The 'inconvenient ocean'

Undesirable consequences of terrestrial carbon sequestration

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It is now well established that the availability of iron exerts a fundamental control on biological productivity in the ocean. We also know that a significant source of this iron is deposition of mineral aerosol from the atmosphere to the ocean surface. That this supply of dust, in turn, is dependent on the state of the land surface, suggests that any future change in how the land is managed and used has the potential to affect atmospheric CO_2 via a remote controlling influence on ocean productivity. This teleconnection within the Earth system has important implications for how we might mitigate future climate change, particularly with respect to activities allowed under the Kyoto Protocol for the removal ('sequestration') of CO_2 from the atmosphere and its storage in vegetation and soils.

Introduction

When the wind speed is sufficient to overcome the cohesive forces that exist between soil particles, fragments of rock minerals and other soil constituents are picked up and may be carried great distances through the atmosphere. Although the individual particles are often nearly invisible to the naked eye, billions of tons of material are eroded from the land in this way every year. Transport events can often be of sufficient intensity to be visible from space, as shown in the accompanying satellite images (Figures 1).

The entrainment of dust by the atmosphere is greatly facilitated by dry, arid conditions, when cohesion between particles is minimal, and also by the absence of vegetation cover, which allows greater wind speeds to be reached at ground level. It comes as no great surprise, therefore, to find that the strongest sources of dust at present are the Sahara and Sahel desert regions of North Africa. There are also important sources associated with the deserts of central Asia, while lesser sources are to be found in arid regions of southern Africa, Patagonia, and Australia. As the prevailing winds carry the suspended dust away from its source, more and more of the initial load of material is removed by being 'washed out' by falling raindrops or by gravitational sedimentation to the land or ocean surface. The distribution of dust deposited to the Earth's surface (Figure 2) then reflects a combination of the strength of sources of dust and the distance from them, and atmospheric circulation patterns. For instance, particularly high rates of deposition occur immediately downwind of the Sahara and Sahel desert regions of North Africa and extending out across the Atlantic to the Caribbean and northeastern South America. In contrast, rates of dust deposition in regions such as the Southern Ocean and equatorial and south Pacific (all of which are relatively remote from any major sources of dust) are very low.

One of the effects that this dust has on the Earth system is in altering the optical properties of the atmosphere. By modifying incoming (ultraviolet and visible) and outgoing (infrared) radiation, the presence of dust in the atmosphere can affect the energy balance at the Earth's surface sufficient to produce locally a seasonal heating or cooling of up to ±2°C.

Once deposited to the land surface, aeolian material can significant affect soil structure, and with it, the nutrient and water-holding characteristics of the soil. This is most apparent in the Loess Plateau region of China, where over the course of the last few million years, dust carried east from the Gobi desert has formed an extremely fertile soil sequence up to 200 m thick. Elsewhere, in places where soils would otherwise be poor and infertile, deposition of nutrients such as phosphate in aeolian material is potentially critical to maintaining the health and productivity of the ecosystem. Dust indeed appears to have such a role in parts of Amazonia (dust transported across the Atlantic from the Sahara and Sahel deserts) and the Hawaiian Islands (dust from the central Asian deserts).

It is clear, therefore, that dust has important effects in both the atmosphere and the terrestrial biosphere. However, it arguably takes on its most important Earth system role when deposited to the ocean surface.

Dust and the ocean carbon cycle

Iron limitation of the biota of the open ocean

A long-standing puzzle in oceanography has been why the primary producers of the open ocean (phytoplankton) do not always fully utilize the major ('macro-') nutrients; phosphate (PO_4^{3-}), nitrate (NO_3^-), and, silicic acid (dissolved silica – H_4SiO_4), that are supplied to them. As shown in Figure 3, in certain regions of the world ocean, most notably the eastern equatorial Pacific, North Pacific, and Southern Ocean, high concentrations of NO_3^- remain in the surface waters (with a similar pattern apparent for both PO_4^{3-} and H_4SiO_4). Despite the ready availability of NO_3^-, standing stocks of phytoplankton are relatively low, leading to the designation of such regions as 'High-Nitrate Low-Chlorophyll' (HNLC).

