Systematic Evaluation of Earth System Models: Developing Benchmarks for ILAMB

Forrest M. Hoffman[†‡], James T. Randerson[‡], Peter E. Thornton[†], and Keith Lindsay*

[†]Oak Ridge National Laboratory, [‡]University of California - Irvine, and *National Center for Atmospheric Research

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 Budgets in CMIP5 Emissions-Forced Simulations

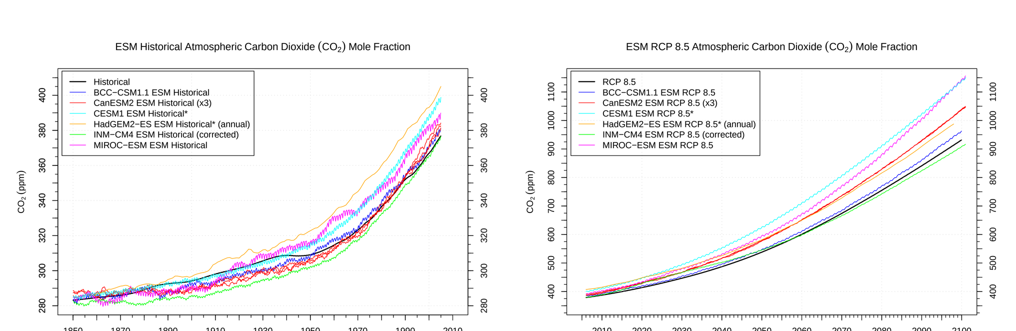

Figure 1: *Atmospheric CO_2 mole fraction from CMIP5 models for the emissions-forced historical (left) and RCP 8.5 (right) simulations.*

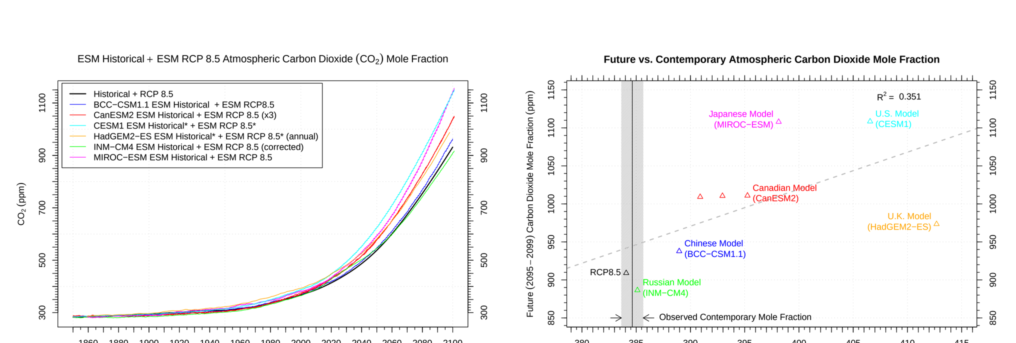

Figure 2: *Left: Atmospheric CO_2 mole fraction from CMIP5 models for the emissions-forced historical and RCP 8.5 simulations. Right: Future vs. contemporary atmospheric CO_2 mole fraction from CMIP5 models for the emissions-forced RCP 8.5 simulation.*

Ocean Carbon Uptake

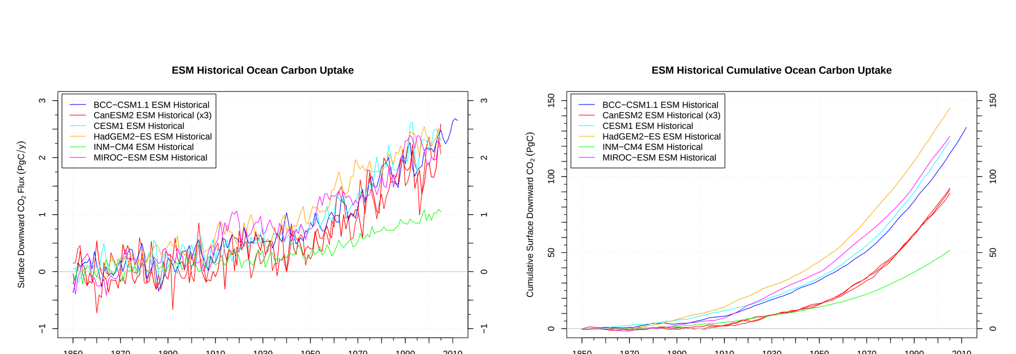

Figure 3: *Ocean carbon uptake (left) and cumulative ocean carbon uptake (right) from CMIP5 models for the emissions-forced historical simulation.*

