Evaluating the importance of atmospheric and sedimentary iron sources to Southern Ocean biogeochemistry.

Alessandro Tagliabue, Laurent Bopp, Olivier Aumont

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Alessandro Tagliabue,[1] Laurent Bopp,[1] and Olivier Aumont[2]

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[1] The predominant iron sources to the Southern Ocean (SO) are atmospheric deposition and sediment supply from the continental margin and their relative importance in governing SO carbon export remains a subject of great debate. Here we report the results of simulations conducted with an ocean general circulation and biogeochemistry model (OGCBM) to quantify the importance of each source at different spatial scales at quasi-equilibrium. Overall, we find sediment derived iron is more important than dust derived iron in sustaining SO export production (by 1.4 to 9 times). Although dust iron is important in certain geographic sectors of the SO, this largely depends on the dust model employed. Apparent geographical correlations between dust deposition and export production can be misleading, since sediment iron can be transported to similar regions. Future generation OGCBMs must better represent spatial variability in deposition fluxes and iron solubility from dust, as well as the poorly constrained, yet regionally important, sediment source. **Citation:** Tagliabue, A., L. Bopp, and O. Aumont (2009), Evaluating the importance of atmospheric and sedimentary iron sources to Southern Ocean biogeochemistry, *Geophys. Res. Lett.*, *36*, L13601, doi:10.1029/2009GL038914.

1. Introduction

[2] The importance of iron (Fe) in governing phytoplankton growth rates and macronutrient utilization in the high nutrient low chlorophyll (HNLC) regions of the worlds oceans has become well established [e.g., *de Baar et al.*, 2005]. Of such regions, the Southern Ocean (SO) is the largest, contains the greatest unused reservoir of macronutrients, and plays a crucial role in the ocean uptake flux of atmospheric CO_2 (FCO_2) [e.g., *Takahashi et al.*, 2009]. Accordingly, Fe modulation of SO productivity and the sequestration of carbon in the ocean interior might be important in understanding how this key oceanic region will respond to postulated future environmental changes [e.g., *Sarmiento et al.*, 2004].

[3] In general, exogenous Fe enters the ocean system via atmospheric deposition (both wet and dry), sediment resuspension, riverine input and hydrothermal activity. Of these, atmospheric deposition has received by far the largest attention [e.g., *Jickells et al.*, 2005], although the potential importance of sedimentary supply is beginning to be acknowledged [*Elrod et al.*, 2004; *Aumont and Bopp*, 2006; *Lam et al.*, 2006; *Blain et al.*, 2007; *Tagliabue et al.*, 2008; *Moore and Braucher*, 2008; A. R. Bowie et al., Biogeochemical iron budgets for subantarctic and polar waters south of Australia during summer, submitted to *Global Biogeochemical Cycles*, 2009]. Recent modeling work suggests variability in chlorophyll induced by concomitant variability in dust fluxes is low, relative to ocean dynamics [*Aumont et al.*, 2008] and that, notwithstanding local changes, the impact of dust Fe variability is reduced when a sediment source is also included [*Tagliabue et al.*, 2008]. However, *Cassar et al.* [2007] used field measurements of net community production and modeled dust deposition in the SO to conclude that export production was strongly coupled to dust deposition. On the other hand, another recent study contends that dust deposition of Fe to the SO is largely overestimated by dust models [*Wagener et al.*, 2008]. As such, a better understanding of the regional importance of sedimentary and atmospheric Fe to carbon export is necessary.

[4] In this study, we report the results of simulations with the OGCBM PISCES [*Aumont and Bopp*, 2006] assuming either no dust or no sediment source of Fe at quasi-equilibrium. We examine the regional importance of sedimentary and atmospheric iron sources to SO biogeochemistry, the significance of geographically based correlations and discuss avenues for future research.

