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Long-term ocean carbon sequestration with macronutrient addition

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Abstract

The uptake of atmospheric carbon dioxide by the ocean can be enhanced by methods such as direct carbon dioxide injection, the addition of the micronutrient, iron, or the adding of macronutrients such as nitrogen. Preliminary simulations of these strategies using ocean general circulation models at LLNL suggest that most the carbon sequestered in the ocean using iron fertilization returns to the atmosphere within decades. Direct injection at mid water depth sequesters carbon for a few hundred years. In contrast, macro nutrient addition can sequester carbon for thousands years. Ocean Nourishment is expected to enhance sustainable fish stocks as well as sequester carbon but should carried out with monitoring to ensure the desired effects are achieved.

Introduction

The desire to manage the level of carbon dioxide in the atmosphere has encouraged research into the options of sequestering in the ocean some of the carbon presently dumped in the atmosphere. Three strategies are available; the carbon can be collected and pumped into the ocean; the alkalinity can be changed to lower the partial pressure of carbon dioxide in the water, eg Caldeira and Rau (2000) or the biological pump can be made more active, eg Jones (2001).

Each one of these techniques has its economic penalties, its environmental costs or benefits and its sequestration time. By the latter we mean the time the carbon is kept in the ocean. While short sequestration time may provide some “breathing space” for climate management, it values less than techniques with long storage time.

The sequestration time is dependent on the vertical circulation of the ocean and the physical, chemical and biological processes that partition carbon between carbon dioxide, inorganic carbon in solution and organic carbon formed by photosynthesis.

The oceans have limited productivity because, it is believed there is a shortage of the micronutrient, iron, in the Southern Ocean, Boyd et al (2000) and some parts of the equatorial Pacific, Coale et al 1996. Over most of the other 80% of the ocean the macronutrient, nitrogen, has been exhausted. Phytoplankton have converted the inorganic nutrients to organic material using the energy of the sun and this process stops when one of the essential nutrients in the photic zone is exhausted. It is assumed that other macro and micronutrients are adequate to support some level of phytoplankton growth if the limiting nutrient were to be provided. While there is some support for this assumption, it deserves to be more fully investigated.

The strategy of macronutrient nourishment of the ocean has only recently been considered, Jones and Young (1997) in part because it was thought that the initial cost would be high. Costing of practical schemes by Shoji and Jones (2001) has shown this is not so. Now it is interesting to examine the sequestration time of carbon exported to the deep ocean as a result of enhanced primary production. Our current understanding of enhanced photosynthesis has been summarised in Jones (2003) while the ability to monitor enhanced ocean production is reviewed in Jones et al (1993).

To gain some understanding of the sequestration times of direct injection and enhanced ocean productivity the Lawrence Livermore National Laboratory ocean models have been used to look at three scenarios. They show that direct injection of carbon dioxide into the ocean at mid depth depends on the time to ventilation of the water into which it is injected. Iron fertilisation also depends on ventilation time because of the assumption about upwelled nutrients used. When the remineralised material is upwelled to iron deficient regions it is assumed it is again short of iron. In the case of nitrogen nourishment, the time to ventilation of the remineralised organic matter is not important as upwelled water, in which the organic material was remineralised, now contains all the nutrients to again support photosynthesis and export into the deep ocean.

Model

The ocean atmosphere system was represented by a numerical model using primitive equations described in Wickett et al 2000. The carbon cycle is as that defined in the Ocean Carbon-cycle Model Intercomparison Project, OCMIP.

The model takes about one day to advance 50 years using a 2 GHz Pentium© chip. It was driven by climatological atmosphere. The model was run up until in equilibrium with the pre industrial carbon dioxide level in the atmosphere of 280 ppm. Then a pulse of macronutrient was added uniformly over the whole ocean including the areas covered by ice. Our pulse of nutrients takes of order 30 days to be exported from the surface layer of the ocean. Enhanced phytosynthetic production and export of organic carbon occurs until the phosphate is reduced to the climatological level. As specified in the OCMIP protocols, calcium carbonate is assumed to make up 7% of the total amount of carbon exported

Creating a carbon sink can be compared with the alternative of not emitting carbon from the smoke stack. To make such a comparison the atmospheric concentration of carbon dioxide should be returned to the value it had before the sequestration activity. This allows us to consider the uptake of carbon as tonnes of carbon dioxide avoided. This is an issue because not all the carbon emitted from the smoke stack stays in the atmosphere. Some moves of its own accord to the ocean and the terrestrial carbon pool. As well, as the equilibrium pressure of carbon dioxide changes so does the amount carbon partitioned between the ocean and the atmosphere.