Although physical (temperature, light levels, and the depth to which the surface ocean is mixed) and grazing regimes must all play a part in controlling phytoplankton standing stocks in HNLC regions, it was suspected that growth limitation through insufficient availability of the micro-nutrient iron might also be important. Open ocean iron fertilization experiments were therefore carried out to test this hypothesis; first in the equatorial Pacific, and more recently in the Southern Ocean (see *Ocean Challenge*, Vol. 10, No. 3). The results of these experiments have demonstrated unequivocally that insufficient iron availability in the surface ocean limits phytoplankton growth (particularly growth of larger diatoms).

Iron supply to the biota

Why should there be an imbalance in nutrient supply to the biota, with insufficient iron relative to the macro-nutrients in some locations in the ocean but not others? The answer lies in the dust distribution in Figure 2. To understand why this is we must look at how nutrients are cycled in the ocean. As phytoplankton cells grow and divide in the sunlit surface layer of the ocean (the euphotic zone), nutrients are removed from solution and transformed into cellular constituents. , Much of this material is subsequently broken down by the action of bacteria and zooplankton within the euphotic zone, and the nutrients returned into solution. However, a fraction (in the form of dead cells, zooplankton fecal pellets, and other particulate organic debris) escapes and settles through the water column under the influence of gravity, being broken down much deeper in the ocean. Although nutrients are eventually returned to the euphotic zone by upwelling and mixing, a vertical gradient is created with lower nutrient concentrations at the surface than at depth. The action of removal by the biota of dissolved constituents at the surface and export (in particulate form) to depth is known as the 'biological pump' (Figure 4).

Supply of iron to the euphotic zone also occurs through upwelling and mixing of ocean waters from waters below (which are enriched as a result of the degradation of biogenic material supplied from above, as per the macro-nutrients). However, unlike the highly soluble macro-nutrients, the dissolved state of iron is not thermodynamically favored in the oxygenated seawater environment, and is scavenged out of solution by attaching to particulate matter setting through the water column. The consequence of this is that there will be a tendency for a relative deficiency (compared to other nutrients required for phytoplankton growth such as NO_3^-) of iron to exist in upwelled water. Although transport by rivers is the dominant route by which iron is supplied to the ocean as a whole, rapid biological uptake and sedimentation in highly productive estuaries and coastal zones removes much of the newly supplied iron from the water column. The result of this is that in the open ocean, rivers are not an important source of iron to the euphotic zone. In order for NO_3^- to become completely used up at the surface, aeolian deposition must therefore supply the shortfall (relative to NO_3) in upwelled iron supply. However, inspecting the dust map (Figure 2), it is clear that the fluxes to the equatorial Pacific and Southern Ocean are extremely low – aeolian supply is insufficient to make up the shortfall, explaining the HNLC condition of these regions.

Iron supply and ocean CO_2 uptake

Alongside factors such as ambient temperature and *p*H, the concentration of dissolved inorganic carbon (DIC) determines the equilibrium concentration of gaseous CO_2 in the surface ocean. Processes that affect DIC concentrations will therefore influence the net transfer of CO_2 between atmosphere and ocean surface. The biological pump is one such process. This is because along with nutrients, carbon is also incorporated into cellular organic constituents by phytoplankton in the euphotic zone and later released into solution at depth (Figure 4). By affecting productivity in the ocean and thus the strength of the biological pump, changes in dust deposition will therefore influence the uptake of atmospheric CO_2 by the ocean.

Dust supply and land use change

One of the consequences of historical changes in land use, such as conversion of natural ecosystems to agriculture, is that the supply of dust to the atmosphere will have increased. The results of models of the processes of dust generation, transport, and deposition are consistent with a component of the total dust load in the atmosphere today being a direct consequence of such human-driven land disturbance. In regions of the ocean where natural sources of iron to the marine biota were previously insufficient to allow the complete utilization of NO_3^-, it is likely that an additional 'anthropogenic' dust component will have helped stimulate marine productivity, enhancing the rate of CO_2 uptake by the ocean. It follows that any loss dust sources would drive a reduction of CO_2 uptake. This has clear implications for future climate change. So, under what circumstances might a reduction in dust supply to the ocean occur?

Terrestrial ecosystem models suggest that in the future there will be a weakening of dust supply to the atmosphere with global warming driving a substantial reduction in the area of desert and semi-desert vegetation. Working against this, population pressures are likely to drive an increase in soil disturbance via the intensification and extensification of agriculture. In addition to source changes, the efficiency with which dust is transported through the atmosphere may also change, with increased removal of dust particles by precipitation (under the more intense hydrological cycle that is expected as part of future climate change) resulting in a reduction in the supply to the remote ocean. However, it is also possible that the land surface might be deliberately modified on a large-scale in an attempt to mitigate climate change.