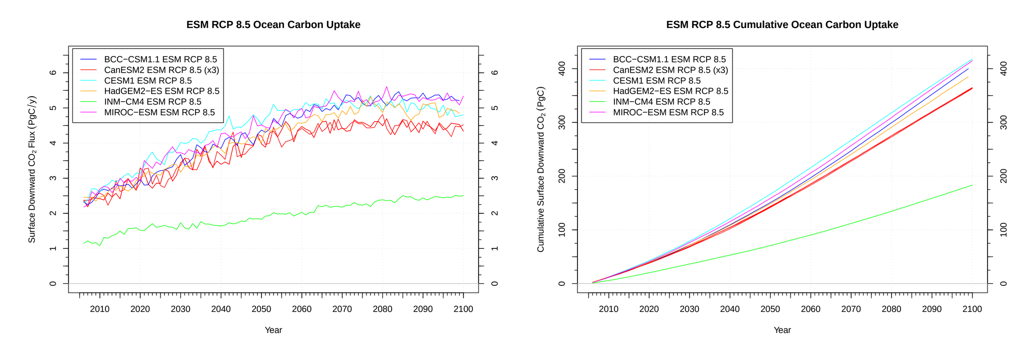

Figure 4: *Ocean carbon uptake (left) and cumulative ocean carbon uptake (right) from CMIP5 models for the emissions-forced RCP 8.5 simulation.*

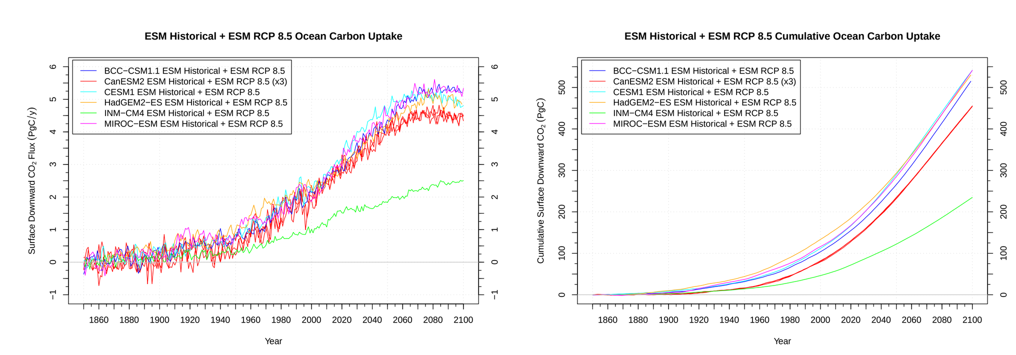

Figure 5: *Ocean carbon uptake (left) and cumulative ocean carbon uptake (right) from CMIP5 models for the emissions-forced historical and RCP 8.5 simulation.*

Land Carbon Uptake

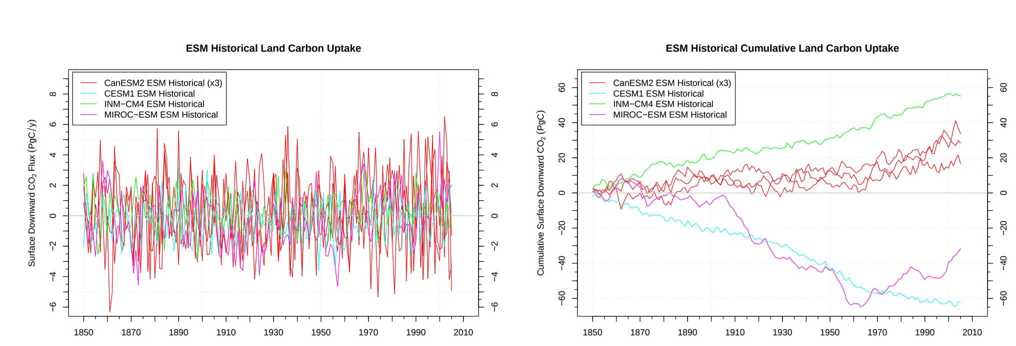

Figure 6: *Land carbon uptake (left) and cumulative land carbon uptake (right) from CMIP5 models for the emissions-forced historical simulation.*

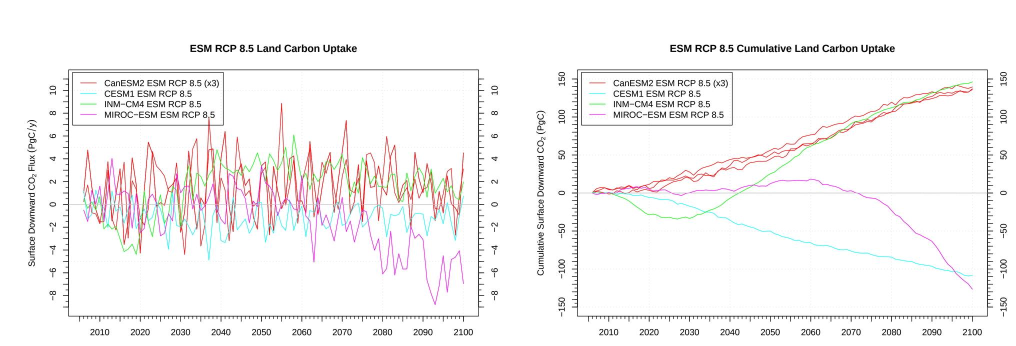

Figure 7: *Land carbon uptake (left) and cumulative land carbon uptake (right) from CMIP5 models for the emissions-forced RCP 8.5 simulation.*

