Project no. GOCE-CT-2003-505539

Project acronym: ENSEMBLES

Project title: ENSEMBLE-based Predictions of Climate Changes and their Impacts

Instrument: Integrated Project

Thematic Priority: Global Change and Ecosystems

D4.1.2 Analysis of the results from the first phase of the Coupled Climate Carbon Cycle Intercomparison Project (C4MIP)

Due date of deliverable: February 2006
Actual submission date: May 2006

Start date of project: 1 September 2004 Duration: 60 Months

Organisation name of lead contractor for this deliverable: IPSL

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	✓
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
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D4.1.2 Analysis of the results from the first phase of the Coupled Climate Carbon Cycle Intercomparison Project (C4MIP)

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C4MIP is coordinated by P. Friedlingstein and P. Cox, and is supported by IGBP/AIMES and WCRP/WGCM.
This C4MIP analysis is in press in Journal of Climate (Friedlingstein et al., 2006)

Introduction

Atmospheric CO_2 concentration is one of the most important factors likely to determine the climate of the 21st century. In projecting the future climate changes, the majority of experiments with comprehensive ocean-atmosphere general circulation models (OAGCMs) still use prescribed CO_2 concentration scenarios, derived a priori from an offline carbon cycle models driven by an emission scenario. Doing so, the climate change simulated by the OAGCM has no impact on the carbon cycle and therefore on the atmospheric CO2 trajectory. However, the atmosphere-land and atmosphere-ocean fluxes of CO_2 are known to be sensitive to climate. For example, the growth-rate of atmospheric CO_2 varies with the El Nino Southern Oscillation (eg. Bousquet et al. 2002), and is also believed to have been affected by the climate perturbation arising from the Pinatubo volcanic eruption (Jones and Cox, 2001, Lucht et al. 2002). In the context of future climate change, offline carbon cycle simulations have been extensively performed (e.g. Prentice et al. 2001). There is a general agreement that future climate change will reduce both and and ocean carbon uptake.

Since an increase in CO_2 leads to climatic change, and climatic change in turn affects the CO_2 concentration, climate, atmospheric CO_2, and the carbon cycle form a feedback loop. The first two OAGCM climate projections to include an interactive carbon cycle showed that the climate-carbon cycle feedback is positive (i.e. amplifying externally induced perturbation) mostly due to the negative impacts of climate change on land carbon storage (Cox et al. 2000; Friedlingstein et al. 2001, Dufresne et al, 2002). But the magnitude of the feedback varied markedly between the results from the Hadley Centre and IPSL models (Friedlingstein et al. 2003). In the context of the Coupled Climate-Carbon Cycle Model Intercomparison Project (C^4MIP), seven coupled OAGCMs and four models of intermediate complexity performed coupled climate-carbon cycle simulations over the historical period and the 21st century (Table 1).

Model Setup

All models used observed anthropogenic fossil fuel emissions for the historical period (Marland et al. 2005) and the IPCC SRES-A2 emission scenario for the 2000-2100 period. The models included land-use associated CO_2 emissions provided by Houghton and Hackler (2002) for the historical and by the IMAGE integrated model for the 21st century (Leemans et al. 1998). However, none of the models prescribed actual land cover changes as boundary conditions of the vegetation model. Changes in physical and biogeochemical properties of the vegetation following land cover changes were hence neglected in this study. Land-use associated emissions are seen here as an external forcing. Each modelling group carried out at least two simulations, one “coupled” simulation in which climate change affects the carbon cycle, and one “uncoupled” simulation in which CO_2 is treated as a non-radiatively active gas (so that the carbon cycle experiences no CO_2-induced climate change). The difference between these two runs defines the effect of climate on carbon cycle and hence on atmospheric CO_2 that is fundamental for the climate-carbon feedback. Table 1 describes the 11 C4MIP models

Main Results

In the coupled simulations, atmospheric CO_2 concentration ranges between 730 ppm for LLNL and 1020 ppm for HadCM3LC by 2100 (Friedlingstein et al., 2006). Apart from UMD and CSM-1, all models simulate historical CO_2 close to that observed. The atmospheric CO_2 concentrations in the CSM-1 simulation during the 20th century are low because the simulation neglected historical land-use emissions, but would reach the observed value if the modeled airborne fraction was used to scale the emissions. UMD atmospheric CO_2 is too high because it has a relatively weak CO2 fertilization effect.

