"SIMULATIONS OF THE CARBON CYCLE IN THE OCEANS"

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YEAR 2 ACCOMPLISHMENTS.

1.1.. MODELS OF OCEANIC CO_2 UPTAKE

Our perturbation simulation of carbon dioxide uptake was published this year (Sarmiento, Orr, and Siegenthaler, 1992). This study gives strong support to estimates of oceanic uptake of fossil CO_2 of order 2 GtC/yr. over the last decade, in disagreement with the recent estimate of <1 GtC/yr. by Tans, Takahashi, and Fung, in their 1990 study published in Science. Sarmiento and Sundquist (1992) argue that the low estimate of Tans et al. is due primarily to the fact that they ignored the large input of carbon to the oceans by rivers which is only partially balanced by the loss to sediments. Sarmiento (1991) gives an overview of the types of observations and measurement precision that would be required to confirm the model estimates of oceanic anthropogenic carbon dioxide uptake.

Siegenthaler and his graduate student, Joos, have further studied and applied the HILDA model (High-latitude exchange/Diffusion-Advection model). The oceanic uptake of anthropogenic CO_2 of a carbon cycle model can be characterized by the model's response to a pulse input of CO_2 into the atmosphere. The response function of the HILDA model, calibrated with bomb-produced and natural ^{14}C and with a depth-dependent eddy diffusivity, is remarkably similar to the response function of the 3-D Princeton ocean carbon cycle model; the airborne fraction of the latter is slightly higher (Siegenthaler and Joos, 1992). This indicates that HILDA simulates the time-dependent CO_2 uptake by the 3-D Princeton model well over a large range of time scales. Thus, an important goal of this proposal has essentially been achieved: to develop a simple model which can be used as a cost-effective substitute for a 3-D carbon cycle model for calculating atmospheric CO_2 scenarios. The HILDA model could probably be made to fit even better the 3-D model's response if it were calibrated using output from the 3-D model.

Joos and Siegenthaler have also simulated the oceanic distribution of CFCs (characteristic time of increase ca. 10 yr.) and of ^{39}Ar (half life 269 yr., cosmic ray produced in the atmosphere) (Joos, 1992). They find that the averaged distributions of both tracers in the ocean are well simulated by the HILDA model. This result is not obvious, and it is a very encouraging confirmation of the value of this "simple" ocean model for simulating the uptake of perturbations from the atmosphere on different time scales.

In the discussion about the relation between fossil fuel consumption and atmospheric CO_2 levels, only the short-term effects of energy use scenarios are sometimes considered. Oeschger et al. (1992) and Joos et al. (1992) point out that the present growth rate of the CO_2 emissions (i.e. of the fossil fuel consumption) sets the initial conditions for the future. The higher the current growth rate, the larger will the energy use (and the emissions) be in 10 or 20 years, and the more stringent reductions will be necessary in order to not exceed some maximum tolerable atmospheric CO_2 level. This is illustrated by the development after the 1973 oil crisis and the period of high oil prices starting around 1980, with a reduction of the average growth rate from 4.4 % per year (1945-1973) to 2% per year (1973-1990). Had the exponential growth of 4.4 % per

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year continued after 1973, then the CO_2 emissions from fossil fuels would have been 63% higher in 1990 than they actually were, and the annual increase of CO_2-induced radiative forcing would have been higher by 77%.

1.2. CARBON SYSTEM MODEL DEVELOPMENT

Sarmiento and Siegenthaler (1992) wrote a paper for a book on ocean primary productivity and biogeochemical cycles which gives an overview of the role of the natural carbon cycle in controlling atmospheric carbon dioxide. Najjar et al. (1992) describe our most recent attempts to develop a model for the remineralization of organic matter in the water column. The salient result from this work is that it is difficult to account for the distribution of nutrients and carbon in the water column by the cycling of particulate organic matter alone. The formation of a readily transportable form of organic matter, such as dissolved organic matter, appears to be required in order to explain the observations.

