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Project name: Simulation of the carbon cycle in the ocean.

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Abstract

A dual carbon-nitrogen biological model of the upper ocean has been developed, which has successfully allowed predictions of fluxes of carbon between atmosphere and the deep ocean to be made. Regarding studying the carbon cycle in the ocean, the modelling has highlighted the need for a good understanding of the interactions between the carbon and nitrogen cycles, and also the importance of zooplankton grazing and levels of overwintering biological stocks. Problems have been encountered with the accuracy of prediction of the partial pressure of carbon dioxide in the surface ocean, and the sensitivity of the model to zooplankton parameters, and those parameters which affect overwintering stocks (e.g. mortality parameters). The model has recently been incorporated into a physical General Circulation Model of the Atlantic Ocean. Future work will involve assessing the performance of the biological model in General Circulation Models, and making necessary refinements in order to improve its predictive ability.

Introduction

Marine biology plays an important role in the biogeochemical cycling of nutrients and carbon in the world's oceans. Two biological processes are of particular importance. Firstly, photosynthesis by phytoplankton consumes carbon dioxide, reducing the partial pressure of the gas in the surface ocean, and thereby increasing the gaseous flux of carbon from atmosphere to ocean. Secondly, living organisms die and sink to depth, the so-called "biological pump" which transports carbon from the surface into the large resevoir provided by the deep ocean. The marine ecosystem is complex, and the various trophic interactions must be adequately modelled in order to study the biological processes outlined above, and to properly assess the role of marine biology in the global carbon cycle.

The primary objective of the project is to develop biological models suitable for studying the role of the ocean in the global carbon cycle. Related to this main objective are a series of subobjectives:

(1) To develop a carbon-based model of the marine ecosystem. Existing biological models tend to be based on a single element, usually nitrogen, as this is the major nutrient which limits primary production in the world's oceans. Simulation models must not neglect this important effect of nutrient limitation on phytoplankton growth, and therefore in order to study the carbon cycle both carbon and nitrogen should be modelled together.

(2) To incorporate the carbon-nitrogen model into physical General Circulation Models (GCMs) of the world's oceans. This will permit the role of the ocean as a whole in the global carbon cycle to be assessed.

(3) To use modelling to study the complexities of the marine ecosystem, both to identify processes and trophic interactions which are particularly important in the biogeochemical cycling of carbon, and to assess what is an appropriate level of detail for a biological model which is to be incorporated into GCMs.

Results and Discussion

(1) <u>Development of a dual carbon-nitrogen model.</u>

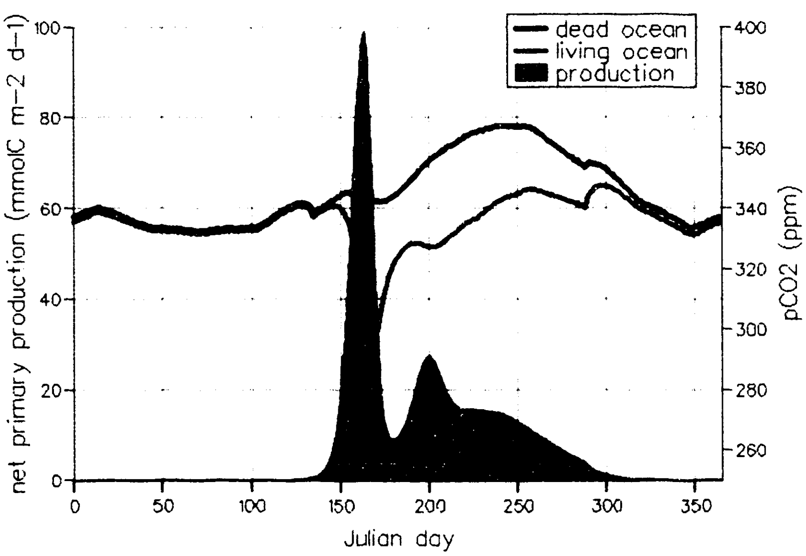
A carbon-nitrogen model of the marine ecosystem in the upper ocean has been developed based on M.J.R. Fasham's existing nitrogen-based model (published in J. Marine Research 48, 591-639, 1990). The interactions between the carbon and nitrogen cycles are often complex, and therefore attention has focussed on identifying and modelling these interactions in a realistic manner (see discussion of objective (3) below). The introduction of carbon has required several new compartments to be introduced over and above those that already existed in M. Fasham's model: dissolved organic carbon, detrital carbon, total inorganic carbon, and alkalinity. The major problem, however, has been the interdependence of model flows: in a single-element model independent equations can usually be written for each flow between model compartments, whereas in a dual-element model complications occur because the magnitude of some carbon flows will influence the magnitude of associated nitrogen flows (and vice versa), often not in a straightforward manner. It is therefore the links between the carbon and nitrogen cycles which have received particular attention.

A detailed treatment of carbonate chemistry has been put into the model, as this is necessary in order to predict the partial pressure of carbon dioxide (pCO_2) in the upper ocean, and hence atmosphere-ocean carbon fluxes. Several problems have been encountered in this part of the model. The predicted pCO_2 can be shown to be sensitive to values calculated for the carbonate equilibrium constants, and it is therefore important to choose equations to calculate these values, as functions of temperature and salinity, carefully. Secondly, predicted pCO_2 can be shown to be markedly influenced by physical aspects of the model, and in particular the quantity of inorganic carbon entrained into the surface mixed layer from the deep ocean. This suggests that an accurate simulation of physical interactions between the surface and deep ocean may be required in order to correctly predict atmosphere-ocean carbon fluxes. Finally, the FORTRAN code associated with calculating pCO_2 consumes large quantities of computer time, which is at a premium when embedding the model in GCMs. Further work will be required to tackle these problems.