Results

The macronutrient was added uniformly over the ocean surface such that if all the nitrogen were converted to biomass in the Redfield ratio, 10Gt of carbon would have been converted to organic matter. This leads to an export of carbon as both dissolved organic matter (DOM) and particulate organic matter (POM). Particular matter dominates the flux of carbon from the ocean surface layer and the additional flux as a result of nourishment is shown in Fig 1.The flux in the first year from the addition of macronutrients is in the range of 1 to 2 moleC/m^2/yr (12 –24 gC/m^2/yr). This additional flux is mostly in the band ±40°of the equator. Following the export of carbon from the surface layer, the reduction in the partial pressure of carbon dioxide in the upper ocean causes a flux 0f carbon from the atmosphere. This is shown for the first year in Fig 2. The particulate flux and the carbon dioxide flux patterns vary mostly because the time scales of the process are different and advection is moving the surface water before it can replace the exported carbon.

Once the carbon is paired with the nutrients in the model, they stay together as the water undergoes its vertical advection. The model does not have denitrification that is believed to occur in low oxygen regions of the deep ocean and thus may overpredict long-term storage. During the first 500 years after the injection of the pulse of macronutrient the model predicts only a slight loss of carbon from the ocean. In Fig 3 the total carbon stored in the ocean as a result of three levels of Ocean Nourishment is shown.

Adding macronutrients to the surface ocean can be contrasted with the strategy of providing the micronutrient, iron to the ocean south of 50°S. It is assumed that the iron allows all the excess macronutrient to be converted to organic matter in the Redfield ratio. After 80 years 70% of the carbon originally converted to organic matter has been remineralised and escaped back to the atmosphere. The model assumes that the iron added as fertilisation is not available when the carbon returns to the ocean photic zone. Fig 4 shows that the rapid loss of carbon.

The other region where iron fertilisation has been considered is the equatorial Pacific. Gnanadesikan et al (2001) found that removal of macronutrients from a patch of the equatorial Pacific resulted in decreased in new primary production elsewhere. This id better thought of lack of initial storage over the relative short time rather than sequent leakage of the carbon as in the case of Southern Ocean fertilisation.

Still another approach is to directly inject the carbon into the deep ocean which while being able to place the carbon in the deep ocean water, loses the carbon to the atmosphere once the water is upwelled to the surface. The retention time is a now primarily a function of the depth of injection. Fig 5 shows that 70% has escaped in 400 years when injected at 1000m depth. Direct injection in contrast with the two ocean nourishment schemes above requires the capture and compression of the carbon dioxide. At present this may be an expensive process compared with nourishment.

Conclusions

Different strategies for storing carbon in the ocean lead to different sequestration times. The LLNL models show that the shortest sequestration time of the three ocean storage strategies considered is that for iron fertilisation in the polar oceans. Direct injection at 1000m depth has lost 70% of its carbon in 400 years while macronutrient nourishment of the surface ocean leads to retention to most of the carbon taken well in excess of 500years.

These results must be regarded as preliminary. The LLNL models have a number of built in assumptions which are important in interpreting the results above and these assumptions deserve further investigations. Furthermore, all options must be evaluated on a wide range of measures (e.g., cost, retention time, ancillary benefits, unintended consequences, etc.). Therefore, it is essential that we do not prematurely narrow the range of potential options explored. Based on the preliminary results presented here, we suggest that macronutrient fertilization options are worthy of further investigation as strategy that could potentially contribute to long-term carbon sequestration.