Under the Kyoto Protocol, a variety of "land-use, land-use change, and forestry" (LULUCF) activities have been proposed for the sequestration of carbon on land. These include changes in soil management practices (including reducing tillage, enhancing the areal and seasonal extent of ground cover, and the 'set-aside' of surplus agricultural land), restoration of previously degraded lands, and forestation. As a result of reduced disturbance and increased stabilization of soils, many of these activities are likely to lead to a reduction in dust supply from the land to the atmosphere. Since dust exerts an important control on the biological pump in the ocean, the effectiveness of carbon removal from the atmosphere via sequestration on land may be diminished by a reduction in the quantity of carbon taken up by the ocean. The potential importance of this teleconnection within the Earth system, with deliberate actions taken on land producing unexpected side effects in the ocean, has been investigated at the University of East Anglia with the aid of a numerical model of the ocean-atmosphere carbon cycle. Results of this model predict a significant impact on ocean productivity of any decrease in dust supply to the ocean, with, for instance, 15-30% less dust producing a reduction of up to 8% in the rate of uptake of anthropogenic CO_2 from the atmosphere. This perturbation of the global carbon cycle exhibits a considerable persistence, with the deficit reaching 20-50×10^9 tons of carbon (or 20-50 PgC) by 2250, and perhaps doubling by the end of the millennium (year 3000). To put this into perspective, the sequestration benefit of widespread alteration of agricultural management practices and forestation is perhaps in the region of 23-110 PgC. Clearly, suppression of the ocean sink has the potential to substantially offset the benefit to the atmosphere of sequestration on land.

The precise effect of this 'land use / ocean productivity' mechanism will be critically dependent upon the details of any sequestration activities and the locations in which they take place. For example, land surface modification undertaken in arid and semi-arid regions will tend to have a much greater impact on dust supply than it might in moist, temperate regions (where dust sources are relatively unimportant). At a minimum, changes in dust supply and the response of the ocean may need to be taken into account when evaluating the relative economic benefits of carbon sequestration via certain LULUCF activities. However, it is within the range of uncertainty that the eventual benefit (in terms of removal of CO_2 from the atmosphere) obtained through implementation of LULUCF mitigation measures could be largely negated by an undesirable antagonistic response induced in the ocean.

Conclusions

The Kyoto Protocol takes a rather narrow and restricted (land-atmosphere) view of the Earth system in judging the benefits of removal ('sequestration') of CO_2 from the atmosphere and its storage in vegetation and soils. This has resulted in "land-use, land-use change, and forestry" activities being viewed as relatively safe and highly desirable mechanisms for helping reduce the rate of accumulation of CO_2 in the atmosphere. Since many of these activities have considerable ancillary benefits (for example, in improved soil fertility), they have even been termed "no regrets" or "win-win". However, by ignoring both the role of the ocean, and the dust that links land, air, and sea, 'side-effects' have obviously been missed. Quantifying the potential consequences of terrestrial carbon sequestration suggests that LULUCF activities many not be as benign as has generally been assumed, and sequestration cannot, therefore, be wholly relied upon as a substitute for reductions in emissions. It would seem that it is only through taking a more holistic view and being receptive to the potential interaction of different components of the Earth system, can we hope to understand the full consequences of our continued experimentation with the planet.

Further Reading

You can read more about the problems of terrestrial carbon sequestration and the possible dust-driven 'side effect' in two recent publications;

Ridgwell, A. J., Maslin, M. A. and Watson, A. J. (2002), Reduced effectiveness of terrestrial carbon sequestration due to an antagonistic response of ocean productivity, *Geophysical Research Letters* **29**, 10.1029/2001GL014304.

