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Reduced effectiveness of terrestrial carbon sequestration due to an antagonistic response of ocean productivity

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[1] Biological productivity in a number of ocean regions appears to be at least partly limited by the availability of iron. Any reduction in the present-day aeolian iron supply to the open ocean is therefore likely to result in further limitation of productivity. The stabilization of soils for the purpose of carbon sequestration could give rise to such an effect. With the aid of a global carbon cycle model, we show that the effectiveness of carbon removal from the atmosphere by sequestration on land will be diminished as a result of a reduction of up to 9% in the rate of anthropogenic CO_2 uptake by the ocean. This interconnectedness, both within the 'natural' system and in relation to human activities, highlights the importance of analyzing global change within an integrated 'Earth system' framework. *INDEX TERMS:* 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 4255 Oceanography: General: Numerical modeling; 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615)

1. Introduction

[2] The deliberate large-scale modification of terrestrial ecosystems by measures such as improved agricultural practices and forestation, has been identified as having considerable potential in the mitigation of climate change [*Metz et al.*, 2001]. However, it has been recognized that historical changes in land use have given rise to globally important sources of dust [*Tegen and Fung*, 1995]. If such changes are partly reversed or ameliorated by sequestration activities, the availability of mineral dust for deflation by wind action will be reduced. Atmospheric transport and deposition of this dust to the open ocean carries with it a major source of the marine phytoplankton nutrient, iron [*Duce and Tindale*, 1991], which is potentially limiting to biological productivity. Since increased rates of iron supply can lead to a downward pressure on the atmospheric mixing ratio of carbon dioxide ($x$$CO_2$) (as observed in open ocean experiments [*Coale et al.*, 1996; *Watson et al.*, 2000]), it follows that decreased aeolian deposition may act to drive atmospheric $x$$CO_2$ higher. Land use and ocean-atmosphere CO_2 exchange are, therefore, intimately linked. This finds some support in a recent study of atmospheric circulation over the south Indian Ocean, in which the locations of subsiding plumes of iron-laden aerosols (derived from arid soils and industry in southern Africa) were found to correspond with regions of enhanced oceanic CO_2 uptake [*Piketh et al.*, 2000]. Although the possibility that global biogeochemistry might be perturbed by measures taken for sequestration has been recognized [*Falkowski et al.*, 2000], the impact upon the ocean carbon sink resulting from a reduction in aeolian iron supply has not previously been analyzed. Here we present model results of the amount of carbon (otherwise taken up by the ocean) that could remain in the atmosphere as a direct result of the enactment of certain land-based mitigation measures for climate change.

2. Modelling Strategy

[3] The ocean-atmosphere carbon cycle model we employ is based upon a zonally-averaged representation of ocean circulation [*Ridgwell*, 2001; *Stocker and Wright*, 1996]. Ocean biogeochemistry follows that of a previous study, in which the effects upon atmospheric $x$$CO_2$ of glacial-interglacial perturbations in dust supply to the ocean were addressed [*Watson et al.*, 2000]. In this scheme, the cycling of three nutrients potentially limiting to biological activity in the ocean (phosphate, silicic acid, and iron) is considered [*Ridgwell*, 2001]. However, since the adjustment time of the sedimentary calcium carbonate reservoir is of order 5–6 ka [*Archer et al.*, 1998] (i.e., much longer than century-scale anthropogenic change), ocean-sediment interactions need not be considered. Similarly, the comparatively long residence time of nitrate in the ocean suggests that omission of the effect of iron supply driven changes in nitrogen fixation [*Falkowski et al.*, 2000] will not significantly affect our results.

[4] The model was configured for the pre-industrial carbon cycle [*Ridgwell*, 2001] and spun-up for a period of 5000 years, using distributions of dust deposition taken from a dust generation-transport-deposition model [*Mahowald et al.*, 1999]. On a global basis, the dominant supply of new (i.e., not recycled within the euphotic zone) dissolved iron to the biota of the surface ocean is from dust (3.0×10^9 mol Fe a^{-1}) rather than from upwelling/mixing (1.1×10^9 mol Fe a^{-1}). This situation is very similar to that deduced in a recent analysis made of iron supply and demand in the upper ocean [*Fung et al.*, 2000], although it differs from a second study, in which supply from upwelling/mixing was predicted to dominate [*Archer and Johnson*, 2000]. At the end of the spin-up period, global export production (calculated at 100 m depth) is some 8.8 PgC a^{-1}, driving a mixing ratio of CO_2 in the atmosphere of 273 ppm. The model was then forced with a prescribed atmospheric $x$$CO_2$ time history over the period 1765 to 2250 (Figure 1a), allowing CO_2 to invade the ocean following *Sarmiento et al.* [1998]. Atmospheric $x$$CO_2$ during this period follows ice core and atmospheric measurements, and the S550 stabilization scenario thereafter [*Enting et al.*, 1994]. Atmosphere-

