CMIP5 Multi-Model Analysis of Global Carbon Cycle Feedbacks: Developing Benchmarks for ILAMB

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Introduction

Rapidly increasing atmospheric carbon dioxide (CO_2) concentrations are altering Earth's climate. The anthropogenic perturbation of the global carbon cycle is expected to induce feedbacks on global climate and future CO_2 concentrations; however, these feedbacks are poorly constrained. In order to reduce the range of uncertainty in climate predictions, model representation of feedbacks must be improved through comparisons with contemporary observations. The International Land Model Benchmarking (ILAMB) Project is developing model evaluation benchmarks based on best-available observational data sets that are accepted by the larger international research community. In this work-in-progress, we apply observational estimates of atmospheric CO_2 and ocean carbon fluxes to analyze the evolution of carbon cycle biases in emissions-forced model results from the Fifth Coupled Model Intercomparison Project (CMIP5).

Earth System Model Data Availability on ESG

Model (CSM, ESM)	Country	ESM Control 5.1	ESM Historical 5.2	ESM RCP8.5 5.3	ESM FixClim1 5.4-1	ESM FixClim2 5.4-2	ESM Fdbk1 5.5-1	ESM Fdbk2 5.5-2	1% CO_2 6.1
ACCESS1.0	Australia	✗	✗	✗	✗	✗	✗	✗	1
BCC-CSM1.1	China	1	1	1	1	1	1	1	1
CanESM2	Canada	1	3	3	1	1	1	1	1
CESM1	U.S.	✗	✗	✗	✗	✗	✗	✗	✗
SCNRM-CM5	France	✗	✗	✗	✗	✗	✗	✗	1
SCSIRO-Mk3.6	Australia	✗	✗	✗	✗	✗	✗	✗	1
SFGOALS-G2	China	✗	✗	✗	✗	✗	✗	✗	1
SGFDL-CM3	U.S.	✗	✗	✗	✗	✗	✗	✗	1
GFDL-ESM2G	U.S.	1	1	✗	✗	✗	✗	✗	1
GFDL-ESM2M	U.S.	1	1	1	1	✗	1	✗	1
HadGEM2-ES	U.K.	1	1	1	✗	1	1	1	1
INM-CM4	Russia	1	1	1	✗	✗	✗	✗	1
IPSL-CM5A-LR	France	1	1	1	1	1	1	1	1
SIPSL-CM5A-MR	France	✗	✗	✗	✗	✗	✗	✗	1
MIROC-ESM	Japan	1	1	1	✗	1	✗	✗	1
SMIROC5	Japan	✗	✗	✗	✗	✗	✗	✗	1
MPI-ESM-LR	Germany	✗	✗	✗	1	✗	1	✗	1
MPI-ESM-P	Germany	✗	✗	✗	✗	✗	✗	✗	1
SMRI-CGCM3	Japan	✗	✗	✗	✗	✗	✗	✗	1
NorESM1-M	Norway	✗	✗	✗	✗	✗	✗	✗	1

As of 25 February 2012

Earth System Model	Country	ESM Historical CO_2	ESM Historical FGCO$_2$	ESM Historical NBP	ESM RCP 8.5 CO_2	ESM RCP 8.5 FGCO$_2$	ESM RCP 8.5 NBP
➔ BCC-CSM1.1	China	1	1	✗	1	1	✗
➔ CanESM2	Canada	3	3[†]	3	3	3[†]	3
CESM1	U.S.	—	—	—	—	—	—
GFDL-ESM2G	U.S.	✗	✗	1	✗	✗	✗
GFDL-ESM2M	U.S.	✗	✗	1	✗	✗	1
HadGEM2-ES	U.K.	✗	1	✗	✗	1	✗
➔ INM-CM4	Russia	1[†]	1	1	1[†]	1	1
IPSL-CM5A-LR	France	✗	1	1	✗	1	1
➔ MIROC-ESM	Japan	1	1	1	1	1	1
MPI-ESM-LR	Germany	—	—	—	—	—	—

