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What does temporal variability in aeolian dust deposition contribute to sea-surface iron and chlorophyll distributions?

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[1] Dust deposition is extremely variable over all timescales. Yet the impact of this variability on ocean biogeochemistry is currently not known, at least on the global scale. Here, we force a global model of ocean biogeochemistry over 1996 to 2001 with daily fields of dust deposition simulated by an atmospheric aerosol model. Our model results suggest that dust deposition explains a large part of the temporal variability of surface iron in the tropical regions and in part of the subarctic Pacific. However, while dust deposition is dominated by daily events, its impact on surface iron is maximal on interannual timescales. The largest fluctuations of surface iron produced by dust occur in oligotrophic regions where phytoplankton growth is not primarily controlled by iron availability. Consequently, the variability of surface chlorophyll induced by aerosol iron is predicted to be very small everywhere, especially relative to the impact of the ocean dynamics. **Citation:** Aumont, O., L. Bopp, and M. Schulz (2008), What does temporal variability in aeolian dust deposition contribute to sea-surface iron and chlorophyll distributions?, *Geophys. Res. Lett.*, *35*, L07607, doi:10.1029/2007GL031131.

1. Introduction

[2] As a result of numerous in situ, laboratory and modeling studies, iron is now undoubtedly acknowledged as exerting a critical control on phytoplankton growth over large areas of the world ocean [e.g., *Martin and Fitzwater*, 1988; *Coale et al.*, 1996; *Aumont et al.*, 2003]. This micronutrient is supplied to the surface ocean from three different sources: (1) dust deposition from the atmosphere, (2) vertical transport of subsurface waters, and (3) vertical and lateral transport from sediment mobilization and hydrothermal vents (for a review, see *de Baar and de Jong* [2001]). Dust deposition is traditionally considered as a major, if not the main, source of iron to the open ocean [e.g., *Archer and Johnson*, 2000; *Fung et al.*, 2000; *Aumont et al.*, 2003; *Moore et al.*, 2004]. Consequently, and as already suggested for the Last Glacial Maximum [*Martin et al.*, 1990], any temporal change in its magnitude could potentially impact surface iron and chlorophyll.

[3] Dust deposition generally consists of episodic events and is highly variable over all time scales (see Figure 1) [*Duce and Tindale*, 1991, and references therein]. The impact of such variability on ocean biogeochemistry has

been previously studied on long time scales globally [*Bopp et al.*, 2003; *Moore et al.*, 2006]. On the other hand, some studies have analyzed this impact on short time scales, typically from days to seasons and at very specific sites in the North Pacific and Atlantic oceans [*Boyd et al.*, 1998; *Wu and Boyle*, 2002; *Weber et al.*, 2005]. Yet, the impact of atmospheric iron supply on daily to interannual variability in ocean biogeochemistry has been thus far unaddressed on a global scale.

2. Methodology

[4] We use the ocean biogeochemical model Pelagic Interaction Scheme for Carbon and Ecosystem Studies (PISCES) [*Aumont and Bopp*, 2006]. PISCES includes four Plankton Functional Groups (Diatoms, Nanophytoplankton, Microzooplankton, Mesozooplankton). Phytoplankton growth is limited by five different nutrients (NO₃, NH₄, PO₄, SiO₃ and Fe) and light. Dissolved iron is represented via one single dissolved pool with a basic description of iron-ligand interactions. Iron is scavenged by both organic and inorganic particles, either by coagulation of the complexed forms or by direct adsorption of the free inorganic pool. Three external sources of iron are considered in the model: dust deposition (see below), sediment mobilization and river discharge. A complete description as well as a short evaluation of the model are provided as supplementary material to the work by *Aumont and Bopp* [2006]. The model is run offline using monthly-mean dynamical fields derived from an interannual simulation performed with ORCA2-LIM [*Madec et al.*, 1998] which was forced with atmospheric fields from the ERA-40 re-analysis [*Uppala et al.*, 2005] over 1996–2001.