Our studies of the potential effect of Southern Ocean nutrient depletion on atmospheric carbon dioxide and ocean chemistry led to the publication of papers by Joos et al. (1991) and Sarmiento and Orr (1991). Changes such as these might occur if the Southern Ocean were fertilized with iron, or if ocean circulation were to change in response to greenhouse warming. The Joos et al. (1991) paper describes in more detail the results of a study with the HILDA model that was reported in a paper published in Nature (vol. 349: 772-774 [1991]) and discussed in last year's report. A prediction of atmospheric carbon dioxide levels showed that Southern Ocean nutrient removal would reduce the expected growth over the next 100 years by of order 100 ppm.

The Sarmiento and Orr (1991) study describes a three-dimensional model simulation of nutrient depletion in various regions of the ocean which gives a reduction in growth of order 70 ppm over the next 100 years. Additional salient results are: (1) The Southern Ocean is the region of the ocean which has by far the largest potential impact on atmospheric carbon dioxide if nutrients are removed. This is because of the high nutrient concentrations that exist there now, and because it is an area which taps into the large volume of water contained in the deep ocean. (2) The impact of such a removal on deep ocean oxygen is substantially less than had been postulated based on earlier box model studies. This result has considerable relevance to our understanding of what led to the reduced carbon dioxide levels of the last ice age, since our previous models of Southern Ocean nutrient depletion had been called into question based on the fact that there is no evidence of low oxygen levels in the last ice age. The much greater vertical and horizontal resolution of the three-dimensional model permits oxygen depletion to occur immediately under the regions of enhanced surface nutrient removal, rather than in the entire deep ocean. However, in these regions the oxygen removal is large enough to cause anoxia. (3) The redistribution of nutrients in the deep ocean has a detailed structure very much like that suggested by nutrient proxy observations of the ice age (the Cd/Ca measurements of Ed Boyle at MIT), of removal from intermediate waters and enhancement at depth.

A final paper based on the Southern Ocean nutrient depletion scenarios is in preparation at the present time reporting on the impact of this scenario on nitrous oxide. Nitrous oxide is a powerful greenhouse gas with an oceanic source that accounts for about 30±15% of the total sources to the atmosphere. Evidence available suggests it is produced by nitrification in the oceans. The increased biological productivity associated with nutrient depletion leads to a doubling of the oceanic production of nitrous oxide.

The greenhouse warming of this gas over the next 100 years is equivalent to about 8 ppm of carbon dioxide. The impact on ozone loss is being evaluated at the present time.

Orr and Sarmiento (1991) used the same approach as the Southern Ocean nutrient depletion scenario to evaluate the potential impact of enhanced marine macroalgae growth as a potential sink for atmospheric carbon dioxide, a topic which has received some attention in the past. The model shows that enhanced macroalgal growth does not provide a sink of any significance to the overall fossil CO_2 budget. On the other hand, the model results suggest that anthropogenic nutrient delivery by rivers may have a larger impact than we had previously thought, because a high fraction of the carbon dioxide removed from the ocean by algal consumption of those nutrients comes from the atmosphere during the first few decades.

Sarmiento et al (in preparation) have almost completed a paper describing our three-dimensional ecosystem model studies. This paper will be submitted for publication by the end of this month. The ecosystem model is aimed at developing the capability for predicting the response of ocean biology to changes in ocean circulation such as must have occurred during the last ice age and have been predicted to occur in response to global warming. The main focus of this paper is on describing the factors that control the surface nutrient content. In our ecosystem model the zooplankton grazing of phytoplankton sets an upper limit to their population which in turn sets an upper limit to their potential nitrate uptake. If the physical transport is large, the potential nitrate input can be greater than the maximum potential uptake and the system responds by allowing nitrate to build up to high values at the surface. The paper explains what factors in the model determine the potential nitrate uptake. The following two sub-section on the nitrogen version of the ecosystem model, and our new carbon-nitrogen version, discuss our further progress in the development of the ecosystem models per se.

(a) The nitrogen model

During the past year work has been concentrated on two areas, evaluating the results of the 3D North Atlantic simulation reported on in Sarmiento et al. (in preparation), and investigating new parameterisations of some of the biological processes of the ecosystem model.

