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KEYNOTE PERSPECTIVE

Anthropogenic CO_2 uptake in a warming ocean

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Stabilization of future atmospheric CO_2 by regulation of emissions requires predicting the response of the ocean carbon sink. The 1994 report of the IPCC provided a scientific basis for international policy decisions, under the assumption that the ocean circulation and biology will remain constant through time (Houghton et al., 1995). From a coupled atmosphere–ocean simulation with time-dependent radiative forcing for 1765 to 2065 (Haywood et al., 1997), it appears possible that the ocean carbon cycle might already be experiencing effects of climate change today, and that this could become significant over the next century (Sarmiento et al., 1998).

The simulated global warming scenario includes the increase in both greenhouse gases and the direct effect of sulfate aerosols for 1765 to 1990, and estimated future trends of both until 2065 in accordance with the IPCC IS92a scenario. The time history of global mean surface air temperature in the model is in reasonable agreement with the observed warming in this century, although the future response is subject to the inevitable uncertainties in the radiative forcing and climate sensitivity of the model. Two ocean CO_2 uptake simulations are carried out: a solubility model, and a biological model which includes the formation of organic matter and $CaCO_3$ (Murnane et al., 1999). The ocean carbon inventory is initialized by allowing the ocean to equilibrate with atmospheric CO_2 fixed at its preindustrial level, after which the atmospheric CO_2 is increased at a prescribed rate, from observations up to 1990 and in a manner consistent with the IS92a scenario thereafter. The biological pump is initialized with the upward supply and downward export of carbon in balance, such as to reproduce the observed distribution of surface phosphate, and the new production is held fixed thereafter except where phosphate runs out (Sarmiento and Le Quéré, 1996).

The annual anthropogenic CO_2 uptake by the ocean begins to diverge from a constant climate scenario before $\sim$1970 for the solubility model, resulting in a cumulative reduction of 27% (124 Pg C) by 2065. Heating of the ocean predominates in the early period; after 1990 however, changes in circulation and mixing account for more than 2/3 of the reduction in uptake. Increased stratification of the surface ocean is a global phenomenon under greenhouse warming, resulting from increased temperature at low latitudes and freshening in high latitudes. The formation of North Atlantic deep water begins to drop as early as next decade, but the reduction in uptake is dominated by the southern ocean, and on the decadal time scales of this simulation, changes in convection and vertical mixing appear more important for the surface CO_2 balance than changes in advection.

In the biology model, the reduction in CO_2 uptake due to warming and changes in ocean circulation is almost counteracted by the reduced

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upward supply of deep dissolved inorganic carbon and nutrients, causing a tendency towards lower surface CO_2 hence increased uptake. The strongest effect of biology is once again concentrated at high latitudes in the southern ocean, which is both the region where most anthropogenic CO_2 enters the ocean and where the sensitivity of marine ecosystems to environmental change may be high. A number of changes which might be relevant to ocean biology are predicted in the present simulation: by the year 2065, (1) warming of the global mean SST by nearly 2.5°C, (2) reduction in the global mean surface phosphate concentration by 37%, (3) changes in horizontal and vertical ocean circulation patterns and mixed layer depths, (4) changes in cloud cover (and hence light supply), and (5) changes in continental dryness and wind patterns affecting the delivery of trace metal micronutrients (e.g., iron or zinc) to the world ocean. The increase in atmospheric CO_2 also affects ocean chemistry, e.g. (1) the increase in mean surface ocean (CO_2) concentration by 82%, (2) the reduction in mean pH by 0.24, and (3) the reduction in mean carbonate ion concentration by 29%.

Beyond the specific predictions of this particular simulation, the experiment demonstrates the critical importance of the southern ocean for the ocean carbon cycle, and the need to represent both its physical circulation and biological sensitivity correctly. A recent study of the effect of warming in a coupled model by Matear and Hirst (1998) using the Gent et al. (1995) parameterization of mixing gives a much smaller impact of warming on the solubility model uptake in the southern ocean.

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