[5] Daily atmospheric dust deposition by wet and dry removal was simulated using the LMDzT-INCA model from 1996 to 2001. Dust fluxes are calculated using ECMWF surface winds at 1°x1° horizontal resolution, using surface maps of threshold velocity and integrated source strength as described by *Schulz et al.* [1998] and *Balkanski et al.* [2004]. Forced by this emission scheme, the atmospheric dust cycle is simulated using the LMDzT atmospheric model coupled to the INCA aerosol module. Realistic variations of synoptic weather are achieved by nudging to reanalysed winds from ECMWF. The LMDzT-INCA dust cycle was characterised recently in the AeroCom model intercomparison and shown to provide one of several valid global dust models [*Textor et al.*, 2006].

[6] The impact of the variability in dust deposition on surface dissolved iron and chlorophyll has been analyzed using five different model experiments over 1996–2001. In the first four experiments, PISCES was driven by monthly climatological dynamical fields constructed from the inter-

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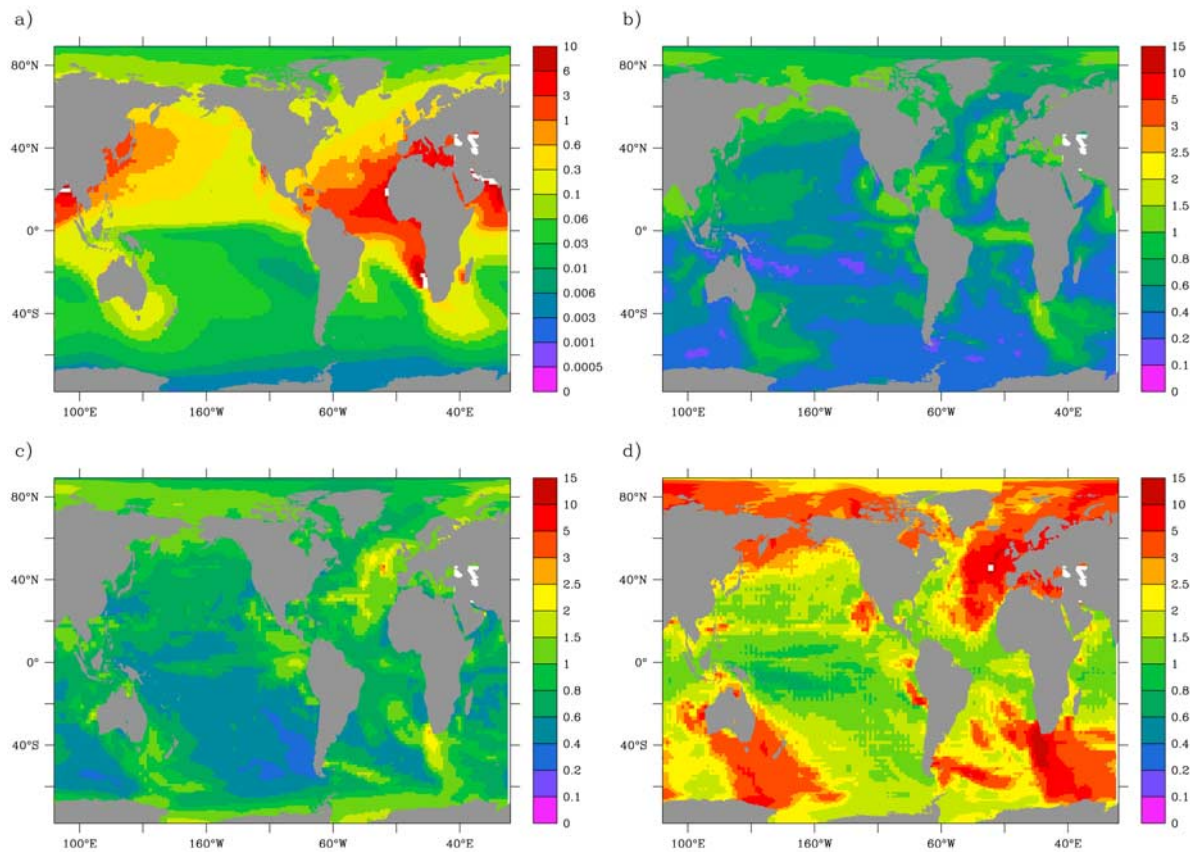