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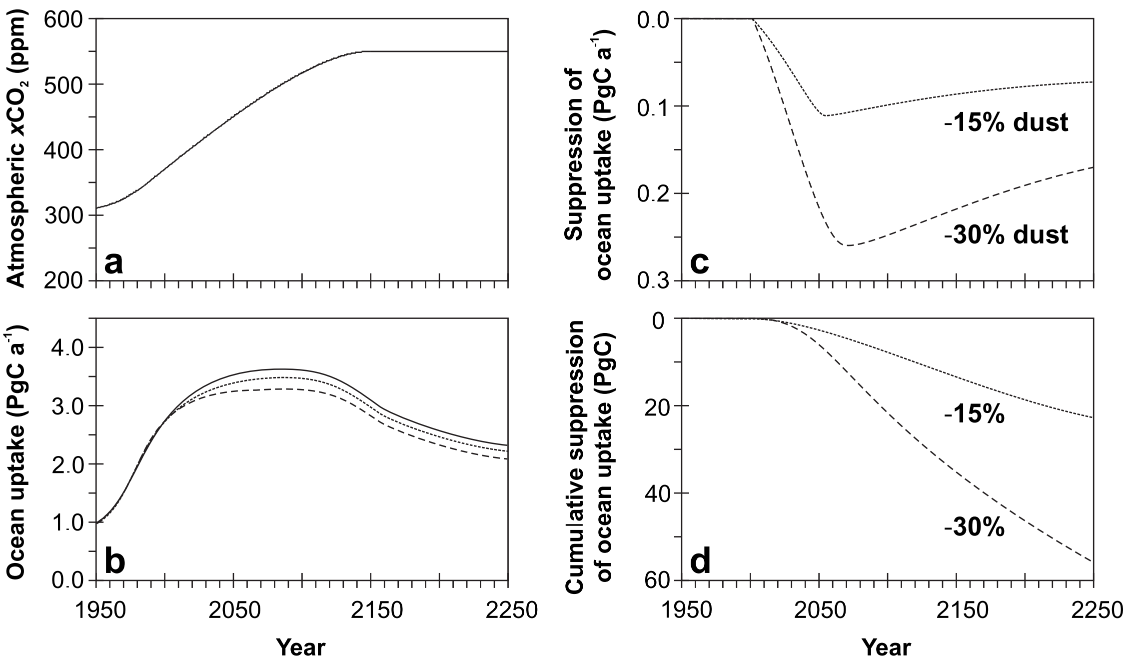

Figure 1. The effect on ocean carbon uptake resulting from a reduction in aeolian iron supply. a) prescribed atmospheric xCO_2 history (IPCC stabilization scenario S550 [*Enting et al.*, 1994]). b) annual net uptake of carbon by the ocean, under three scenarios; baseline (i.e., no modification in dust) as a solid line, 15% dust reduction (short dashes), and 30% (long dashes). c) suppression of the annual ocean uptake of carbon driven by reduced dust supply (lines representing the two dust scenarios represented as before). d) cumulative suppression of ocean carbon uptake.

ocean fluxes predicted by the model for the periods 1980–9 (1.7 PgC a^{-1}) and 1990–9 (2.0 PgC a^{-1}) are consistent with IPCC estimates [*Houghton et al.*, 2001].

[5] A series of model integrations are carried out, each driven by a different time history of dust supply to the ocean. In addition to a baseline scenario (in which dust deposition rates are held constant), various perturbation scenarios are considered, in which dust supply is linearly reduced over a period of 50 years, starting in 2000. The contribution made to atmospheric dust loading associated with land surface disturbance has been estimated to be 30–50% [*Tegen and Fung*, 1995; *Tegen et al.*, 1996]. Inherent within this estimate is a component having its origin in soils disturbed by climatic variability. We therefore assume that as an upper bound, a reduction in deposition rates of 30% characterizes the complete reversal of the effects of anthropogenic land surface modification and disturbance. However, since it is highly unlikely that future sequestration activities would have such a severe impact, a second scenario is considered; one of a more modest 15% reduction in dust. Other than prescribed atmospheric xCO_2 and dust depositional histories, no other model boundary conditions (specifically, ocean surface temperatures and circulation patterns) are varied.