Royal Society (2001), "The role of land carbon sinks in mitigating global climate change", Royal Society Document 10/01. (http://www.royalsoc.ac.uk/files/statfiles/document-150.pdf)

Further articles on the role of dust in the global carbon cycle and climatic change can be found at: http://tracer.env.uea.ac.uk/e114/publications.html

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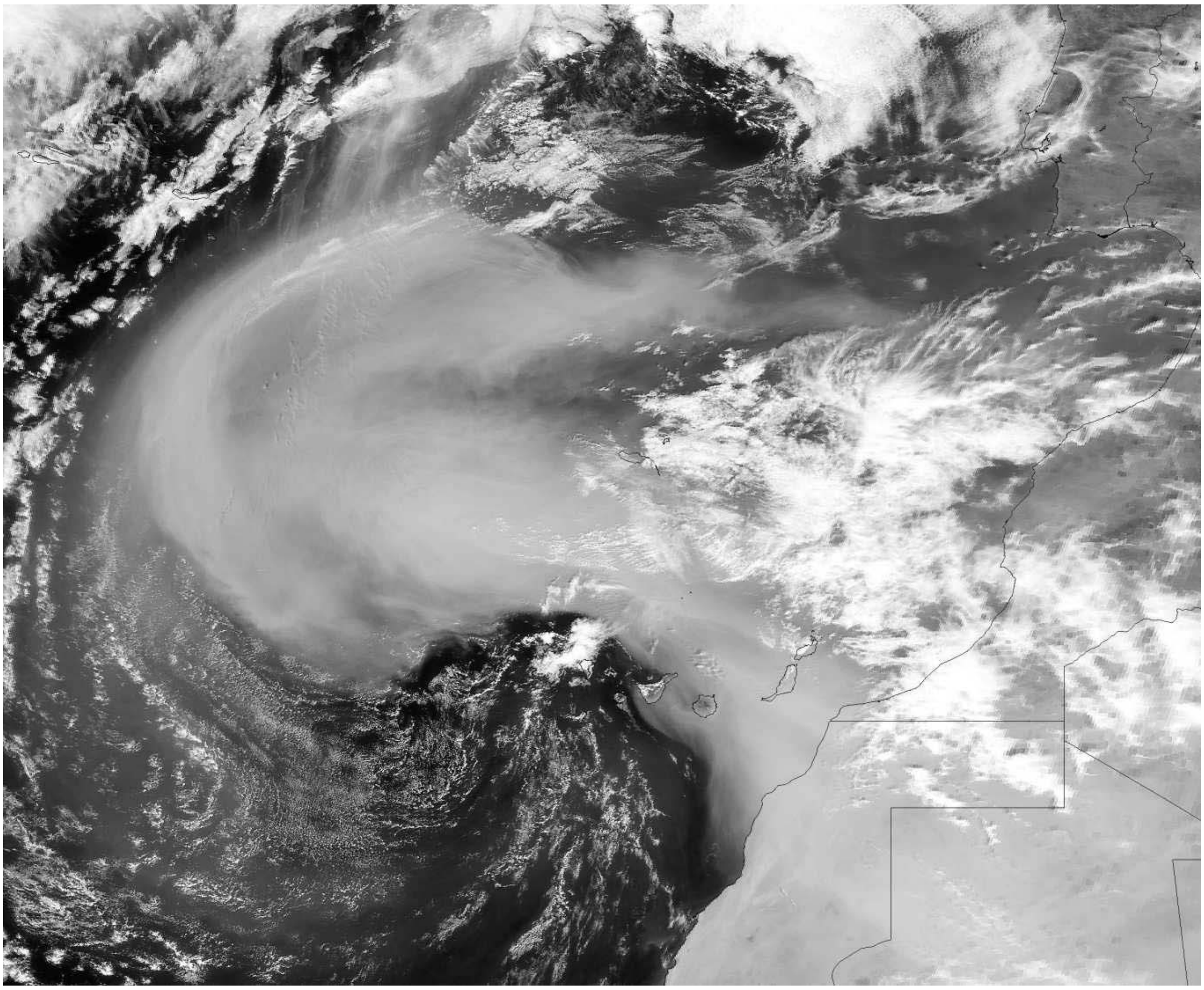
After graduating from Cambridge University, Andy Ridgwell spent much of the 1990s variously working in industry and being involved in the environmental protest movement (including living in a tree for a year!). More recently, after an MSc at Nottingham University, he completed a PhD at the University of East Anglia in the modeling of the Quaternary carbon cycle. He is currently an Earth system modeler based at the School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK, and is supported by a grant from the Tyndall Centre for Climate Change Research (www.tyndall.ac.uk), University of East Anglia, Norwich NR4 7TJ, UK. His research interests range from global climate dynamics to marine biogeochemical cycles, and from the distant geological past to historical and future anthropogenic change. Email: A.Ridgwell@uea.ac.uk