Figure 1. (a) Annual mean atmospheric deposition of iron (in $\text{mmol Fe/m}^2/\text{year}$) averaged over 1996–2001. Variability in dust deposition (percent) on (b) seasonal, (c) interannual and (d) daily time-scales.

annual simulation. These four runs differ in the temporal sampling of dust deposition, specifically, annual mean climatological, monthly mean climatological, monthly mean interannual, and daily mean interannual fields. In the fifth experiment, the model was forced by monthly mean interannual dynamical fields in addition to daily mean interannual dust deposition fields. Therefore, the relative contribution of either daily, seasonal or interannual variability can be appraised by evaluating differences between the aforementioned experiments. We define variability as the absolute standard deviation for surface chlorophyll, and as the relative standard deviation for both dust deposition and surface iron.

3. Results

[7] Dust deposition fluctuates markedly over all time scales (Figure 1). The spatial structure of the daily, seasonal and interannual variabilities is in general agreement with results from previous studies [Werner *et al.*, 2002; Mahowald *et al.*, 2003]. As already shown [Mahowald *et al.*, 2003], daily variability is by far the largest due to the highly episodic nature of dust transport (Figure 1c). The three types of variability (daily, seasonal, interannual) generally display similar spatial patterns. In particular, the high dust regions do not necessarily exhibit the largest variability. Variability is also large at high latitudes, as a result of the

interactions between dust transport and precipitation [Werner *et al.*, 2002].

[8] The full temporal variability in surface dissolved iron concentrations is generally high, exceeding 50% over most of the world ocean (Figure 2a). Unfortunately, iron observations are insufficient to validate the model predictions. Along the coasts, the variability is on average lower because iron levels are determined by the balance between strong input from the sediments and scavenging/coagulation which do not vary temporally in our model [Aumont and Bopp, 2006]. In the subtropical gyre of the southern Pacific ocean, surface iron concentrations show the smallest variations due to very stable physical conditions and low and constant dust deposition. The variability is maximal at high latitudes and in the equatorial Pacific.

[9] Dust deposition explains this temporal variability in iron, at least in the tropical regions and in the northern mid-latitudes (Figures 2b–2d). The largest dust-induced variability in iron concentrations is predicted in the northern Pacific ocean. At high latitudes, dust deposition produces almost no variability (Arctic Ocean, Southern Ocean). In the latter regions, iron is supplied to the surface mainly from the sub-surface, either by vertical mixing or vertical advection. As a result, dust deposition plays only a secondary role [Archer and Johnson, 2000; Aumont *et al.*, 2003]. Interestingly, there is no obvious relationship between the magnitude of the variability in dust deposition and its impact on the variability of surface iron. In particular, the response of