When comparing the coupled and uncoupled simulated atmospheric CO_2, all models show a larger CO_2 in the coupled simulation. That is to say, all models have a positive climate-carbon cycle feedback. This confirms the initial findings of Cox et al, (2000) and Friedlingstein et al. (2001). However, the additional CO_2 concentration induced by this feedback ranges between 20 ppm for CSM-1 and 200 ppm for HadCM3LC. Six of the eleven models have a CO_2 concentration difference ranging between 50 and 100 ppm. There is no systematic difference between the behaviors of OAGCMs and EMICs.

The 2100 land net CO_2 flux ranges between an uptake of 11GtC/yr for LLNL to a source of 6GtC/yr for HadCM3LC. The range of the ocean carbon fluxes is much smaller. The lowest uptake is simulated by LLNL and reaches 3.8 GtC/yr by 2100; the largest is simulated by UMD and reaches 10 GtC/yr.

The difference between the coupled and uncoupled land and ocean carbon fluxes is then evaluated. All models produce a negative anomaly for the atmosphere-land fluxes, although this anomaly is weak for CSM-1 and IPSL-CM4-LOOP. The difference between the atmosphere-land fluxes of the coupled and uncoupled runs ranges between less than 1GtC/yr (CSM-1) and more than 10GtC/yr (for HadCM3LC) by 2100. The range of the changes in ocean uptake is much lower than on the land side. It ranges between a reduction of 2GtC/yr (UMD) to an increase of about 1GtC/yr in HadCM3LC.

Feedback Analysis

The effect of climate induced changes in carbon budget on the rate of increase of atmospheric CO_2 can be quantified by:

$$\Delta C_A^c = 1/(1-g)\ \Delta C_A^u \tag{1}$$

where ΔC_A^c is the change in atmospheric CO_2 in the coupled run, ΔC_A^u is the corresponding change in CO_2 in the uncoupled run, and g is the gain of the climate-carbon feedback as defined for climate system feedbacks (Hansen et al. 1983). In order to isolate the key influential components, the model experiments are compared in terms of the response of the land and ocean carbon uptake to climate and CO_2 (Friedlingstein et al. 2003).One can define the change in land and ocean carbon storage as:

$$\Delta C_A^c = \beta_L \Delta C_A^c + \gamma_L \Delta T^c \tag{2}$$

$$\Delta C_A^c = \beta_O \Delta C_A^c + \gamma_O \Delta T^c \tag{3}$$

where ΔC_L^c and ΔC_O^c are the change in land and ocean carbon storage (in GtC) in the coupled simulation arising from an increase in atmospheric CO_2 concentration of ΔC_A^c (ppm) and a temperature increase of ΔT^c (K). $\beta_L(\beta_O)$ is the land (ocean) carbon sensitivity to atmospheric CO_2, and γ_L (γ_O) is the land (ocean) carbon sensitivity to climate change.

Similarly, one can define the same storage changes for the uncoupled simulation as:

$$\Delta C_L^u = \beta_L \, \Delta C_A^u \tag{4}$$

$$\Delta C_O^u = \beta_O \, \Delta C_A^u \tag{5}$$

The effect of changing CO_2 on global mean temperature can be approximated as:

$$\Delta T^c = \alpha \Delta C_A^c \tag{6}$$

where α is the linear transient climate sensitivity to CO_2 in K ppm^{-1}. (1), (2), (3) and (6) can be manipulated to yield an expression for the gain in terms of the sensitivity coefficients of the land and ocean carbon cycle (Friedlingstein et al. 2003):

$$g = -\alpha\,(\gamma_L + \gamma_O) / (1 + \beta_L + \beta_O) \tag{7}$$

The gain and sensitivity coefficients are shown on figure 1 and summarized in table 2.

All models have a positive gain factor, *g*, that is to say, climate change will increase the fraction of anthropogenic CO_2 emissions which remain airborne, producing a positive feedback on climate change. For two models (CSM-1 and IPSL-CM4-LOOP), however, this gain is very small. We also note that the gain is not constant in time (Figure 1b). There is a clear tendency across the models to show an increase in g with time. This amplification of the gain has to be found in the evolution of γ_L, and γ_O, both increasing with time. By 2100, the additional CO_2 ranges between 20 and 200 ppm. This would lead to an additional warming ranging between 0.1 and 1.5 °C.