The evaluation of the 3D model results was carried out by comparing the predicted seasonal cycles of the concentrations of phytoplankton, bacteria, nitrate and ammonium, plus primary production and particulate flux out of the euphotic zone with observations from Bermuda Station "S" (31°N 65°W) and Ocean Weather Station "India" (59°N 19°W). A paper describing this work has been completed and is about to be submitted for publication (Fasham et al., in preparation). It was found that the model simulated the seasonal cycles of phytoplankton, bacteria, and nutrients at both sites with a reasonable degree of success bearing in mind the simplicity of the model. However, the model over-estimated the magnitude of the spring bloom and this was found to be due to deficiencies in the zooplankton model resulting in over wintering zooplankton concentrations being too low. Zooplankton also have a critical affect on the dynamics of the euphotic zone by controlling phytoplankton production in the period following the spring bloom and making the major contribution to ammonium production.

The sinking rate of detritus was found to be a critical parameter that affects the balance between regenerated and new primary production. A low sinking rate allows detritus to be recycled within the euphotic zone by zooplankton or bacteria thereby increasing regenerated production and reducing the f-ratio. New production is mainly controlled by physical transport but may be modulated by differences in sinking rate.

The model predicts high summer nitrate levels at O.W.S "India" that are in agreement with observations. The model results suggested that these high levels arise because of a combination of high vertical transport of nitrate, ammonium inhibition of nitrate uptake, and zooplankton grazing control of summer phytoplankton levels.

The 3D model results demonstrated that there may be deficiencies in the zooplankton process model and so alternative parameterisations have been investigated using the simple mixed layer model (Fasham et al., 1990). It was found that, in order to obtain a good a good simulation of the seasonal cycle at OWS "India", it was necessary to model the zooplankton mortality rate as a density-dependent function rather than as a constant. This change produced higher over wintering concentrations of zooplankton than the previous model, resulting in higher grazing pressure during the spring bloom and lower bloom phytoplankton concentrations (Fasham, 1992). This new nitrogen model has now been run in the North Atlantic GCM and the results are being analyzed.

Two other aspects of the ecosystem model have also been re-evaluated, namely the parameterisation of the relative uptake of nitrate and ammonium by phytoplankton and food switching by zooplankton. It has been found that these processes can be regarded as special cases of a general resource allocation model based on queueing theory which will lead to a simplification of the ecosystem model. These results are in the process of being written up for publication (Fasham, in prep).

(b) The carbon-nitrogen model.

An operational first version of the coupled ecosystem model was completed a year ago. Since then, work has concentrated on refining the processes and parameter values to improve the use of the model in accurately simulating biogeochemical cycles. Research has focused in three areas: development of a coupled model for relating dynamics of heterotrophs (zooplankton and bacteria) to carbon and nitrogen contents of their food, the design of a new, more accurate, model of marine photosynthesis, and the embedding of the coupled biological model into the North Atlantic GCM developed at Princeton University.

A complex bioenergetic model was developed to explore how amounts of growth, carbon respired and nitrogen excreted by marine zooplankton and bacteria are influenced by the carbon and nitrogen contents of their food. Model predictions compared favorably with experimental observations. It was found that the model predictions could be approximated using simpler nutrient-balancing models, although critical assumptions about organisms' net growth efficiency had to be made for their application. A paper has been submitted to J. Plank. Res. (Anderson, submitted)

The penetration of light into sea water and the resulting photosynthesis are complex processes, which are strongly influenced by the spectral properties of light and the spectrally-related properties of absorbing and photosynthetic substances. Computationally efficient algorithms for predicting primary production are required for use in GCMs; the analytic depth and time integrals which are necessary use wavelength-independent parameterisations of the processes detailed above. A new empirical model of light penetration and photosynthesis has been developed which simulates these processes using wavelength-averaged parameters, but which maintains a high level of accuracy. A paper describing this new model is in preparation (Anderson in prep.).

A completed version of the coupled ecosystem model has been embedded in the Princeton North Atlantic GCM. Preliminary results have been encouraging, although more work is required to fully assess its performance.

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A ** or ++ indicates papers describing research funded in full or in part by the ongoing grant. The 13 ** papers are new since last year's annual report. The 6 ++ papers appeared in last year's annual report; 4 of these have since been published and the remaining 2 will be submitted for publication in the near future.

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