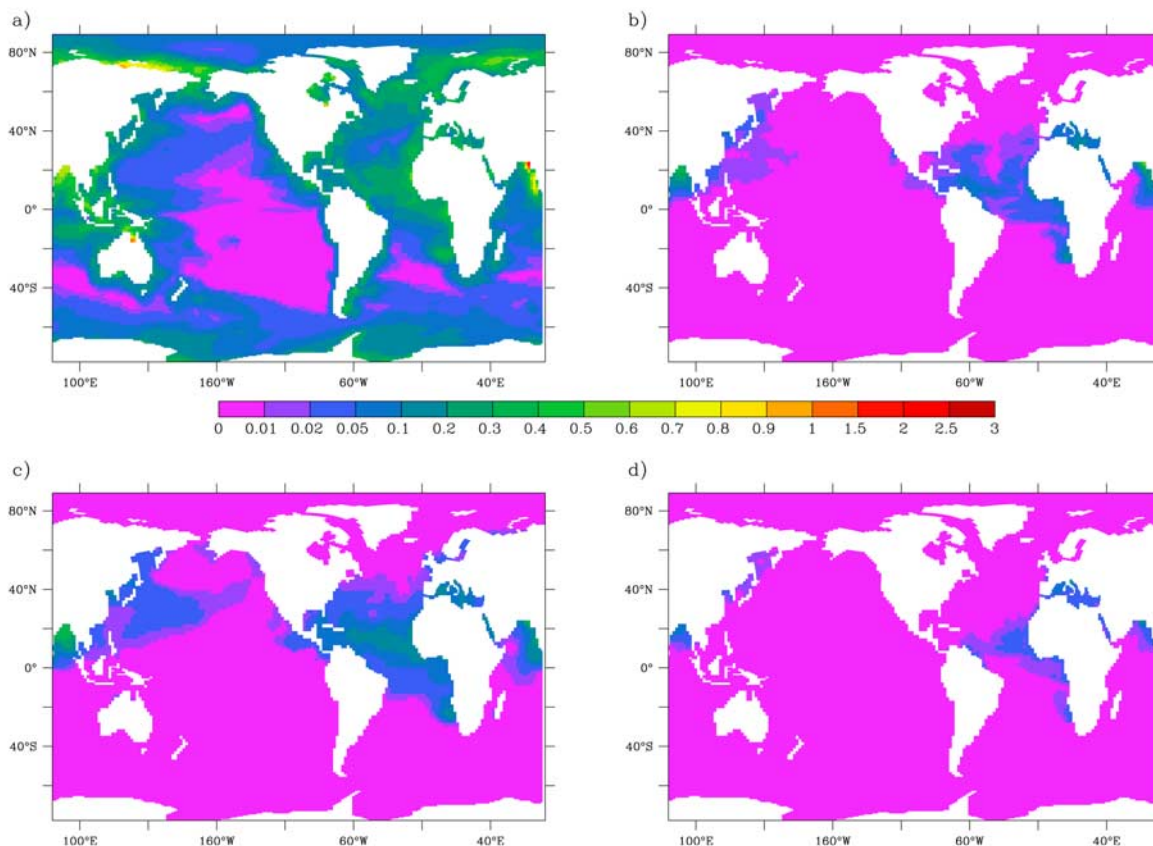


Figure 2. Temporal variability in surface dissolved iron over 1996–2001 (percent). (a) Variability induced both by variations in dust deposition and in ocean circulation/climate forcing. Variability induced by variations in dust deposition on (b) seasonal, (c) interannual and (d) daily time-scales. The annual-mean surface iron distribution can be inferred from *Aumont and Bopp [2006, Figure 2]*.

iron concentrations to daily variations in the atmospheric supply of iron is the smallest (Figure 2d) whereas the latter variations were shown to largely dominate the temporal signal of dust deposition. Interannual variations in dust deposition induce the largest temporal fluctuations in surface iron.

[10] For the full temporal variability in sea-surface chlorophyll, the model compares very well with the satellite data [*McClain et al., 1997*] (Figures 3a–3b). It is beyond the scope of this study to present a full description of this variability, which was already analysed in previous regional or global studies [e.g., *Le Quéré et al., 2003, 2005*]. However, we show that the variability induced by dust deposition is negligible almost everywhere and for all types of temporal variability (Figure 3c). Very small daily and interannual variations in chlorophyll are only produced at the southern limit of the Pacific subpolar gyre and on the northern edge of the eastern equatorial Pacific.

4. Discussion

[11] Field observations have shown that dust deposition can produce large temporal variations in surface dissolved iron concentrations in the eastern subpolar Pacific [*Boyd et al., 1998*], in the northern subtropical Pacific [*Boyle et al., 2005*] and in the northern subtropical Atlantic [*Sedwick et al., 2005*]. In agreement with these observations, our model

results suggest that the eolian imprint on the temporal variability in iron is significant in the tropical regions and part of the subpolar Pacific. This imprint is predicted to be negligible elsewhere. Such result is not surprising as a significant ocean response to any atmospheric supply requires a large dust supply, a shallow mixed layer depth and a small iron consumption by either biological activity or scavenging/coagulation. All these conditions are met in the subtropical gyres and in part of the subpolar Pacific ocean.