2. Methods

[5] We use the OGCBM PISCES, which has been employed for a variety of studies concerning ocean biogeochemistry [e.g., *Aumont et al.*, 2008; *Tagliabue et al.*, 2008]. In brief, PISCES includes nanophytoplankton and diatoms, meso- and micro-zooplankton, 2 detrital sizes, carbon-13, calcium carbonate, biogenic silica, dissolved inorganic carbon, carbonate, dissolved organic carbon, nitrate, phosphate, silicic acid, and Fe [*Aumont and Bopp*, 2006]. Fixed ratios are employed for nitrate and phosphate, while the ratios of both silica, and Fe, to carbon vary.

[6] The fundamentals of the PISCES Fe cycle processes remain the same as previously detailed [*Aumont and Bopp*, 2006; *Tagliabue et al.*, 2008], with Fe supplied from atmospheric deposition, sediments, and rivers. Pre-industrial dust deposition (*dustdep*) is from *Mahowald et al.* [2006] and we assume Fe is 3.5% of dust ($Fe_{content}$) with a solubility (Fe_{sol}) of 0.5% [see *Tagliabue et al.*, 2008]. We also account for the subsurface dissolution of dust particles by assuming that dust particles sink at 5 m d^{-1} and dissolve at 0.0002% d^{-1} [*Aumont and Bopp*, 2006]. In subsequent analyses it is the dissolved Fe (dFe) flux from dust that we will consider, rather than the total dust flux (i.e., Fe_{dep} =

[1]Laboratoire des Sciences du Climat et de l'Environnement, UVSQ, IPSL, CEA, CNRS, Gif-sur-Yvette, France.
[2]Laboratoire d'Océanographie et Climatologie: Expérimentation et Approches Numériques, IRD, IPSL, Plouzané, France.

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Table 1. Percentage Contribution by Region to Total Carbon Export (ExP), Dust Supply of Fe (Dust Fe), Sediment Supply of Fe (Sed Fe) and Total Fe Inputs (Total Fe) for the SO South of 35°S[a]

	Percent of Total (>35°S)				Δ ExP	
Region	ExP	Dust Fe	Sed Fe	Total Fe	Nodust	Nosed
Atlantic	24.03	56.36	29.63	37.13	−19	−20
West Indian	20.78	9.87	3.7	5.43	−17	−16
East Indian	13.58	14.23	13.33	13.59	−14	−15
West Pacific	16.96	14.23	14.07	14.12	−14	−18
East Pacific	13.68	4.36	12.59	10.28	−7	−14
Shelf	10.97	0.95	26.67	19.45	−5	−47
TOTAL	100	100	100	100	−14	−20

[a]For reference, annual total carbon export, dust supply of dFe and sediment supply of dFe is 2.37 Pg C, 29.4×10^9 g dFe, and 75.4×10^9 g dFe, respectively. The final two columns detail the percentage change in ExP (ΔExP) for each region during the *nodust* and *nosed* runs (see Methods). The Atlantic region (ATL) is between 70°W and 20°E. The West Indian region (W-IND) is between 20°E and 90°E. The East Indian region (E-IND) is between 90°E and 150°E. The West Pacific region (W-PAC) is between 150°E and 140°W. The East Pacific region (E-PAC) is between 140°W and 70°W. All offshore regions are between 35°S and 65°S, whereas the Antarctic continental shelf region (SHELF) is defined as the circumpolar region south of 65°S.

$dustdep*Fe_{content}*Fe_{sol}$). The total integrated annual Fe_{dep} from dust is 29.4×10^9 g dFe (>35°S), which is similar to 23.6×10^9 g dFe from *Tegen and Fung* [1995]. The sediment Fe source is a function of bathymetry and uses a high resolution topographical map to calculate a shelf Fe flux that is a function of depth (a proxy for the oxygen content of the sediment) for each model grid cell (see *Aumont and Bopp* [2006] for more details) and results in an annual flux of 75.4×10^9 g dFe (>35°S). As discussed by *Tagliabue et al.* [2008], PISCES is able to reproduce global dFe distributions. Correlation coefficients with a dFe observational database [*Moore and Braucher*, 2008] (after log transformation) from the *control* simulation (>35°S) are 0.61 (n = 2438) and 0.48 (n = 250) between 0–100m and 1000–2000m, respectively, for the SO (>35°S).