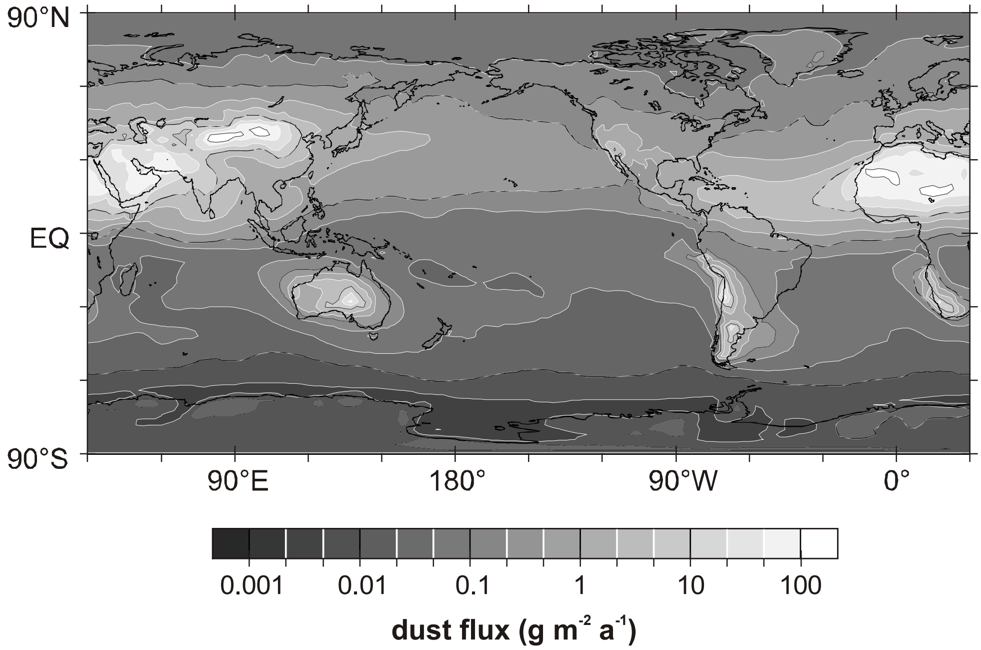
Figure 1. Satellite (SeaWiFS) image taken on February 26th 2000 of a massive sandstorm blowing off northwest Africa and reaching over 2000 km into the Atlantic. (The SeaWiFS image was provided by NASA DAAC/GSFC and is copyright of Orbital Imaging Corps and the NASA SeaWiFS project.)

Figure 2. Model simulated distribution of the annual mean (1981-1997) rate of dust deposition to the Earth's surface. (data from: Ginoux, P., *et al.*, Global simulation of dust in the troposphere: Model description and assessment, *J. Geophys. Res.*, **106**, 20,255-20,273, 2001.)

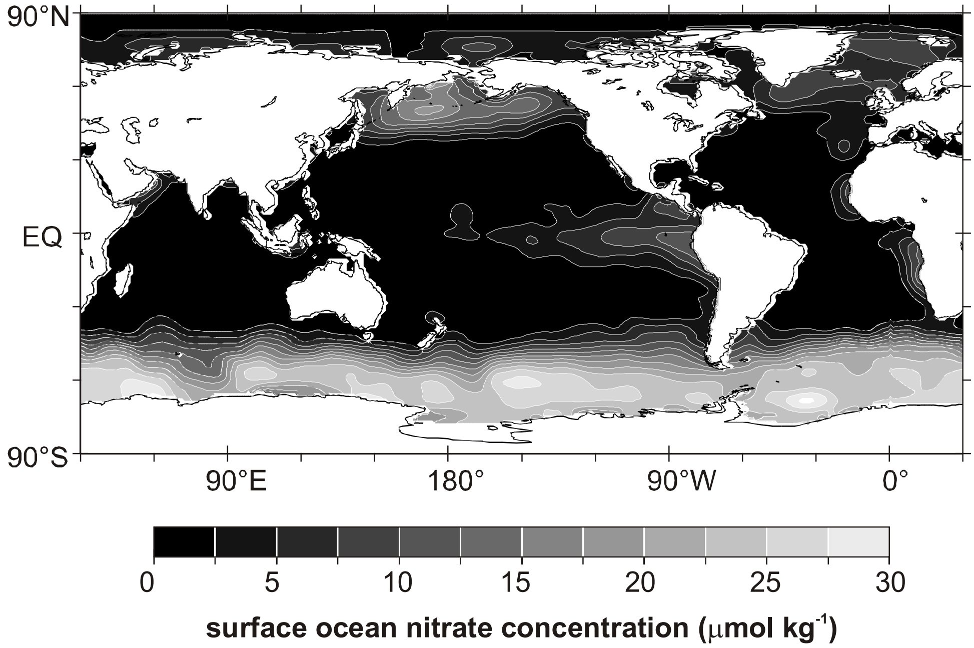
Figure 3. Global distribution of surface ocean nitrate (NO_3^-) concentrations. (data from: Conkright, M. E., *et al.*, World Ocean Atlas 1994 Volume 1: Nutrients, NOAA Atlas NESDIS 1, U.S. Department of Commerce, Washington, D.C. 150 pp, 1994.)