The carbon-nitrogen model has been successfully used to simulate the marine ecosystem at various sites in the North Atlantic Ocean. A typical set of results, comparing simulations for a living and dead (no biology) ocean for the surface mixed layer at 60'N 20'W are shown in Figure 1 (overleaf). The figure clearly shows how phytoplankton production causes a significant depression in the pCO_2 of the surface ocean.

Further refinements of various model process and parameters will almost certainly be required in the future; such refinements will largely be made in association with the results generated from embedding the model in GCMs, where much work still has to be done (see discussion of objective (2)). The current version of the model has three main biological compartments: phytoplankton, zooplankton and bacteria. This is somewhat simplistic, in that in reality these compartments each comprise a wide range of organisms of different sizes, morphologies and physiological characteristics. A pertinent area for future research would be to split up the existing compartments into

Figure 1. Predicted influence of primary production on pCO2 at 60'N 20'W.



new compartments representing organisms with different sizes, etc., so as to examine whether this can significantly improve simulation results.

(2) Incorporation of the model into General Circulation Models.

The biological modelling work is being done collaboratively with Prof. J.L. Sarmiento and others at the Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey, U.S.A. General Circulation Models of various parts of the world's oceans have been developed there, and the aim is to test the performance of the new carbon-nitrogen model in these. The biological model has recently been successfully embedded in a North Atlantic GCM developed at Princeton. Analysis of the performance of the biological model in this GCM is yet at an early stage: there will be a considerable amount of work required in the future to complete this. Refinements in the biological model will probably have to be made both to improve model predictions, and to speed up computer running time where possible.

Currently, the GCMs use a relatively simple mathematical approach to recycling biological material which is exported from the surface mixed layer into the deep ocean. Because of the sensitivity of model predictions (e.g. pCO_2 and phytoplankton growth) to entrainment of inorganic carbon and nitrogen, a worthwhile future project would be to develop a more realistic biological model of the recycling of this exported material in the ocean's interior.

(3) Use of modelling to study the marine ecosystem.

Computer models provide insight into the relative importance of different processes and parameters in the functioning of the marine ecosystem as a whole. The work has focussed on those aspects of the system which influence the marine carbon cycle most. In particular, recent work has highlighted the need for a proper understanding of the interactions between the carbon and nitrogen cycles, and also the sensitivity of the model to zooplankton grazing.

Marine organisms require both carbon and nitrogen in different amounts for incorporation into biomass. Careful consideration has been taken when deciding how to calculate growth as a function of separate availabilities of carbon and nitrogen in food. Organic compounds are also required to provide the energy required to maintain basal metabolism, and other energetic needs. Carbon dioxide is evolved, and if nitrogen is present in the substrate, then it is excreted as a waste product. This process (respiration) has been identified as a potentially very important, and somewhat complex, link between the carbon and nitrogen cycles in the marine ecosystem. A bioenergetic model was developed to explore how the dynamics of marine organisms are influenced by the carbon and nitrogen contents of their food, and their respiration rates. Results using the bioenergetic model were compared to those derived when using simple nutrient-balancing models. The simpler models performed well for microheterotrophs, but were found to be less appropriate for larger zooplankton. This is of major importance in ecosystem modelling; if it can be successfully argued that the bulk of heterotrophic activity in the ocean is by microzooplankton and bacteria then the simple models can be successfully applied, but more complex models should be used for simulating larger zooplankton.

The modelling work has shown that both the timing and magnitude of the spring phytoplankton bloom in the North Atlantic (which have a large impact on pCO_2) are strongly influenced by zooplankton grazing, and the levels of overwintering phytoplankton. Much attention has therefore been paid to factors which influence overwintering of biological stocks, and zooplankton parameters, particularly grazing and mortality parameters. The sensitivity of the model to parameters associated with zooplankton grazing and overwintering stocks is a problem, and future work will be required to investigate further these aspects of the model.

Summary and Conclusions

The modelling work has clearly demonstrated that marine biology plays a major role in the uptake by the ocean of atmospheric CO_2, and in transporting this carbon to the deeper ocean. The carbon-nitrogen model which has been developed has provided valuable insight into the complex interactions that occur between the carbon and nitrogen cycles in the marine ecosystem, and hence our ability to simulate the carbon cycle in the ocean and its interaction with the atmosphere. The biological model has performed well in simple physical models of the ocean, and has recently been incorporated into a physical GCM of the Atlantic Ocean developed at Princeton, and initial results have been encouraging. There is, however, a considerable volume of work to be done to fully assess the performance of the biological models in GCMs.

Future work will concentrate on improving the performance of the biological model in physical GCMs. More specifically, the following areas will require further work:

(1) Analysis of simulation results generated from running the biological model in physical GCMs developed at Princeton University.

(2) The refinement of various aspects of the biological model; this may be largely dictated by results generated by the GCMs.

(3) Use of the biological model in conjunction with simple physical models to further our understanding of the relationship between the carbon and nitrogen cycles in the ocean.

(4) The development of a size-based biological model.

(5) Further research into the methods for calculating the partial pressure of carbon dioxide in the surface ocean, and the sensitivity of this variable to physical processes in the model. This is currently a major area of some concern regarding the accurate simulation of atmosphere-ocean carbon fluxes.

(6) Development of a biological model to improve predictions for mid-water processes that recycle organic material which has left the surface layers of the ocean.

List of Deliverables

(1) A new carbon-based biological model of the oceanic mixed layer has been completed, coded in FORTRAN.

List of Publications

(1) Anderson, T.R. (submitted). "Modelling the influence of food C:N ratio, and respiration on growth and nitrogen excretion in marine zooplankton and bacteria." Submitted to Journal of Plankton Research (9 Sept. 1991).

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