3. Experimental Design

[7] PISCES was spun up for 3000 years under pre industrial forcing, which resulted in NPP, export production (the flux of organic carbon at 100m, ExP) and FCO_2 of 41, 8.1, and −0.19 PgC a^{-1} (thereby balancing riverine input and sediment burial), respectively. We then performed sensitivity simulations wherein either dust or sediment was assumed to have no Fe (*nodust* and *nosed*, respectively), which were each integrated for a further 500 years (at which point the rate of change in FCO_2 is ∼0) alongside a *control* simulation. To evaluate the regional importance of atmospheric and sedimentary Fe, we divided the SO into regions (see Table 1 legend). Firstly, we calculated the total Fe inputs to a given region and the simulated ExP when both sources of Fe are present (i.e., during the *control* simulation). We then used these regions as a framework within which to explore the spatial response of ExP to our *nodust* and *nosed* experiments.

4. Results

[8] Using the *control* simulation we can already examine the relationship between Fe inputs and ExP for our defined SO regions (Table 1). The Atlantic Ocean region (ATL) region has the largest ExP (24% of total) and receives the greatest total Fe inputs (37% of total), which result from dust that originates in southern South America (56% of total) and sediment Fe from the Patagonian continental shelf (30% of total). The eastern Indian (E-IND) and western Pacific (W-PAC) regions also receive moderately high Fe inputs (both ∼14% of total) and contribute 14 and 17% to total ExP, respectively. The E-IND and W-PAC regions receive dust from the Australian continent and sediment Fe from the continental plateau that encompasses the region south east of Australia and New Zealand. Despite receiving only 15% of total Fe inputs (from dust and sediment sources) combined, the eastern Pacific (E-PAC) and western Indian (W-IND) ocean regions contribute a combined 35% to total SO ExP (Table 1). In other words, over one third of total ExP is supported by little direct Fe input. Finally, the Antarctic shelf region receives the lowest dust fluxes (<1% of total), but the second highest sedimentary flux of Fe (27% of total) from its extensive continental shelf and this region contributes almost 11% to total SO ExP (Table 1). Overall, the spatial distribution of ExP in the SO reflects the importance of local and non-local sources of Fe from both sediments and the atmosphere.

[9] Over the entire SO, sediment Fe is at least as important as dust-derived Fe and, in some places, is the dominant driver of ExP. We use the percentage change in ExP during *nodust* and *nosed* to quantitatively evaluate the importance of each source for a given region (Table 1). At the extremes, the high ExP rates typical of the ATL region are controlled to a similar degree by dust and sediment Fe, while those on the continental shelf are almost entirely controlled by sediment Fe. For the 2 regions that receive little direct input of Fe, it is apparent sediment Fe is a major contributor to ExP in the E-PAC, whereas both dust and sediment Fe play roughly equal roles in the W-IND (Table 1). In the E-PAC, Fe supplied from the large shelf south east of Australia and New Zealand is twice as important as dust deposition, while in the E-IND, dust and sediments are equally important (Table 1). Across the entire SO (>35°S), sediment Fe is around 1.4 times more important than dust Fe in supporting ExP (Table 1).

[10] Although, in general, ExP and dFe anomalies are greater during *nosed*, dust Fe is important in certain regions of the SO. Local dFe concentrations and ExP in the ATL region appear to be controlled by both Patagonian dust and shelf Fe (Figure 1). East of Patagonia, the W-IND region relies slightly more upon dust Fe than shelf-derived Fe to elevate Fe concentrations and thus ExP (Figure 1). Since the W-IND receives only 10% of total dust inputs (Table 1), model results suggest that transport of unused dust Fe from the ATL to the W-IND could be an important Fe supply mechanism. In contrast, Fe and ExP anomalies in the W-PAC and E-PAC regions are more influenced by the long range transport of sediment derived Fe than Australasian dust (Figure 1).