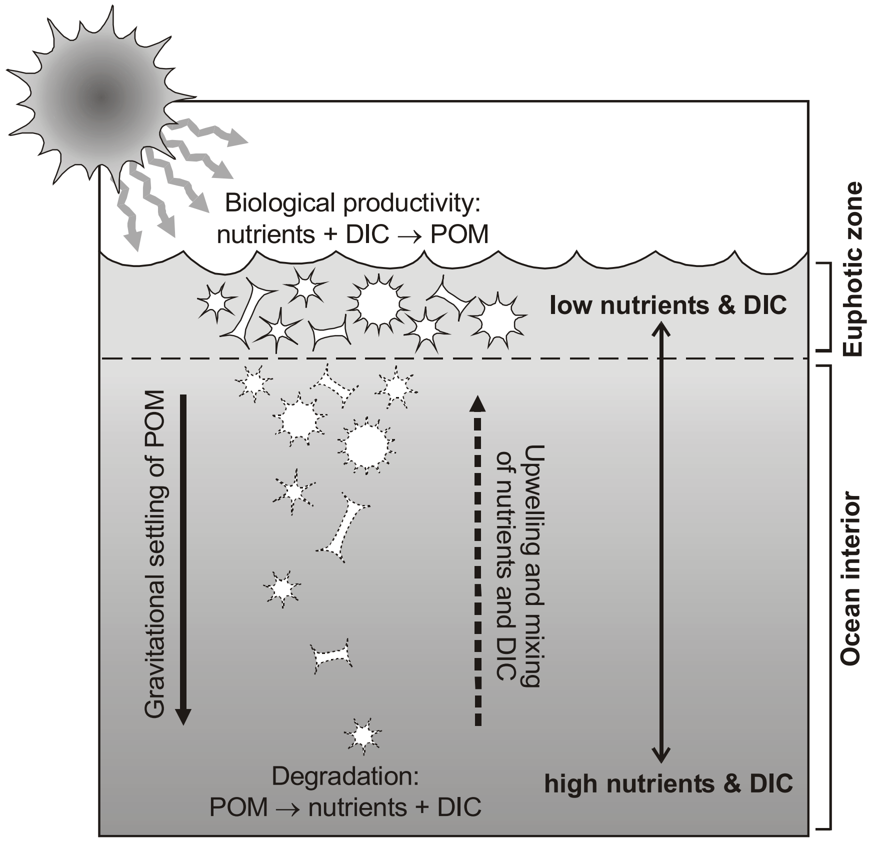
Figure 4. Schematic diagram of the operation of the 'biological pump' in the ocean. 'DIC' = (total) dissolved inorganic carbon ($CO_{2(aq)}$ + H_2CO_3 + HCO_3^- + CO_3^{2-}). 'POM' = particulate organic matter (primarily living and dead phytoplantkon cells and zooplankton fecal pellets).





90°N
EQ
90°S
90°E
180°
90°W
0°
0.001
0.01
0.1
1
10
100
dust flux (g m-2 a-1)


90°N
EQ
90°S
90°E
180°
90°W
0°
0
5
10
15
20
25
30
surface ocean nitrate concentration (μmol kg-1)


Biological productivity:
nutrients + DIC → POM
low nutrients & DIC
Euphotic zone
Gravitational settling of POM
Upwelling and mixing of nutrients and DIC
Ocean interior
Degradation:
POM → nutrients + DIC
high nutrients & DIC