[†]Possible units problem — As of 25 February 2012

Carbon in CMIP5 Emissions-Forced Simulations

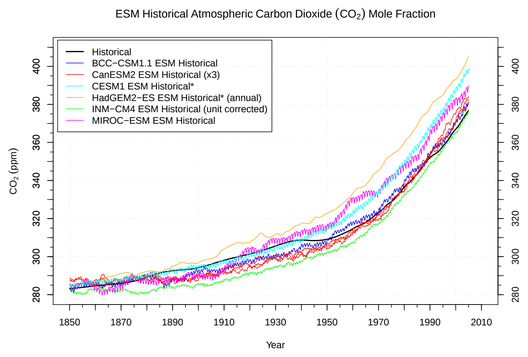

Figure 1: *Atmospheric CO_2 mole fraction from CMIP5 models for the emissions-forced historical.*

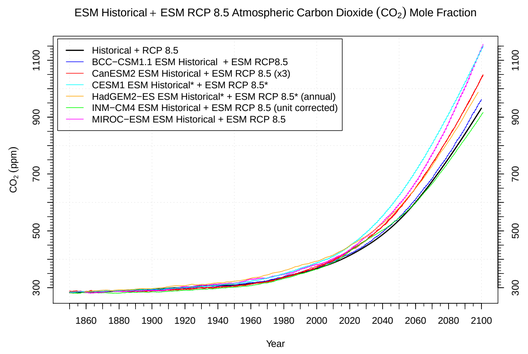

Figure 2: *Atmospheric CO_2 mole fraction from CMIP5 models for the emissions-forced historical and RCP 8.5 simulations combined.*

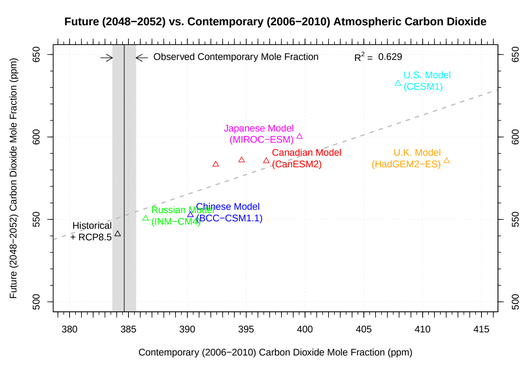

Figure 3: *Future vs. contemporary atmospheric CO_2 mole fraction from CMIP5 models for the emissions-forced RCP 8.5 simulation.*

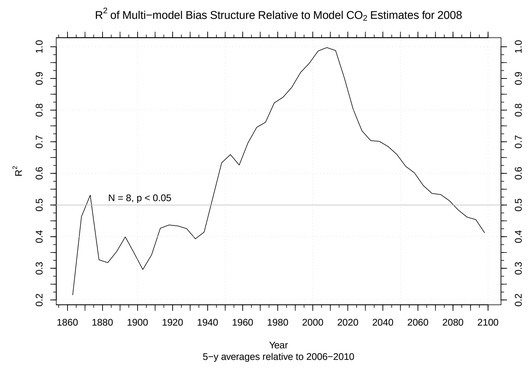

Figure 4: *The R^2 of multi-model bias structure relative to the model CO_2 estimates for 2008. Five year average atmospheric CO_2 projections are compared to the 2006–2010 average. For $N = 8$, an $R^2 \approx 0.5$ is significant to the $p < 0.05$ level.*

Ocean Carbon Uptake

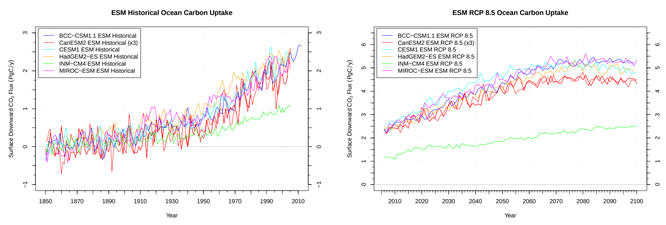

Figure 5: *Ocean carbon uptake from CMIP5 models for the emissions-forced historical simulation (left) and the emissions-forced RCP 8.5 simulation (right).*

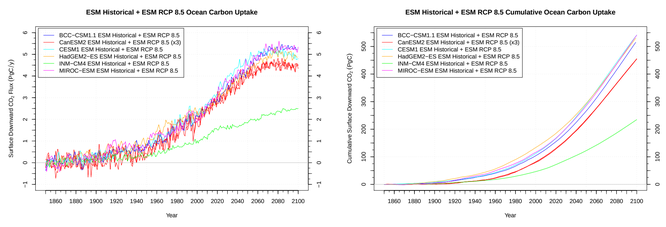

Figure 6: *Ocean carbon uptake (left) and cumulative ocean carbon uptake (right) from CMIP5 models for the emissions-forced historical and RCP 8.5 simulation.*