5. Discussion

[11] The importance our simulations ascribe to sedimentary derived Fe (in terms of SO ExP) partly disagrees with the coupling between dust and ExP noted by *Cassar et al.*

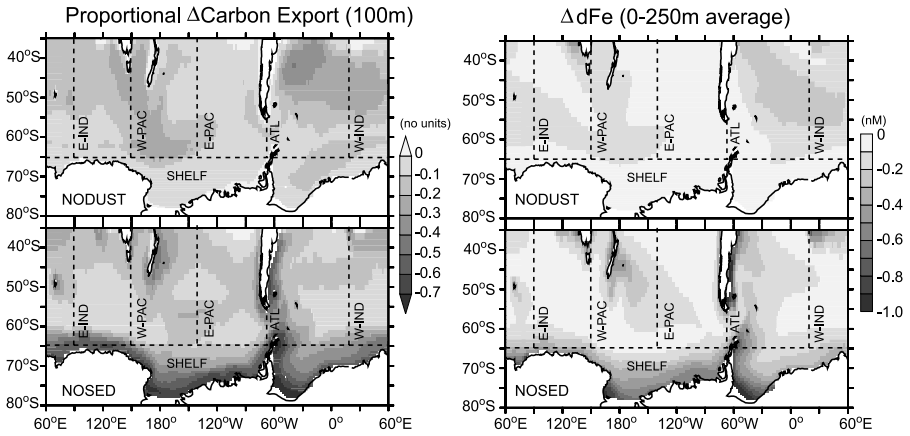

Figure 1. Anomalies in carbon export (proportional, at 100m, no units) and dFe (absolute, surface to 250m average, nM) for the (top) *nodust* and (bottom) *nosed* simulations, relative to the *control* simulation.

[2007], but supports the study of *Wagener et al.* [2008]. To resolve these differences, we examined the spatial relationship between modeled dust deposition and ExP (in a similar fashion to *Cassar et al.* [2007]; Table 2), both with and without dust Fe. Our analysis underscores our previously noted relationship between dust Fe and ExP in the ATL region ($R^2 = 0.54$), which declines when dust is assumed to contain no Fe ($R^2 = 0.27$). The W-IND region exhibits the highest R^2 (0.72), but since this changes little when dust contains no Fe (to 0.67) it suggests that Fe advected from the Patagonian shelf might also be important in supporting ExP therein and the high correlation with dust fluxes could be coincidental. In the remaining regions of the SO there is, at best, a weak relationship between dust and ExP (Table 2) that changes little when dust contains no Fe (Table 2). Our analysis suggest that any coupling between dust deposition and ExP outside of the ATL region is not causal, since sediment Fe is evidently supplied to similar locations and this will complicate the interpretation of geographically-based correlations. Moreover, if SO dust models do indeed overestimate Fe supply [*Wagener et al.*, 2008] then this may further lessen the importance of dust Fe, even in the ATL [e.g., *Meskhidze et al.*, 2007].