Summary

In summary, CO_2 increase alone will tend to enhance carbon storage by both the land and the ocean, whereas climate change alone will tend to release land and ocean carbon to the atmosphere. Together, ocean and land still will act as a sink for anthropogenic carbon during the whole 21st century, but the relative importance of these removal mechanisms is reduced because of carbon-climate feedbacks as the fraction of anthropogenic emission staying airborne increases for all coupled models relative to their uncoupled simulations. However, there is much less agreement on the magnitude of these various effects. All but one model (HadCM3LC) produce a positive climate-carbon cycle gain in the range 0. to 0.2. Also, amongst the 9 models producing a gain larger than 0.1, all (8) but one (UMD) attribute this gain to the climate induced reduction of land carbon uptake.

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Table 1. Major characteristics of the C^{4}MIP models components.

Model	Atmosphere	Ocean	Land Carbon	DGVM	Ocean Carbon	Reference
HadCM3LC	HADCM3 2.5°×3.75°,L19	2.5°×3.75°, L20 flux-adjustment	MOSES/ TRIFFID	Yes	HadOCC	Cox et al. 2000
IPSL-CM2C	LMD5 64x50, L19 (5°x4°)	OPA-7, 2°x2°,L31 no flux adjustment	SLAVE	No	NPZD	Dufresne et al. 2002
IPSL-CM4-LOOP	LMDZ-4 96x72, L19 (3°x3)	ORCA2, 2°x2°, L31, no flux-adjustment	ORCHIDEE	Not here	PISCES	Marti et al., 2005 Krinner et al., 2005 Aumont et al., 2003
CSM-1	CCM3 T31, L18	NCOM 3.6 ° long 0.8-1.8 ° lat	LSM, CASA	No	OCMIP-biotic	Doney et al. 2006; Fung et al. 2005
MPI	ECHAM T63, L31	MPI-OM, 1.5 °, L40, no flux adjustment	JSBACH	No	HAMOCC5	Raddatz et al. 2005
LLNL	CCM3, 2.8°×2.8°, L18	POP 0.6 ° x0.6 °, L40	IBIS, Flux adjustment	Yes	OCMIP	Thompson et al. 2004
FRCGC	CCSR/NIES/FRCGC T42(2.8°×2.8°),L20	COCO No flux adjustment, (0.5-1.4°)×1.4°, L20	Sim-CYCLE	No	NPZD	Kawamiya et al. 2005 Hasumi & Emori, 2004
UMD	QTCM 5.6°x3.7°	Slab mix-layer, 5.6°x3.7°	VEGAS	Yes	3 box model	Zeng et al. 2004
UVic-2.7	EMBM 1.8°x3.6°	Mom 2.2, 1.8°x3.6°, L19, no flux adjustment	MOSES/ TRIFFID	Yes	OCMIP Abiotic	Meissner et al. 2003 Matthews et al. 2005a
CLIMBER2-LPJ	2.5-D, 10°x51° statistical-dynamical	Zonally-averaged; 2.5°lat, 3 basins	LPJ	Yes	NPZD	Brovkin et al. 2004 Sitch et al. 2005
BERN-CC	EBM 2.5°×3.75°	HILDA box-diffusion model	LPJ	Yes	Perturbation approach	Joos et al. 2001 Gerber et al. 2003

Table 2. Carbon cycle gain, g, along with component sensitivities of climate to CO_2 (α), land and ocean carbon storage to CO_2 (β_L, β_o), and land and ocean carbon storage to climate (γ_L, γ_o). Calculations are done for year 2100

Model	α (K/ppm)	β_L (GtC/ppm)	β_o (GtC/ppm)	γ_L (GtC/K)	γ_o (GtC/K)	Gain
HadCM3LC	0.0066	1.3	0.8	–177	–24	0.31
IPSL-CM2C	0.0065	1.6	1.6	–98	–30	0.15
IPSL-CM4-LOOP	0.0072	1.3	1.1	-20	-16	0.06
CSM-1	0.0038	1.1	0.9	-23	-17	0.04
MPI	0.0082	1.4	1.1	-65	-22	0.20
LLNL	0.0068	2.8	0.9	–70	–14	0.10
FRCGC	0.0059	1.2	1.2	-112	-46	0.21
UMD	0.0056	0.2	1.5	–40	–67	0.14
UVic-2.7	0.0063	1.2	1.1	–98	–43	0.20
CLIMBER	0.0053	1.1	0.9	–57	–22	0.10
BERN-CC	0.0046	1.6	1.3	-105	-39	0.13
Models Average	0.0061	1.35	1.13	-79	-30	0.15