Land Carbon Uptake

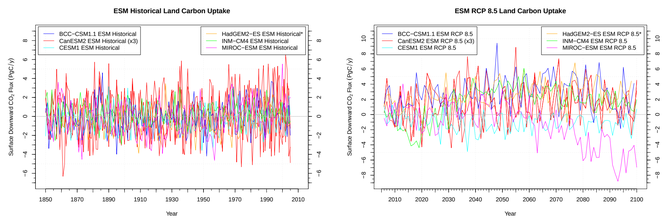

Figure 7: *Land carbon uptake from CMIP5 models for the emissions-forced historical simulation (left) and the emissions-forced RCP 8.5 simulation (right).*

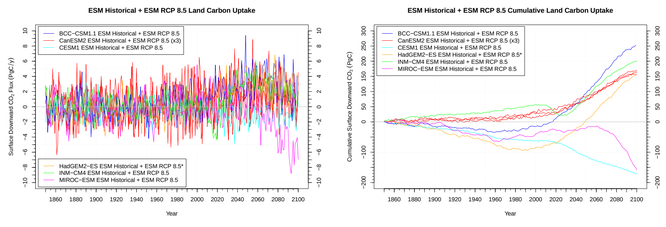

Figure 8: *Land carbon uptake (left) and cumulative land carbon uptake (right) from CMIP5 models for the emissions-forced historical and RCP 8.5 simulation.*

Comparisons with Contemporary Observations

Table 1: *Projected anthropogenic CO_2 budget for the emissions-forced historical simulation for 1850–1994.*

Model	Realization	Fossil (Pg C)	Atmosphere (Pg C)	Ocean (Pg C)	−F−A−O (Pg C)	Land (Pg C)
Sabine et al. (2004)[†]		244 ± 20	-165 ± 4	-118 ± 19	39 ± 28	
Waugh et al. (2006)				$-(94–121)$		
Khatiwala et al. (2009)[‡]				-114 ± 22		
BCC-CSM1.1	r1i1p1	240	−163	−92	15	(15)
CanESM2	r1i1p1	240	−159	−70	−11	−23
	r2i1p1	240	−157	−69	−14	−28
	r3i1p1	240	−167	−70	−3	−16
		240	-162 ± 5	-69.5 ± 0.5	-8.5 ± 3	-22 ± 6
CESM1	r1i1p1	240	−194	−99	53	60
HadGEM2-ES*	r1i1p1	240	−209	−119	88	(89)
INM-CM4	r1i1p1	240	−157	−41	−42	−54
MIROC-ESM	r1i1p1	240	−188	−103	51	48

[†]Sabine et al. (2004) estimates are for 1800–1994.
[‡]Khatiwala et al. (2009) estimates are for 1765–1994.
*HadGEM2-ES simulation begins in 1860.

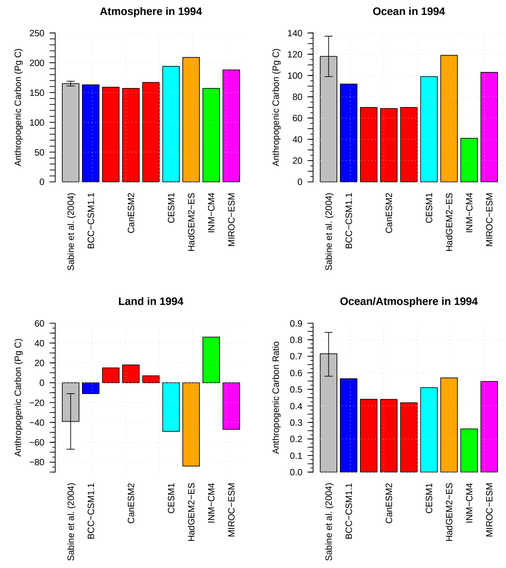

Figure 9: *Carbon accumulation through 1994 for the atmosphere, ocean, and land (computed as the difference) from CMIP5 models for the emissions-forced historical simulation. In the lower-right panel, the ocean uptake has been divided by the atmospheric uptake in order to remove the atmospheric CO_2 bias.*

