Atmospheric iron delivery and surface ocean biological activity in the Southern Ocean and Patagonian region

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[1] Iron is a limiting nutrient for biologic activity in much of the world ocean. We present a method to quantitatively address the response of surface ocean biology to inputs of atmospheric Fe associated with atmospheric dust. We merge two enabling technologies, global models of Earth system processes and satellite derived chlorophyll concentrations to assess the importance of Fe in oceanic biogeochemistry. We present an objective correlation analysis to elucidate the spatial response of chlorophyll to iron flux considering the ocean surface meridional center of mass in areas with high correlation. Several regions between 40°S and 60°S show correlations from 0.6 to 0.95, significant at the 0.05 level, particularly the Patagonian region. Surface chlorophyll and iron flux follow similar patterns, however chlorophyll may be displaced to different latitudes than where Fe input occurs due to meridional ocean transport. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1640 Global Change: Remote sensing; 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504); 0330 Atmospheric Composition and Structure: Geochemical cycles. **Citation:** Erickson, D. J., III, J. L. Hernandez, P. Ginoux, W. W. Gregg, C. McClain, and J. Christian, Atmospheric iron delivery and surface ocean biological activity in the Southern Ocean and Patagonian region, *Geophys. Res. Lett.*, *30*(12), 1609, doi:10.1029/2003GL017241, 2003.

1. Introduction

[2] The role of iron in oceanic biogeochemical cycles has been a topic of increasing research interest for several years [*Martin and Fitzwater*, 1988; *Martin et al.*, 1994; *Arimoto et al.*, 1990; *Duce*, 1995; *Behrenfeld et al.*, 1996; *Witter et al.*, 2000]. Since much of the global ocean is far removed from significant oceanic sources of iron, such as rivers, upwelling and shallow water sediments, the flux of dust iron transported by the atmosphere may play a significant role in biological activity. We perform an empirical analysis between ocean surface monthly averages of simulated atmospheric dust-iron deposition (Φfe) and remotely sensed chlorophyll (*Chl*). The premise that we are testing involves the idea that atmospheric iron deposition could be correlated with surface ocean remotely sensed chlorophyll. The correlations are expected to be the highest where iron is an important limiting nutrient [*Martin*, 1991; *Fung et al.*, 2000; *Banse*, 1995], however we focus on regions where high correlations in the Southern hemisphere are observed. The first part of our analysis is to identify, with 2.0° × 2.5° latitude-longitude spatial resolution, regions of the world ocean where *Chl* is correlated in time with Φfe. We study the correlation of the monthly anomalies, computed by subtracting the mean of the time series from each monthly value, to assess the response of *Chl* departures to those of Φfe. It is important to note that high correlations do not imply a tight coupling between Φfe and *Chl*. We carry out an objective analysis by computing their meridional band 'Center of Mass' in the regions where we find high correlations. This allows us to estimate the loci of higher *Chl* and Φfe every month and to determine if there is a relationship when the two fields are collocated. Finally, we augment this computation with an interpretation of the time mean surface ocean transport to elucidate the latitude deviations between *Chl* and Φfe center of masses. These results may be useful in understanding the biogeochemical cycles in these regions and highlight specific regions of the ocean where observational studies could be focused to assess the importance of atmospheric Fe deposition on ocean biology.

2. Data and Methods

[3] This analysis uses two state-of-the-art geophysical data sets. One is an indicator of ocean biological activity, as reflected in ocean surface chlorophyll derived from remotely sensed platforms. The 2000–2001 monthly averages of SeaWiFs *Chl* is used here as a metric for oceanic