[12] Our model suggests that dust deposition and surface iron variabilities are characterized by rather different time-scales. Dust deposition is dominated by daily variations, whereas surface dissolved iron concentrations show much smaller variations, which are maximal on interannual time-scales. In fact, as a result of the small solubility of aerosol iron prescribed in the model (1%), even strong dust events have only a small imprint on surface iron concentrations. However, the accumulation, or absence, of such events over several weeks or months have a significant impact on surface iron. This impact is enhanced by the longer residence time of surface dissolved iron in the subtropical gyres, relative to more productive or dynamically active regions. In these oligotrophic regions, these longer time-scales translate into quite strong interannual modulations of the seasonal cycle of surface dissolved iron by aerosol iron, most noticeably under high dust regions like the northern subtropical Atlantic ocean.

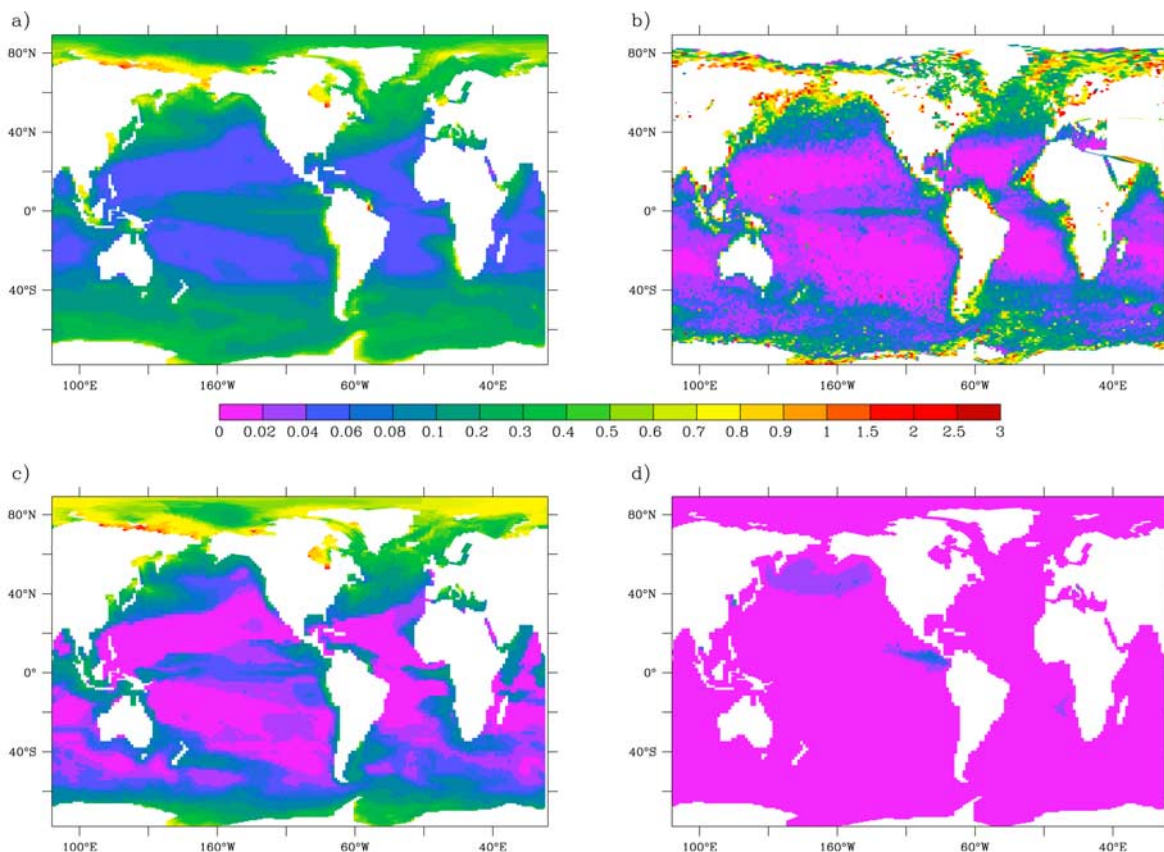


Figure 3. (a) Annual mean surface chlorophyll concentrations simulated by PISCES and averaged over 1997–2001 (in mg Chl a/m³). Temporal variability in surface chlorophyll (in mg Chl a/m³) over 1997–2001. (b) Variability deduced from SeaWiFS satellite data. (c) Variability predicted by the model induced both by variations in dust deposition and in ocean circulation/climate forcing. (d) Variability induced by daily, seasonal and interannual variations in dust deposition. The latter variability has been computed from the difference between the climatological simulation forced by the daily dust deposition fields and the climatological simulation driven by annual-mean dust deposition (see the methodology section). All variabilities have been computed from 8 days-mean fields both for SeaWiFS and PISCES.

[13] Our analysis was restricted to the surface. Yet, dust deposition may also induce temporal variations in iron in the subsurface by several pathways. First, dust particles probably also dissolve as they sink in the water column. Second, some of the iron that is supplied by dust at the surface is scavenged, especially in high dust regions, and is potentially released in the subsurface. Third, variations in the phytoplanktonic Fe/C ratios produced by varying surface iron concentrations change the amount of iron that is exported below the surface by the biological activity. This subsurface variability can then be transmitted to the surface by the ocean dynamics with a spatial and temporal lag. The short length of our model simulations may thus not be sufficient to fully resolved this subsurface pathway, resulting in an underestimation of the variability in surface iron. However, the subsurface variability is predicted to be very small by the model, suggesting that it has at most only a marginal impact on surface iron.

