Thesis abstract

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Modelling the oceanic uptake of carbon dioxide and anthropogenic tracers: feedbacks and sensitivities to global warming

Climate models suggest that oceanic feedback mechanisms associated with global warming may in turn affect climate via the greenhouse effect, and hence further enhance global warming and climate change. I have performed global warming simulations with a physical-biogeochemical climate model of reduced complexity [*Marchal et al.*, 1998] to investigate in detail these global warming-marine carbon cycle feedbacks and to evaluate their impact on the oceanic uptake of carbon dioxide (CO_2) [*Joos et al.*, 1999; *Plattner et al.*, 2001a] and the distribution of anthropogenic CO_2 between ocean, terrestrial biosphere, and atmosphere [*Plattner et al.*, 2001b]. Furthermore, I have performed simulations with direct injection of CO_2 into the ocean to investigate, within the framework of the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP-2), the efficiency of such a strategy to mitigate the atmospheric CO_2 increase [*Orr et al.*, 2001]. The model's ability to simulate the uptake and the distribution of anthropogenic tracers has been evaluated within OCMIP-2 using chlorofluorocarbons (CFCs) [*Dutay et al.*, 2001].

The 2D Bern physical-biogeochemical climate model was used to project atmospheric CO_2 and global warming for scenarios developed by the Intergovernmental Panel on Climate Change [*Joos et al.*, 1999; *Plattner et al.*, 2001a]. The model is forced by emissions of CO_2 and other greenhouse agents or by CO_2 stabilization profiles. The North Atlantic thermohaline circulation (THC) weakens in all global warming simulations and collapses at high levels of CO_2. Projected changes in the marine carbon cycle have a modest impact on atmospheric CO_2. Compared with a constant climate simulation, atmospheric CO_2 increased by 4% at year 2100 and 20% at year 2500. The oceanic uptake of CO_2 is reduced between 7 to 10% by year 2100 compared to simulations without global warming. The reduction can mainly be explained by sea surface warming. The projected changes in the marine biological cycle compensate the reduction in downward mixing of anthropogenic carbon, except when the North Atlantic THC collapses. The reduction in oceanic CO_2 uptake is of similar size in the Southern Ocean and in low-latitude regions (32.5°S - 32.5°N) until 2100, whereas low-latitude regions dominate the reduction on longer time scales. In the North Atlantic the CO_2 uptake is enhanced, unless the North Atlantic THC completely collapses. At high latitudes, biologically mediated changes enhance ocean CO_2 uptake, whereas in low-latitude regions the situation is reversed. The total reduction in oceanic CO_2 uptake until year 2100 compared to the constant climate simulation ranges between 5 to 16% for different implementations of the marine biosphere. Further sensitivity tests indicate that the uncertainties in the oceanic uptake of atmospheric CO_2 associated with changes in sea surface temperature, circulation, and ocean biosphere are of similar magnitude as those associated with the incomplete knowledge of the rates of surface-to-deep transport. Overall, these model simulations indicate that global warming may lead to large-scale changes in the oceanic environment in physical, chemical and biological parameters. For example, the oceanic O_2 inventory is significantly reduced in all global warming simulations.

We have investigated how global warming and volcanic eruptions affect sea-to-air oxygen (O_2) fluxes and, in turn, the carbon budgets for the last two decades deduced from the observed trends in atmospheric CO_2 and O_2 [*Plattner et al.*, 2001b]; the latter estimated from measurements of the ratio of oxygen to nitrogen (O_2/N_2) in air. A significant oceanic O_2 outgassing results when forcing the Bern 2D physical-biogeochemical climate model with reconstructed natural and anthropogenic radiative forcing. The net sea-to-air flux of O_2 is mainly due to changes in ocean circulation and biological cycling (78%) and, to a lesser extent, due to surface warming (22%). Simulated sea-to-air O_2 fluxes and ocean heat uptake rates are tightly correlated on multi-annual to multi-decadal time scales. A change in oceanic heat uptake of 10^{22} J corresponds to an increase in atmospheric O_2/N_2 of 1.56 per meg when correlating simulated heat fluxes and associated O_2/N_2 changes over the period 1900 to 2000. This model-derived relation is combined with data of ocean heat uptake and atmospheric O_2/N_2 and CO_2, to account for internal climate variability not readily reproduced by models for individual decades. The inferred terrestrial carbon sink for the 1990s is reduced by a factor of two compared with the most recent estimate by the Intergovernmental Panel on Climate Change. This also brings into agreement calculated oceanic CO_2 uptake rates with estimates from global carbon cycle models, which indicate a higher oceanic CO_2 uptake during the 1990s than during the 1980s.

The direct injection of CO_2 in the deep ocean, proposed as one possibility to help mitigate rising atmospheric CO_2, has been examined with the Bern 2D physical-biogeochemical model and compared to model results from six OGCMs in the framework of OCMIP-2 [*Orr et al.*, 2001]. The efficiency of artificial sequestration of CO_2 is investigated, by looking at the time the injected CO_2 remains buried in the ocean when injected at different coastal sites and different depths close to large CO_2 production areas. Overall, these simulations confirm, that deeper injection is more efficient compared to shallower injection in all models. However, results also show that the differences between the models are substantial with regard to the efficiencies of different injection sites as well as with regard to the temporal evolution of the global efficiency.

Model results of the projection of future atmospheric CO_2 concentrations depend strongly on the model's ability to simulate the uptake and the distribution of anthropogenic CO_2 by the ocean. This ability has been tested using CFCs in the framework of OCMIP-2 [*Dutay et al.*, 2001]. The model results from the Bern 2D physical-biogeochemical model are compared to observations and to model results from twelve OGCMs. It is found that ocean carbon cycle models still have difficulties to correctly simulate the physical exchange of CFCs, and thus carbon, between surface and deep ocean as revealed by these simulations using circulation tracers such as CFCs and confirmed by deep ocean ^{14}C simulations. However, these problems can partly be resolved by a better representation of the physical transport of carbon in the ocean, especially isopycnal diffusion, subgrid-scale eddy mixing, and sea ice formation.

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