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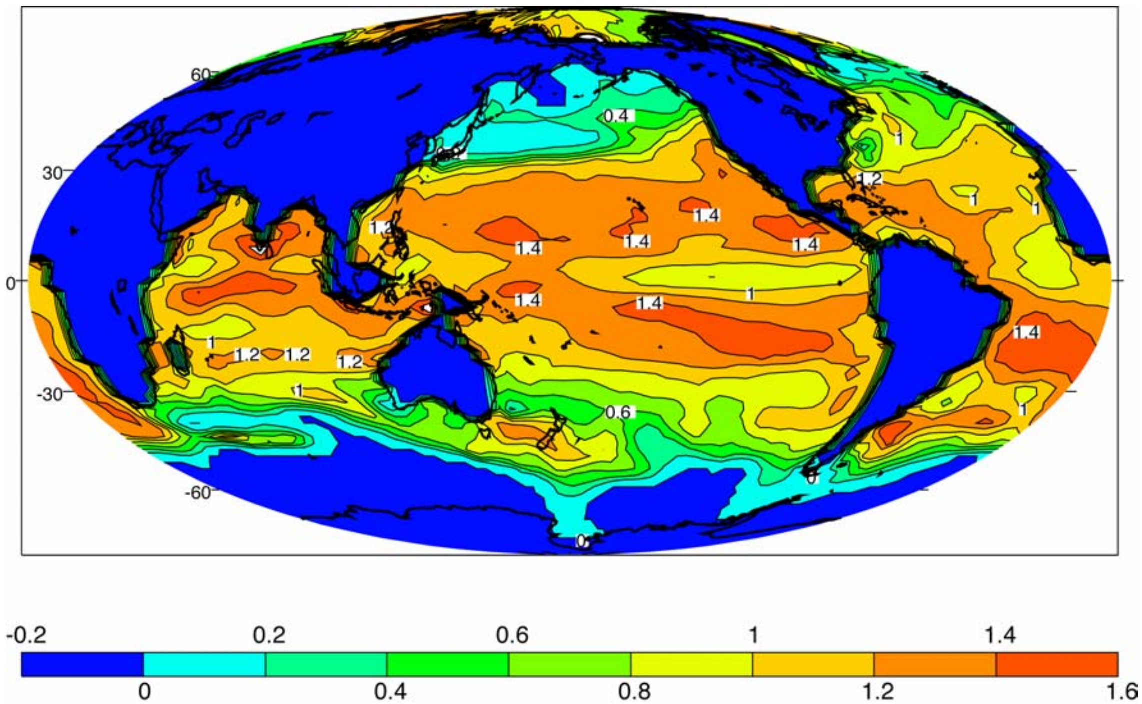

Fig 1 Increase in particulate organic carbon flux from the ocean surface layer one year after a pulse of macronutrient was added o the whole ocean. Contours in moles $C/m^2/yr$.

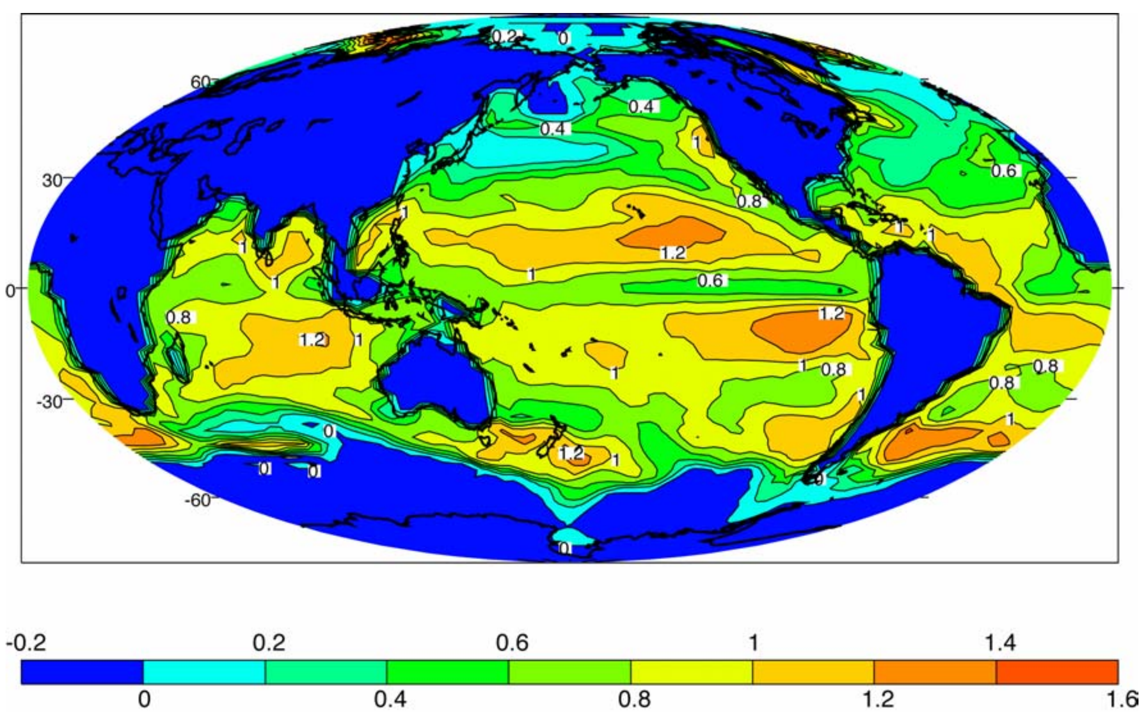

Fig 2 Increase in the air-to-sea carbon flux from the ocean surface layer one year after a pulse of macronutrient was added o the whole ocean. Contours in moles $C/m^2/yr$.