3. Results

[6] We find that reduction in dust supply to the ocean has a significant impact on the rate of uptake of anthropogenic CO_2 from the atmosphere (Figures 1b and 1c). Peak impact occurs a little after the end of the prescribed 50-year period of decline in dust supply, with the ocean sink strength some 0.11 to 0.22 PgC a^{-1} lower than in the baseline case, depending on the dust reduction scenario. The effect of the perturbation diminishes slightly with time, but still represents a deficit in the rate of ocean uptake of 0.07–0.17 PgC a^{-1} by 2250. These changes are driven by a decline in the rate of export of particulate organic matter from the surface ocean — some 2.3–4.4% lower by 2050, and 3.9–7.7% lower by 2250. However, there are considerable gaps in our knowledge concerning the details of the biogeochemical cycling of iron in the ocean [*Wu et al.*, 2001] that add substantial uncertainty to these estimates. For instance, with an alternative distribution of dust deposition [*Duce et al.*, 1991] the sensitivity of the rate of anthropogenic CO_2 uptake to a (15% or 30%) reduction in aeolian iron supply is a factor 2–3 lower. A similar reduction in sensitivity arises if different assumptions regarding the role and concentrations of Fe-binding ligands in the ocean are made (0.3 nM vs. the 0.0 nM we assumed previously). In this case it is likely that ligand-bound iron supply to some extent 'buffers' the supply of Fe to the surface ocean against dust perturbation. These analyses suggest that our estimates may represent an upper limit of response, although we note that our model sensitivity is consistent with the effect of a more substantial (50%) reduction in dust exhibited by the (ligand-buffered) model of *Archer and Johnson* [2000].

[7] The effect of dust reduction on the carbon cycle is of the same order as that estimated to result from climatically induced changes in ocean circulation and marine productivity [*Bopp et al.*, 2001; *Sarmiento et al.*, 1998]. This highlights the need for predictions of future climate change to take into account possible changes in aeolian iron supply to the ocean [*Harrison et al.*, 2001]. There are clearly also important implications for the simulation of the observed historical trend in atmospheric xCO_2.

4. Discussions and Conclusion

[8] A variety of "land-use, land-use change and forestry" (LULUCF) activities have been proposed for the sequestration of carbon [*Metz et al.*, 2001; *Royal Society*, 2001]. As a result of reduced disturbance and increased stabilization of soils, many of these activities are likely to affect atmospheric dust loading. Of particular importance in this respect are measures rooted in the agricultural sector, such as changes in soil management practices (for example, reducing tillage, enhancing the areal and seasonal extent of ground cover, and the "set-aside" of surplus agricultural land) together with the restoration of previously degraded lands [*Metz et al.*, 2001]. The

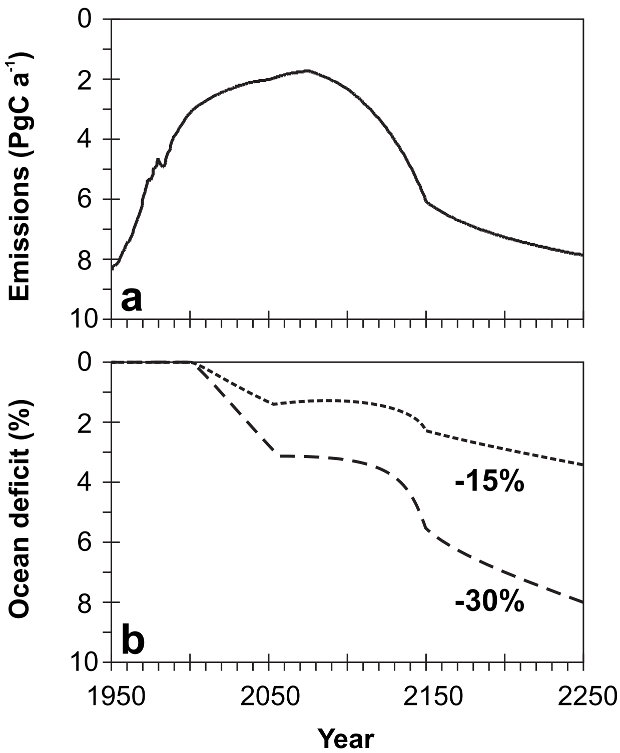

Figure 2. Deficit in ocean uptake compared to anthropogenic emissions. a) estimated anthropogenic emissions [*Enting et al.*, 1994] required in order to obtain the prescribed atmospheric xCO_2 history shown in Figure 1a. b) the deficit in the rate of carbon uptake by the ocean as a percentage of total anthropogenic emissions for the two dust reduction scenarios; 15% dust reduction (short dashes), and 30% (long dashes).

benefits by the year 2050 of these mitigation options have been estimated to be in the region of 23–44 PgC [*Metz et al.*, 2001]. In the forest sector, forestation and reforestation activities (with a sequestration potential of 49–66 PgC [*Metz et al.*, 2001]) might also tend to be associated with previously disturbed land, and thus affect dust supply. Depending on whether the agriculture sector is considered in isolation or in conjunction with changes in the forest sector, the potential sequestration of carbon arising from measures associated with reduced mineral dust availability is in the range 23–110 PgC.