Table 2: *Projected anthropogenic CO_2 budget for the emissions-forced historical simulation for 1980–1999.*

Model	Realization	Fossil (Pg C)	Atmosphere (Pg C)	Ocean (Pg C)	−F−A−O (Pg C)	Land (Pg C)
Sabine et al. (2004)		117 ± 5	-65 ± 1	-37 ± 8	-15 ± 9	-39 ± 18
BCC-CSM1.1	r1i1p1	117	−69	−37	−11	(−10)
CanESM2	r1i1p1	117	−76	−33	−7	−10
	r2i1p1	117	−74	−35	−8	−9
	r3i1p1	117	−80	−36	−1	−5
		117	-77 ± 3	-34.5 ± 1.5	-4.5 ± 3.5	-7.5 ± 2.5
CESM1	r1i1p1	117	−82	−41	6	6
HadGEM2-ES	r1i1p1	117	−74	−43	0	(0)
INM-CM4	r1i1p1	117	−70	−17	−30	−12
MIROC-ESM	r1i1p1	117	−74	−40	−3	−4

Table 3: *Estimated ocean inventory and uptake rate of anthropogenic CO_2 in 2008 for the emissions-forced historical (1850–2005) and emissions-forced RCP 8.5 (2006–2008) simulations.*

Model	Realization	Ocean Inventory (Pg C)	Ocean Uptake (Pg C y^{-1})
Khatiwala et al. (2009)		140 ± 25	2.3 ± 0.6
BCC-CSM1.1	r1i1p1	122.0	2.32
CanESM2	r1i1p1	98.4	2.40
	r2i1p1	96.2	2.45
	r3i1p1	99.2	2.25
	Ensemble Mean	97.9	2.37
CESM1	r1i1p1	131.1	2.70
HadGEM2-ES*	r1i1p1	152.1	2.45
INM-CM4	r1i1p1	55.0	1.15
MIROC-ESM	r1i1p1	133.5	2.62

*HadGEM2-ES simulation begins in 1860.

Table 4: *Estimated atmosphere, ocean, and land uptake rates of anthropogenic CO_2 for the emissions-forced historical (1850–2005) and emissions-forced RCP 8.5 (2006–2008) simulations. For models, land values in parentheses are computed as differences; other land accumulation values come from model results. The units for all carbon accumulation values are Pg C y^{-1}.*

Model		1980s Atmos	1980s Ocean	1980s Land	1990s Atmos	1990s Ocean	1990s Land	2000–2006 Atmos	2000–2006 Ocean	2000–2006 Land
Khatiwala et al. (2009)			1.8	0.3		2.0	1.1		2.3	1.1
			(1.3–2.3)	(−0.3–0.8)		(1.4–2.6)	(0.5–1.8)		(1.7–2.9)	(0.4–1.8)
IPCC AR4			1.8	0.3		2.2	1.0		2.2	1.3
			(1.0–2.6)	(−0.6–1.2)		(1.8–2.6)	(0.4–1.6)		(1.8–2.6)	(0.7–1.9)
BCC-CSM1.1	r1i1p1	3.41	1.79	(0.26)	3.49	1.96	(0.77)	4.70	2.27	(0.22)
CanESM2	r1i1p1	3.95	1.60	−0.06	3.62	1.71	1.07	5.48	2.21	0.00
	r2i1p1	3.93	1.75	−0.10	3.50	1.72	1.04	5.63	2.04	0.10
	r3i1p1	3.08	1.61	0.61	4.90	1.98	−0.11	4.92	2.13	0.38
	Mean	3.65	1.65	0.15	4.01	1.80	0.67	5.34	2.13	0.16
CESM1	r1i1p1	3.98	1.90	−0.46	4.20	2.19	−0.13	4.24	2.34	0.29
HadGEM2-ES	r1i1p1	3.85	1.99	(−0.39)	3.54	2.31	(0.37)	4.47	2.31	(0.40)
INM-CM4	r1i1p1	3.47	0.78	0.38	3.58	0.90	0.81	4.77	1.04	−0.12
MIROC-ESM	r1i1p1	3.38	1.73	0.14	4.04	2.25	0.30	3.21	2.05	1.80

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