[12] The relationship between dust deposition and ExP is controlled by the ratio of carbon exported to Fe deposited by dust (Fe_{dep}/ExP), which measures the Fe demand of a given region/parcel of water rather than that of the phytoplankton (which is Fe_{phy}/C_{phy}). Fe_{dep}/ExP can deviate from Fe_{phy}/C_{phy} if 1) non-biogenic losses of dust Fe are high, 2) unused dust Fe is transported large distances or 3) an additional Fe source also fuels ExP and phytoplankton uptake of Fe and C. We calculate the difference between Fe_{dep}/ExP and Fe_{phy}/C_{phy} (average over the top 100m) for our *control* simulation and denote this as Φ (μmol Fe mol C^{-1}). While it is apparent that regions of high dust deposition (i.e., adjacent to Australian and Patagonian sources) provide more dust per unit ExP than is required by the phytoplankton, they are also typified by high rates of non-biogenic dFe loss, i.e., $\Phi \gg 0$ (Figure 2). Outside of the high dust regions, Φ is negative (Figure 2), which highlights the importance of non-local Fe sources in reconciling low values of Fe_{dep}/ExP with higher Fe_{phy}/C_{phy} values (typically 5–10 μmol Fe mol C^{-1}). We find all waters south of ~60°S, as well as large areas of the EPAC and WIND regions, to be typified by negative Φ (Figure 2). Overall our simulations suggest that 56.4% of all waters south of 35°S have negative Φ, further highlighting the importance of non-local Fe inputs and, in particular, sediment sources (Figures 1 and 2).

[13] Field observations of net community production (NCP, used to infer ExP) and modeled dust deposition produce a global SO Fe_{dep}/C_{ex} ratio of 2.5 μmol Fe mol C^{-1} [*Cassar et al.*, 2007]. If translated directly to Fe_{phy}/C_{phy}, such a value is typical of species that are either highly adapted to low Fe concentrations or high light levels [e.g., *Raven*, 1990; *Sunda and Hunstman*, 1997] and would

Table 2. A Spatial Analysis of the Relationship Between Modeled Dust Deposition and Carbon Export by Region[a]

	Dust Contains Fe		Dust Does Not Contain Fe	
Region	R^2	Slope	R^2	Slope
Atlantic	0.54	0.6	0.27	0.3
West Indian	0.72	7.7	0.67	6.4
East Indian	0.28	1.4	0.26	1.2
West Pacific	0.43	2.3	0.54	2.6
East Pacific	0.28	2.2	0.34	2.6
Circumpolar	0.36	0.6	0.18	0.4

[a]When dust is (i.e., *control* simulation) and is not assumed to contain Fe (i.e., *nodust* simulation). When dust does not contain Fe, continental shelf sediments are the sole source of Fe and we compare the resulting carbon export to the dust deposition from the *control* simulation. The slope is in units of $\times 10^5$ mol C (mol Fe $yr^{-1})^{-1}$. We do not include the shelf region and other regions are as specified in the Table 1 legend (with 'circumpolar' being between 35–65°S).

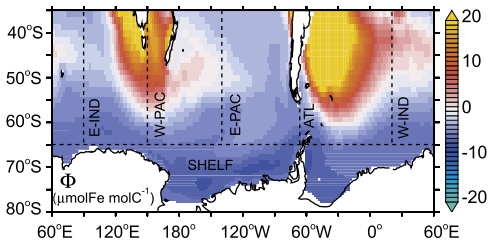

Figure 2. Φ (Fe_{dep}/ExP − Fe_{phy}/C_{phy}, μmol Fe mol C^{-1}) for the *control* simulation.

require minimal scavenging of the dust-deposited Fe to be reconciled with these specific environmental conditions. Although certain phytoplankton taxa can exhibit Fe_{phy}/C_{phy} values that approach 2.5 μmol Fe mol C^{-1}, such as the haptophyte *Phaeocystis antarctica* that dominates the Ross Sea ecosystem [*Sunda*, 1997], values greater than 5 μmol Fe mol C^{-1} appear more typical of offshore SO waters [*Twining et al.*, 2004; *Frew et al.*, 2006]. In agreement we find Fe_{phy}/C_{phy} values of between 5 and 10 μmol Fe mol C^{-1}. However, if continental shelf sediments are a significant dFe source, then the ExP fuelled by this unconsidered source would explain the relatively low Fe_{dep}/C_{ex} ratio reported by *Cassar et al.* [2007].