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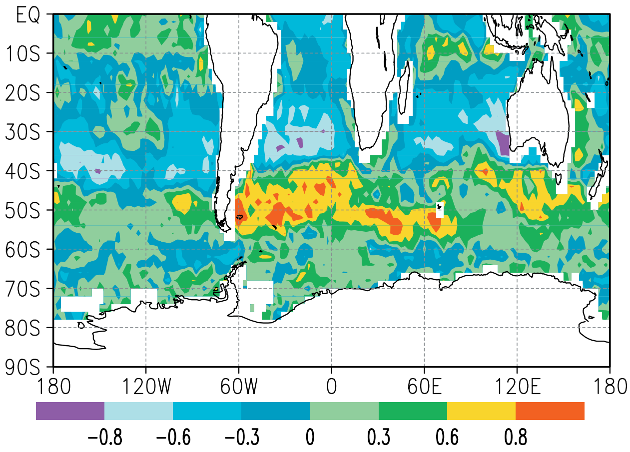

Figure 1. Atmospheric dust Fe flux and SeaWiFS chlorophyll (*Chl*) anomaly correlation maps for the Southern Hemisphere. Large regions east of Patagonia show a strong correlation between *Chl* and atmospheric supply of dust-Fe. These data are from 2000–2001 monthly averages of Fe deposition and SeaWiFS *Chl*.

biological activity. The iron (Fe) data set was derived from a detailed atmospheric dust generation, transport and deposition model [*Ginoux et al.*, 2001]. The model is driven by assimilated meteorological fields from the Goddard Earth Observatory Data Assimilation System (GEOS DAS). The Fe deposition data sets have been simulated since 1981 and we have sub-sampled the global Fe deposition field for the Southern hemisphere and the years 2000–2001.

[4] We argue that the comparison between these datasets gives good first order inferences on the generalized problem of iron deposition-ocean chlorophyll relationships and gives insights into the design of more detailed correlation experiments when all the germane data sets are available for the exact same time intervals for several years. The overall objective is to assess, in a Southern hemisphere perspective, those regions of the ocean where biological activity is closely linked to atmospheric Fe supply. In many ways, this is similar to quantifying a natural Fe addition experiment with high resolution data on the hemisphere scale. A novel aspect of these calculations is the merging of 2 independent state-of-the-art geophysical data sets: The output of a global, 3-D atmospheric chemistry/aerosol model and remotely sensed quantities from space based platforms.

[5] We have decided to focus on the Southern hemisphere where significant regions are described as High Nutrient-Low Chlorophyll (HNLC) and the notion that the delivery of atmospheric Fe may illicit a quick (days-week) response from the Fe limited oceanic biology [*Archer and Johnson*, 2000; *Johnson et al.*, 1997; *Wells*, 1994]. Figure 1 shows the anomaly correlation fields for the 2000–2001 iron deposition flux estimates [*Ginoux et al.*, 2001] and simultaneous SeaWiFS data. There are large regions of the Southern Ocean where the correlations are greater than 0.8, like the South Atlantic east of Argentina, a region highly influenced by aeolian iron flux from the Patagonian Desert. This region is influenced by intense western boundary currents, Brazil and West wind drift (part of the nutrient rich Antartic Circumpolar Current) and its domain includes the large continental shelf of Falkland Island. South of Australia, a HNLC region, a moderate correlation is found ranging from 0.6–0.8. Although the Patagonian region is affected by several biophysical forcings that can affect Fe concentrations, we consistently found a high correlation here using other periods and satellite observations [*Hernandez et al.*, 2002]. Because of this we center our attention to explore direct response between the two fields in this region. Figure 2 shows the zonal means for the region 0°–60°W of the anomaly correlation, indicating a strong relationship between atmospheric Fe flux to the surface ocean and biological activity from 40°–60°S. An important point to note is that these are maps of anomaly correlation coefficients and the high values indicate those regions where Fe deposition and biological activity are strongly coupled via the biogeochemistry of a limiting nutrient, Fe. These regions are, in fact, regions of relatively low absolute atmospheric Fe flux compared to many Northern hemisphere oceanic regions downwind from large desert areas. This indicates that regions that may be Fe limited are very efficient at using even small amounts of Fe very quickly.