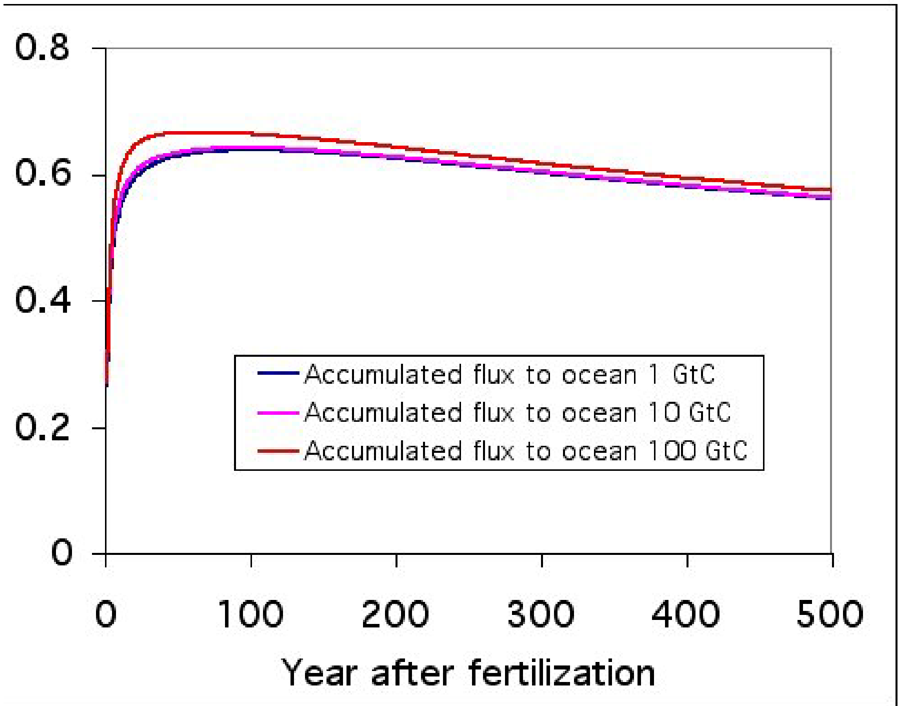

Fig 3 Retention of carbon in the ocean after intial nourishment. Addition of nutrients are three different intensities have been normalised by the amount of nitrogen provided. Vertical axis is in arbitrary units.

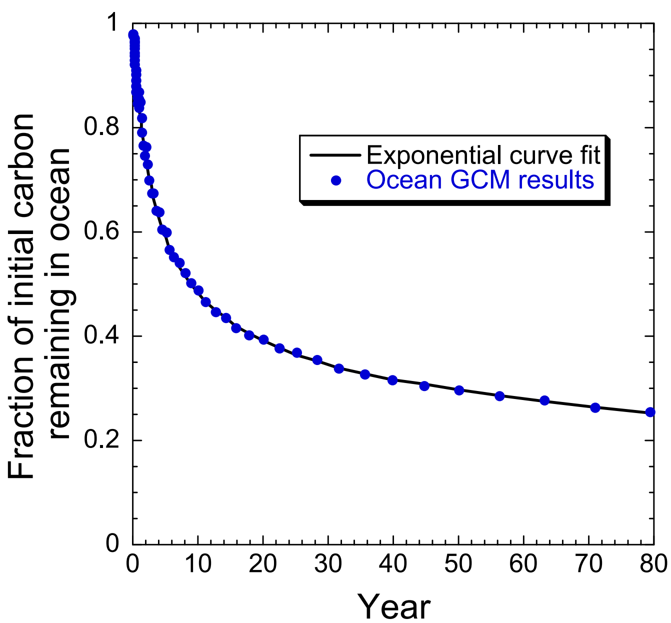

Fig 4 Retention of carbon as a result of iron fertilisation of the Southern Ocean (after Caldeira in press)

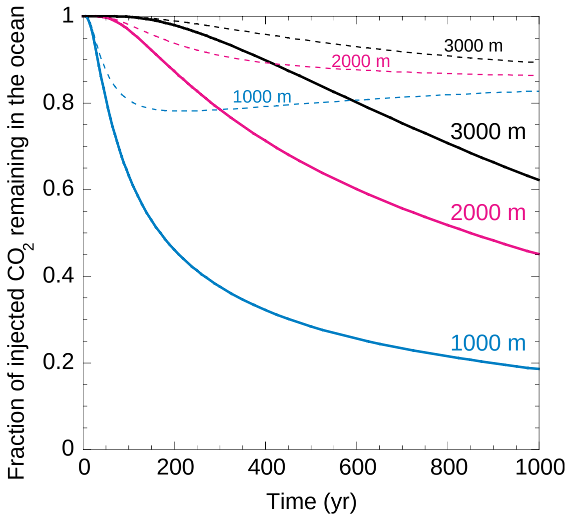

Fig 5 Retention of carbon as a result of the direct injection of carbon at three different depths. The broken line indicates a different atmospheric scenario. (after Caldeira et al, 2001)