[14] Field observations report large variabilities in iron surface concentrations on short timescales (days to weeks) that are not captured by our model. In the Sargasso Sea, surface dissolved iron concentrations were observed to increase by about 0.6 nM over 13 days [Sedwick *et al.*,

2005]. The modeled variability over similar timescales is rather modest, with maximum variations of about 0.2 nM Fe in the northern subtropical gyre of the Atlantic ocean. Differences in the solubility of aerosol iron may explain this disparity. In our model, this solubility has been set to 1%, a value typically prescribed in ocean biogeochemical models [Parekh *et al.*, 2005; Moore *et al.*, 2004; Aumont and Bopp, 2006]. Yet, values up to 40% have been deduced from short-term variations in surface iron concentrations [Sedwick *et al.*, 2005; Boyle *et al.*, 2005]. Nevertheless, prescribing such high values in ocean models yields unrealistic surface iron distributions. Three potential factors may explain this apparent inconsistency. First, the (rather simplistic) description of the iron cycle in biogeochemical models might be incomplete [Tagliabue and Arrigo, 2006]. Second, solubility of aerosol iron is strongly variable both over time and space and not constant as assumed in our model [e.g., Luo *et al.*, 2005]. Third, processes other than dust deposition may explain the observed rapid variations in surface iron, such as mesoscale dynamics [Wu and Boyle, 2002; Sedwick *et al.*, 2005].

[15] The impact of the variability in dust deposition on surface chlorophyll is predicted to be very small or negli-

gible over the ocean, especially relative to the variability induced by the ocean dynamics and the climate forcing. Yet, this is not the case for surface iron over large areas of the ocean. In fact, high dust regions, over which the variability induced by iron aerosol is the largest, are mostly oligotrophic regions with elevated iron levels where phytoplankton growth is not controlled by iron availability, at least in surface waters and for non nitrogen fixing diazotrophs [e.g., Aumont *et al.*, 2003; Moore *et al.*, 2004]. As a consequence, any change in iron does not result in a modification of the phytoplankton biomass. On the other hand, in the High Nutrient-Low Chlorophyll regions in which iron is a limiting factor [Martin and Fitzwater, 1988], dust deposition over all timescales (from days to years) remains too small to have any noticeable impact on surface chlorophyll.

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