Evolution of Carbon Sinks in a Changing Climate

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Abstract 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 NCAR-CSM1 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.

Table 1. Summary of experiments with the NCAR carbon-CSM1. Experiments are designated with the prefix “Ctl” for the control, “H” for the historical fossil fuel emissions for the 19th and 20th centuries, and “A1B” or “A2” for the SRES fossil fuel emission scenarios for the 21st century. The suffix *R* denote that radiative CO_2 in the atmosphere is given by the column average of the atmospheric CO_2 resulting from the interactive carbon cycle; and the suffices *L, O* denote that the land and ocean carbon cycles are forced by the evolving CO_2 in the lowest 60mb of the atmosphere.

Experiment	Fossil Fuel Emission	Radiative CO_2	CO_2 for Land Photosynthesis	CO_2 for Air-sea Exchange	Carbon-climate Coupling
Ctl_ROL	None	Prognostic	Prognostic	Prognostic	Yes
H_ROL	Historical	Prognostic	Prognostic	Prognostic	Yes
H_OL	Historical	283 ppmv	Prognostic	Prognostic	-
H_RO	Historical	Prognostic	280 ppmv	Prognostic	Yes
H_O	Historical	283 ppmv	280 ppmv	Prognostic	-
A1B_ROL	SRES A1B	Prognostic	Prognostic	Prognostic	Yes
A1B_OL	SRES A1B	283 ppmv	Prognostic	Prognostic	-
A2_ROL	SRES A2	Prognostic	Prognostic	Prognostic	Yes
A2_OL	SRES A2	283 ppmv	Prognostic	Prognostic	-
A2_RO	SRES A2	Prognostic	280 ppmv	Prognostic	Yes
A2_O	SRES A2	283 ppmv	280 ppmv	Prognostic	-

Table 2: Cumulative carbon budgets for the 19th to 21th centuries. Cumulative fossil fuel emission is 276 PgC for the 19th and 20th centuries. Cumulative fossil fuel emission for the 21st century is 1380 PgC and 1732 PgC for SRES A1B and SRES A2, respectively. ΔT (column 2) is the difference in global 5-year mean surface air temperature between the end of the period and the beginning of the period.

Experiment	ΔT (K)	Atmospheric CO_2 at end of period (ppmv)	Airborne fraction (%)	Land fraction (%)	Ocean fraction (%)
	1820 – 2000 AD				
H_ROL	0.35	345	49	29	22
H_OL	(0.18)*	343	47	31	22
H_RO	0.48	373	70	-3	33
H_O	(0.06)*	372	69	-2	33
	2001– 2100 AD				
A1B_ROL	1.21	661	48	28	24
A1B_OL	-0.12	647	47	29	24
A2_ROL	1.42	792	54	25	21
A2_OL	0.12	773	52	26	22
A2_RO	1.79	997	76	-2	26
A2_O	-0.13	970	73	0	27

* not statistically significant. 1σ=0.1K from Ctl_ROL.

Supporting Information

The resolution of the atmosphere model is T31 (~3.6°) in the horizontal with 10 levels in the troposphere and 8 levels in the stratosphere. The land module has the same horizontal resolution as the atmosphere. The ocean and sea-ice modules have a horizontal resolution of 3.6° in longitude and 0.8-1.8° in latitude (T31x3). There are 25 vertical levels extending through the full depth of the ocean. The water cycle is closed through a river runoff scheme, and modifications have been made to the ocean horizontal and vertical diffusivities and viscosities from the original version (CSM 1.0) to improve the equatorial ocean circulation and interannual variability. The 3-D atmospheric CO_2 distribution is advected and mixed as a dry-air mixing ratio using a semi-Lagrangian scheme, and the model CO_2 field affects the shortwave and longwave radiative fluxes through the column average CO_2 concentration.

Globally, there are 14 plant functional types (PFT), with fractional coverage of up to 4 PFT's within each model gridbox. Gross primary productivity (GPP) is the canopy integral of carbon assimilation, calculated as the optimal carbon assimilation to minimize transpiration loss of water for ambient light, temperature, moisture and Vmax conditions. CASA' assumes 50% of the GPP is lost to autotrophic respiration, and tracks the carbon flow through 3 vegetation carbon pools and 9 soil carbon pools, with the flow rates modulated by climate.

To facilitate analysis of the model, we have separated atmospheric CO_2 into three "species": tracer CO_2 (C_{tracer}), which is radiatively inert, and is the three-dimensional signature of the variations in the sources and sinks; biogeochemical CO_2 (C_{BGC}), which is C_{tracer} averaged over the lowest two layers of the atmospheric model (~60 mb) and which is the CO_2 forcing for terrestrial photosynthesis and for air-sea CO_2 exchange; and radiative CO_2 (C_{rad}), which is the value of CO_2 used in the atmospheric radiation computations. With carbon-climate coupling, C_{rad} is the column average of C_{tracer}.