[6] In order to further examine the spatial correlation maps and interpretations discussed above, we have preformed an objective analysis of the monthly averages for SeaWiFS *Chl* and and Φfe in the region where there are persistent high correlations exist. We have binned the fluxes and chlorophyll data and computed a 'center of mass' (CM) for specific areas using the relationship

$$Y_i = \frac{\sum_j Y_{ij} f_{ij}}{\sum_j f_{ij}} \quad (1)$$

This allows us to compute the latitude-band (Y_i) where the Fe and chlorophyll (designated by $f_{ij,}$) are physically concentrated; i and j are longitude and latitude indexes respectively. Figure 3 shows CM calculations for the two year monthly average. While high Φfe is not always associated with high chlorophyll, a general relationship was found where in some longitude bands the mass of Fe deposited was co-located or nearly co-located with the chlorophyll maximum. This is a persistent feature of the analysis for most of the Patagonian region. We find several instances where the chlorophyll CM's are moved south of

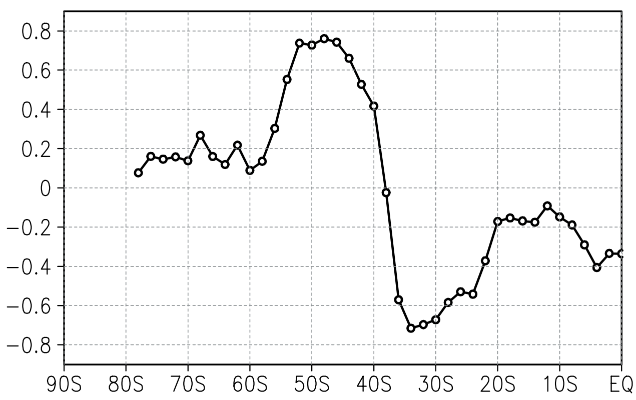

Figure 2. Zonal mean of the anomaly correlations in Figure 1 for the region O-60W.

the point of highest Φfe by ocean circulation. We use equation 2 for horizontal wind stress (τ) from UWM-COADS data [*Da Silva et al.*, 1994] and the latitudinal variation of the coriolis parameter (f) to compute the meridional Sverdrup transport (My).

$$M_y = \frac{curl_z \ \tau_h}{\partial f / \partial y} \qquad (2)$$

Here $\mathrm{curl}_z \ \tau_h$ represents the vertical component of the curl of wind stress. Around 50°S–45°S the region experiences a southerly transport of about 0.5 Sv that moves the water mass with significant atmospheric Fe input a bit to the south, resulting in a movement south of the chlorophyll CM's. This may in some cases explain the lack of direct correlation between the mean and/or anomaly fields of dust deposition and chlorophyll.

[7] Lastly, we find it informative to examine the monthly standarized time series of *Chl* and Φfe over the 24 months. Figure 4 shows these time series for the Patagonian region. Standardization was done by simply taking the largest values in each of the time series and dividing the monthly records by that maximum. The gross features of the time series comparison show significant correlation between the two fields.

[8] Based on independent analyses of the correlation of iron deposition and remotely sensed chlorophyll, there are high correlations in several regions of the mid-high latitude Southern hemisphere. This is consistent with presently held tenets where Fe may be a limiting micronutrient [*Fung et al.*, 2000]. We note that the regions of highest correlations are not the regions of highest dust flux. This analyses points out those regions where ocean biology is possibly tightly coupled with atmospheric Fe deposition. An additional conclusion is that there are many areas that have relatively high Fe deposition but little or no correlation with *Chl*.