[9] Offsetting these gains on land is the antagonistic effect on marine productivity suggested by our results. The 23–110 PgC benefit (typically assumed to be accrued on a 50-year time frame [*Metz et al.*, 2001; *Royal Society*, 2001]) arising from land use change exceeds the cumulative 2.5–5.0 PgC loss in ocean sink predicted to have occurred by 2050 (Figure 1d). However, newly created terrestrial sinks will tend to become saturated on timescales of 50–100 years [*Metz et al.*, 2001], and confer little additional benefit thereafter [*Royal Society*, 2001]. In contrast, the perturbation of oceanic uptake exhibits a considerable persistence with time (Figure 1c), with the deficit in uptake rate declining with an *e*-folding time of order 300 years. Cumulative loss will, therefore, continue to increase for some time, reaching 20.3–48.5 PgC by 2250, and perhaps double this by the end of the millennium (year 3000). Suppression of the ocean sink thus has the potential to substantially offset the benefit to the atmosphere of carbon sequestrated on land. This situation would be further exacerbated should there be any degradation of soil carbon stocks with future climate change [*Cox et al.*, 2000; *Lenton*, 2000]. Emissions scenarios may need to take into account the increasing relative significance with time of the deficit in ocean sink strength (Figure 2).

[10] Even in the absence of mitigation activities, significant changes in the rate of dust supply to the ocean might be expected to occur. The strength of dust sources is predicted by terrestrial ecosystem models generally to weaken as a result of the effects of climate change upon land biota, perhaps by as much as 20% [*Harrison et al.*, 2001], while soil stability has been found to be enhanced under higher ambient CO_2 concentrations [*Rillig et al.*, 1999]. Working against this, future population pressures may drive an increase in soil disturbance via the intensification and extensification of agriculture. Dramatic changes in the response of regional biomes to climatic change may also affect dust sources, and act in either direction. For instance, some climate models have demonstrated the possibility for substantial climate-driven loss of the Amazon rainforest [*Cox et al.*, 2000], while others hint at the existence of a stable 'green' vegetated state of the Sahara/Sahel region [*Brovkin et al.*, 1998]. Finally, the efficiency of dust entrainment and transport through the atmosphere to the open ocean may change, heavily influenced by the intensity of the hydrological cycle [*Tegen and Fung*, 1995].

[11] Effects upon ocean productivity arising from modification of land use are likely to be highly spatially and seasonally heterogeneous, dependent upon such factors as the distribution of iron limitation in the present-day ocean, atmospheric transport patterns, and the specific locations of dust sources. With respect to the latter, since mineral dust entertainment by wind action is more effective with relatively dry and vegetation-free soils [*Tegen and Fung*, 1995], changes in land use in arid and semi-arid regions are likely to have a disproportionate influence. Elucidation of interregional differences in the impact of land use change requires the use of a more spatially explicit (i.e., 3-D) ocean biogeochemical model than we have used here, and in conjunction with detailed analysis of the sensitivity of atmospheric aerosol loading to climatic and anthropogenic influences upon major dust sources. However, socio-economic uncertainties in future land use modification and implementation of sequestration measures are likely to dominate in any prediction of future oceanic uptake.

[12] Although necessarily simplistic, the importance of our analysis lies in the recognition and potential significance of a direct causal link between the enactment of sequestration measures on land and the suppression of the oceanic sink. At a minimum, the 'land use/ocean productivity' mechanism we describe here may need to be taken into account when evaluating the economics of certain LULUCF activities. However, it is within the range of uncertainty that the eventual benefit (in terms of reduced atmospheric xCO_2) could be largely negated by an antagonistic response induced in the ocean.

[13] We are only just starting to understand and quantify the multifarious dynamical interactions that exist within the Earth system [*Falkowski et al.*, 2000; *Schellnhuber*, 1999]. Land surface modification of the sort planned for carbon sequestration will affect many aspects of this complex system. In addition to the 'land use/ocean productivity' effect, atmospheric aerosol loading exerts an important forcing upon climate as a result of the radiative absorption and reflection properties of dust [*Tegen et al.*, 1996]. It is also likely that any albedo changes brought about by the creation of new forests will cause a substantial forcing of climate. In boreal regions, this might offset the reduced greenhouse gas forcing arising from the sequestration of carbon by newly-created forests [*Betts*, 2000]. This interconnectedness, both within the "natural" system and with human actions and activities, highlights the importance of the use of "integrated assessment models" in the analysis of future climate change.

[14] Many LULUCF activities have considerable ancillary benefits (for example, in improved soil fertility), and as such have been described as "no regrets" or "win-win" solutions [*Metz et al.*, 2001]. However, the complex interconnected nature of the Earth system, exemplified by the results of this study, suggests that these activities many not be as benign as has generally been assumed.

Sequestration cannot, therefore, be wholly relied upon as a substitute for emissions reductions.

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