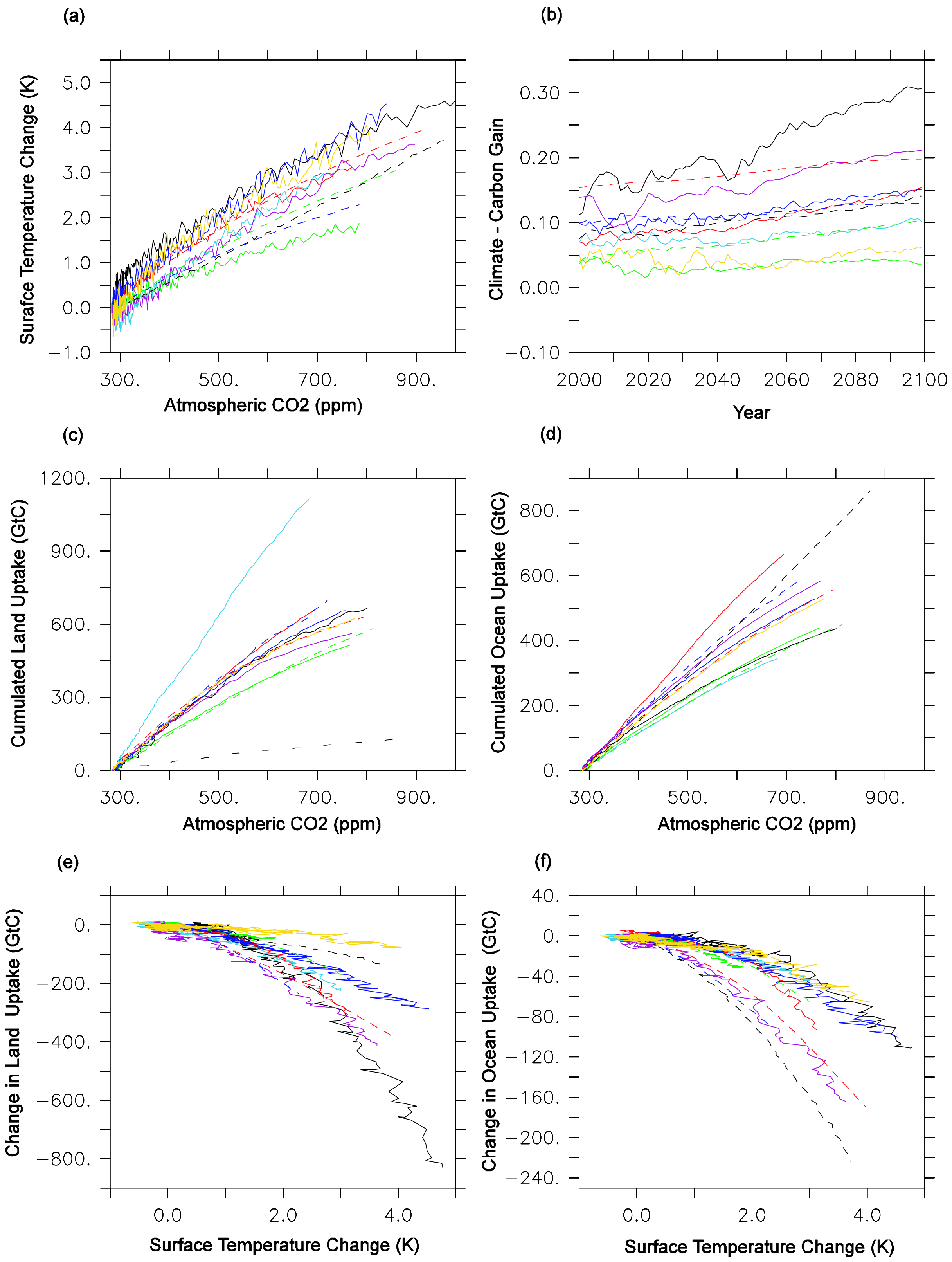

Figure 1. (a) Simulated surface temperature response to atmospheric CO2. (b) Time evolution of the climate-carbon gain. (c) Sensitivity of land carbon storage to atmospheric CO2