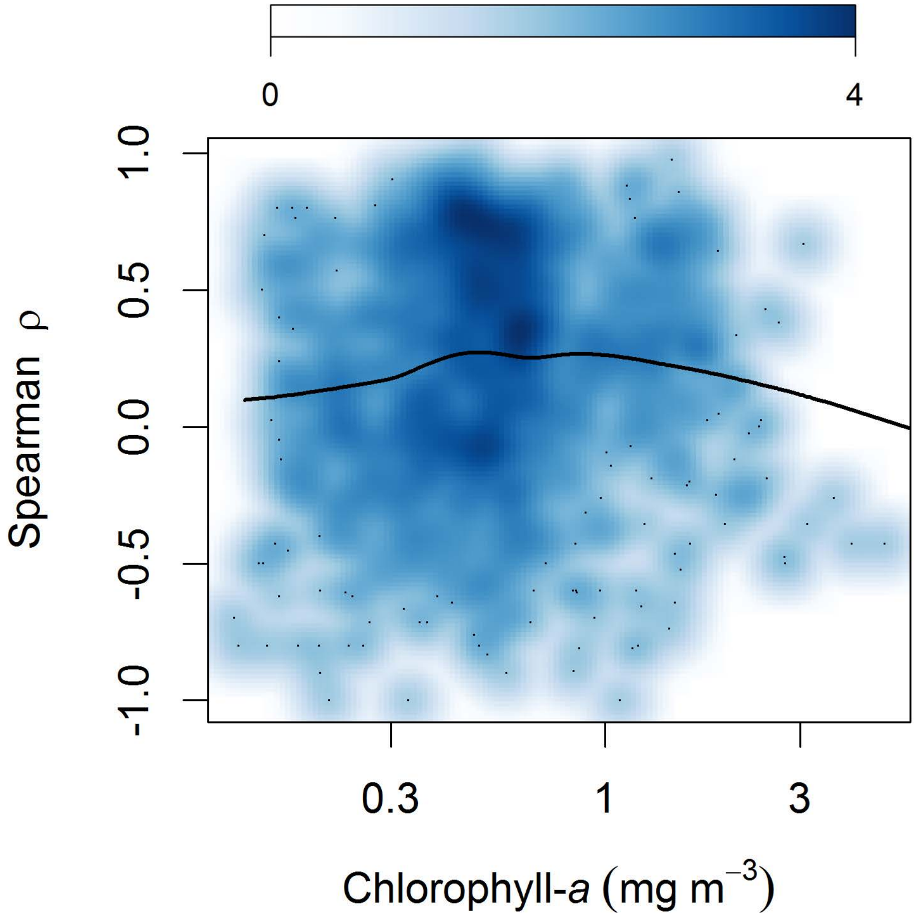

Figure 4. Density plot of Spearman correlation indices dependency on Chl *a* for the Southern Ocean (> 40° S). Colour scale show number of points per bin. Thick line shows a robust locally weighted regression (Cleveland, 1979).

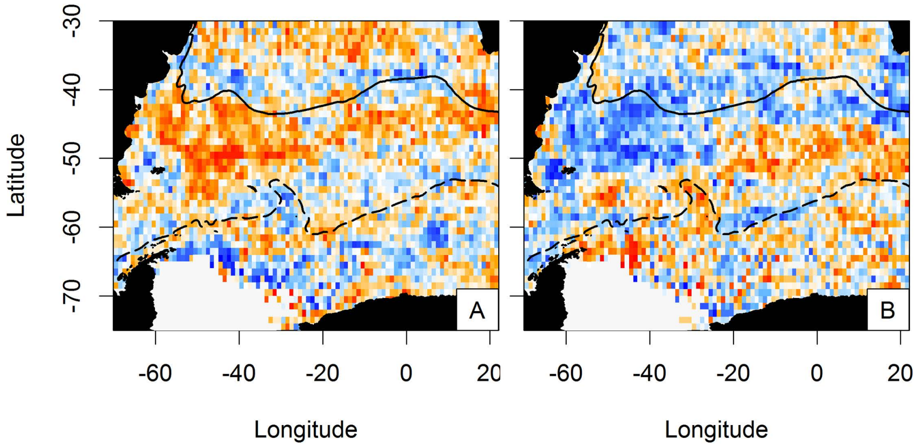

Figure 5. Correlation of mean AAI over source areas in Patagonia and Diatom **(A)** and Synechococcus **(B)** relative abundances over the Atlantic sector of the Southern Ocean. Grey corresponds to areas with < 4 years of phytoplankton data. The scale is the same of Fig. 3.