CARBON-CLIMATE SYSTEM FEEDBACKS TO NATURAL AND ANTHROPOGENIC CLIMATE CHANGE

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ABSTRACT

A new three-dimensional global coupled carbon-climate model is presented in the framework of the Community Climate System Model (CSM-1.4). A 1000-year control simulation has stable global annual mean surface temperature and atmospheric CO_2 with no flux adjustment in either physics or biogeochemistry. At low frequencies (timescale > 20 years), the ocean tends to damp (20-25%) slow, natural variations in atmospheric CO_2 generated by the terrestrial biosphere. Transient experiments (1820-2100) show that carbon sink strengths are inversely related to the rate of fossil fuel emissions, so that carbon storage capacities of the land and oceans decrease and climate warming accelerates with faster CO_2 emissions. There is a positive feedback between the carbon and climate systems, so that climate warming acts to increase the airborne fraction of anthropogenic CO_2 and amplify the climate change itself. Globally, the amplification is small at the end of the 21st century in our model because of its low transient climate response and the near-cancellation between large regional changes in the hydrologic and ecosystem responses.

MODEL

The physical climate core of the coupled carbon-climate model is a modified version of NCAR CSM1.4, which consists of atmosphere, land, ocean and ice components that are coupled via a flux coupler. Into CSM1.4 are embedded a modified version of the terrestrial biogeochemistry model CASA, termed CASA' and a modified version of the OCMIP-2 oceanic biogeochemistry model. CASA' follows the life cycles of plant functional types from carbon assimilation via photosynthesis, to mortality and decomposition, and the return of CO_2 to the atmosphere via microbial respiration. There are three live vegetation pools and nine soil pools, and the rates of carbon transfer among them are climate sensitive. The carbon cycle is coupled to the water cycle via transpiration, and to the energy cycle via dynamic leaf phenology (and hence albedo). A terrestrial CO_2 fertilization effect is possible in the model because carbon assimilation via the Rubisco enzyme is limited by internal leaf CO_2 concentrations; net primary productivity (NPP) thus increases with external atmospheric CO_2 concentrations, eventually saturating at high CO_2 levels. The ocean biogeochemical model includes in simplified form the main processes for the solubility carbon pump, organic and inorganic biological carbon pumps, and air-sea CO_2 flux. New/export production is computed prognostically as a function of light, temperature, phosphate and iron concentrations. A fully dynamic iron cycle also has been added including atmospheric dust deposition/iron dissolution, biological uptake, vertical particle transport, and scavenging.

RESULTS

A sequential spin-up strategy is utilized to minimize the coupling shock and drifts in land and ocean carbon inventories. In the 1000 year control, global annual mean surface temperature is ±0.10 K and atmospheric CO_2 is ±1.2 ppm (1σ) (Fig. 1). The control simulation compares reasonably well against observations for key annual mean and seasonal carbon cycle metrics; regional biases in coupled model physics, however, propagate clearly into biogeochemical error patterns. Simulated interannual to centennial variability in atmospheric CO_2 is dominated by terrestrial carbon flux variability, ±0.69 Pg C

y^{-1}, reflecting primarily regional changes in net primary production modulated by moisture stress. Power spectra of global CO_2 fluxes are white on timescales beyond a few years, and thus most of the variance is concentrated at high frequencies (timescale < 4 years). Model variability in air-sea CO_2 fluxes, ±0.10 Pg C y^{-1} (1σ), is generated by variability in temperature, wind speed, export production, and mixing/ upwelling.

Climate change is expected to influence the capacities of the land and oceans to act as repositories for anthropogenic CO_2, and hence provide a feedback to climate change. A series of experiments with the coupled carbon-climate model shows that carbon sink strengths are inversely related to the rate of fossil fuel emissions, so that carbon storage capacities of the land and oceans decrease and climate warming accelerates with faster CO_2 emissions. Furthermore, there is a positive feedback between the carbon and climate systems, so that climate warming acts to increase the airborne fraction of anthropogenic CO_2 and amplify the climate change itself. Globally, the amplification is small at the end of the 21st century in this model because of its low transient climate response, and the near-cancellation between large regional changes in the hydrologic and ecosystem responses. Analysis of our results in the context of comparable models suggests that destabilization of the tropical land sink is qualitatively robust, though its degree is uncertain.

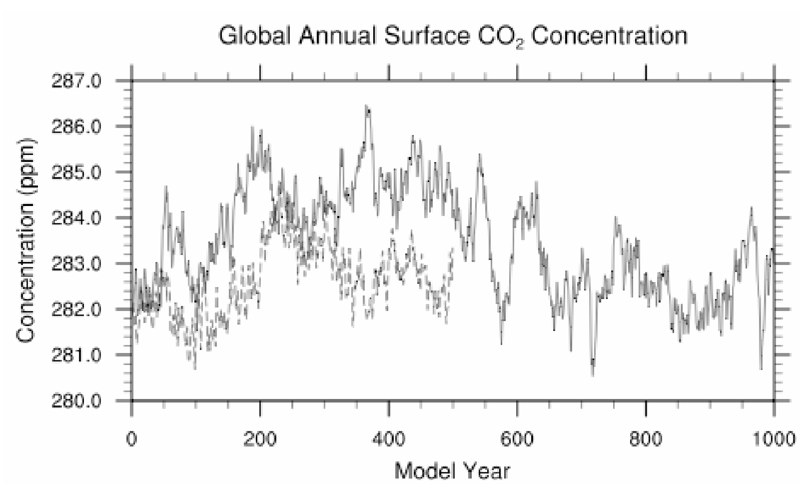

Fig 1. Time-series of global surface CO_2 concentration from CSM1.4-carbon control simulations.

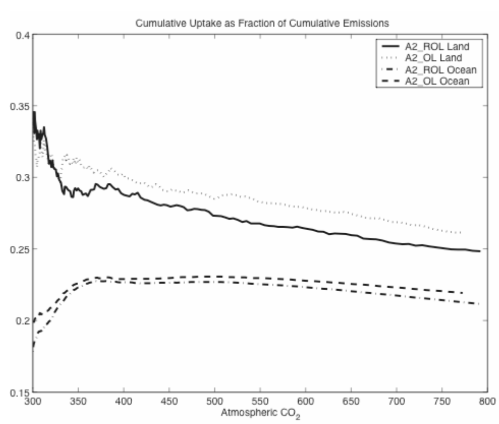

Fig 2. Fractional uptake of anthropogenic CO_2 into land and ocean sinks as a function of atmospheric CO_2 concentration from transient simulation (1820-2100) using prescribed historical and SRES A2 CO_2 emissions.