3. Conclusions

[9] We present evidence of a strong temporal correlation between Φfe from a global erosion and transport model and

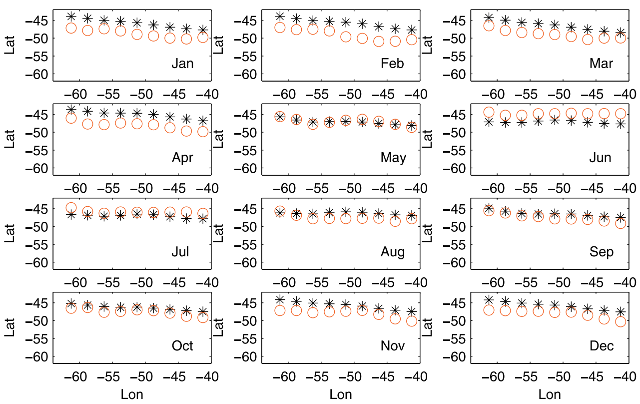

Figure 3. The 'Center of Mass calculation' for SeaWiFS ocean color and Fe deposition for the region 40°S–65°S, 40°W–70°W. The circles indicate chlorophyll and the stars indicate dust (Fe) flux. The main point is that the Center of Mass (CM) of the Fe flux and the chlorophyll are for the most part co-located for most of the analyses in the region of high anomaly correlation. Surface currents may advect the *Chl* signal away from the region of highest Fe input.

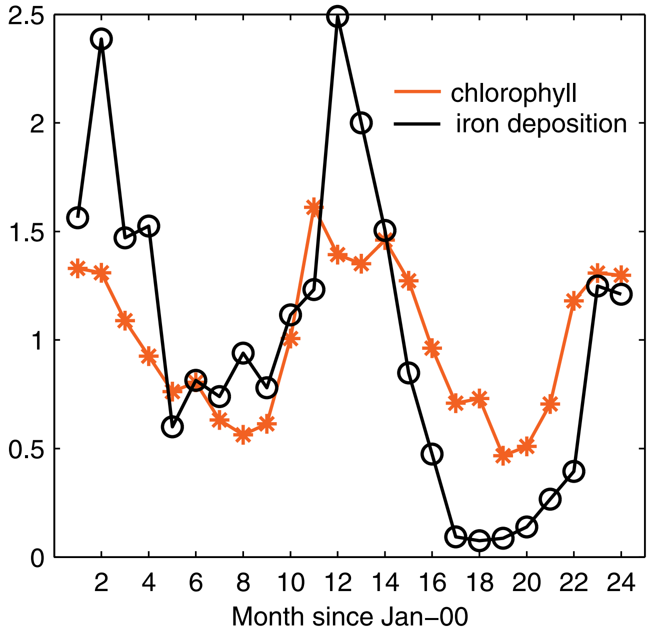

Figure 4. The standarized time series of the SeaWiFS chlorophyll and dust-Fe deposition for the 24 month period for the region 62.5W-42W, 40S-60S. This simple representation of the data averaged over the study region indicates correlation between Fe deposition and *Chl* that is more quantitatively represented in Figure 1.

Chl as observed by satellite ocean color sensors. These correlations are strongest in a coherent region of the subantarctic south Atlantic that substantially overlaps the region where enhanced dust deposition and biogenic sedimentation are inferred to have occurred during the last glacial maximum [*Anderson et al.*, 2001; *Kumar et al.*, 1995; *Anderson et al.*, 2002].

[10] Using the CM calculation and a basic understanding of the ocean transport in the study region, we can attempt to explain deviations of several trends in the studied parameters. Basically, dust deposition of Fe may occur in one region and then ocean circulation moves the fertilized water mass away from the area of highest Fe flux. This results in a non-co-location of high *Chl* and high dust flux even though the causative influence of Fe on Chl and biota may still be strongly linked.

[11] Analyses such as these provide tests of various conceptual biogeochemical models and are the result of two emerging technologies, large computational models evaluated on supercomputers [*Mahowald et al.*, 1999; *Tegen et al.*, 1996] and space based remotely sensed satellite data. Such calculations may provide guidance and input for the planning of field experiments and will become increasingly more valuable as more satellite data becomes available and numerical simulations of global biogeochemical cycles are included explicitly in Earth system models.

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