6. Future Work

[14] Improving our understanding of the relative roles of sediment and atmospheric Fe in controlling SO ExP and dFe will require improvements in the representation of these sources in future OGCBMs. For dust Fe, the discrepancies between modeled and observed dust fluxes [*Wagener et al.*, 2008] must be addressed. Moreover, all OGCBMs currently assume dust has a fixed $Fe_{content}$ and Fe_{sol} in seawater [e.g., *Aumont and Bopp*, 2006; *Moore and Braucher*, 2008]. Recent observations highlight variability in Fe_{sol} that is likely driven by mineralogy, particle size, atmospheric transit time (and hence exposure to photochemical reactions), aerosol type (anthropogenic or natural), and the mode of deposition (wet or dry) [e.g., *Baker and Croot*, 2009]. The impact of including such factors [e.g., *Fan et al.*, 2006] in an OGCBM needs to be addressed at the regional and global scales.

[15] As an additional sensitivity test, we also examined the importance of eliminating sediment Fe (i.e., making dust the only source and following an identical experimental design) when dust deposition was taken from the LMDzT-INCA model [*Balkanksi et al.*, 2004]. Fe_{dep} from LMDzT-INCA to the SO (4.6×10^9 g dFe) is around 6-fold lower that that of our *control* (despite having an Fe_{sol} of 1.4%), which positions it more in line with recent observations suggestive of lower fluxes [*Wagener et al.*, 2008] (Figure S1 of the auxiliary material).[1] Unsurprisingly, when LMDzT-INCA deposition is the only source of dFe, ExP declines by ~30%, and sediment Fe becomes almost 9-times more important than dust in supporting SO ExP. While using LMDzT-INCA only further enhances the role of sediment Fe, we draw attention to regional changes in ExP and dFe anomalies, mostly due the reduced Patagonian dust source (Figure S2).

[16] Regarding sediment Fe, although the current parameterization that relates the ensuing Fe flux to shelf depth (a proxy for redox conditions [*Aumont and Bopp*, 2006]) is relatively simple, it is clearly an improvement on not considering such a source of Fe (see *Tagliabue et al.* [2008] for a discussion). However, the role of spatial and temporal variability in sediment type and redox conditions will likely play a role in driving more regional heterogeneity in the sediment Fe source than is currently considered. We hope new SO measurements as part of GEOTRACES will aid in better representing this important source of Fe in OGCBMs. Finally, we also draw attention to the potential role of sea ice [e.g., *Lannuzel et al.*, 2007] as a means by which water column and dust derived Fe can be stored, transported, and released to surface waters as a springtime pulse (not included in the OGCBM-PISCES at present).

7. Conclusions

[17] We used an OGCBM to address the relative importance of Fe derived from atmospheric deposition and the continental shelf in governing variability in SO ExP. We find that the relative importance of each source varies by region and that sediment-derived Fe is 1.4 to 9 times as important as dust Fe in sustaining SO ExP (depending on the dust model). Outside of the ATL, geographic correlations between dust deposition and ExP that are used to infer causality [e.g., *Cassar et al.*, 2007] can be complicated by the transport of sediment-derived Fe to similar locations to where dust is deposited. We draw attention to the role of sediment Fe when attempting to reconcile estimates of Fe_{dep}/C_{ex} with Fe_{phy}/C_{phy}. Future improvements in the representation of Fe_{sol} and, in particular, spatio-temporal variability in the sediment-derived Fe flux will aid further understanding of how variability in these Fe sources controls SO ExP over various timescales.

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O. Aumont, Laboratoire d'Océanographie et Climatologie: Expérimentation et Approches Numériques, IRD, IPSL, BP 70, F-29280 Plouzané CEDEX, France.

L. Bopp and A. Tagliabue, Laboratoire des Sciences du Climat et de l'Environnement, UVSQ, IPSL, CEA, CNRS, Orme des Merisiers, Bat 712, F-91198 Gif-sur-Yvette CEDEX, France. (alessandro.tagliabue@lsce.ipsl.fr)