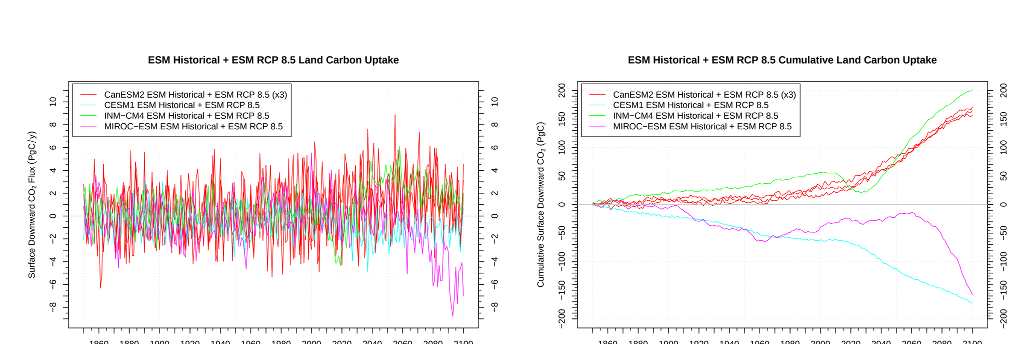

Figure 8: *Land carbon uptake (left) and cumulative land carbon uptake (right) from CMIP5 models for the emissions-forced historical and RCP 8.5 simulation.*

Comparisons with Contemporary Observations

Table 1: *Projected anthropogenic CO_2 budget for esmHistorical 1850–1994*

Model	Realization	Fossil (Pg C)	Atmosphere (Pg C)	Ocean (Pg C)	$-F-A-O$ (Pg C)	Land (Pg C)
?[†]		244 ± 20	-165 ± 4	-118 ± 19	39 ± 28	
?				$-(94–121)$		
?[‡]				-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

[†]? estimates are for 1800–1994.
[‡]? estimates are for 1765–1994.
*HadGEM2-ES simulation begins in 1860.

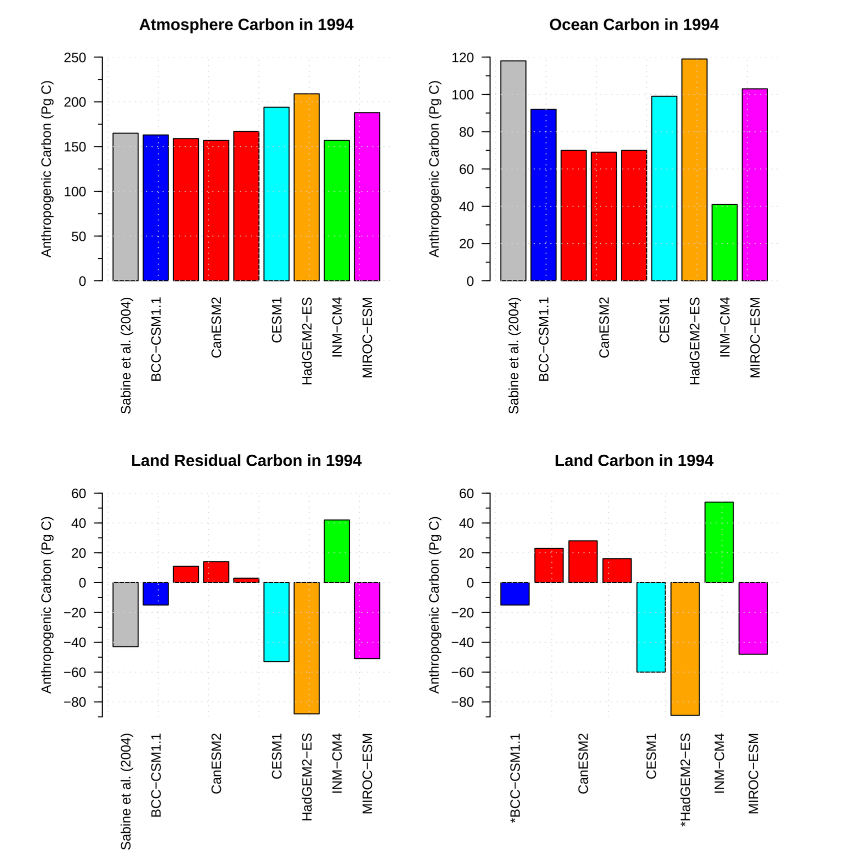

Figure 9: *Carbon accumulation through 1994 for the atmosphere, ocean, residual land, and land from CMIP5 models for the emissions-forced historical simulation. Models with an asterisk (*) have not reported land carbon fluxes, so the residuals have been substituted.*

Table 2: *Projected anthropogenic CO_2 budget for esmHistorical 1980–1999*

Model	Realization	Fossil (Pg C)	Atmosphere (Pg C)	Ocean (Pg C)	$-F-A-O$ (Pg C)	Land (Pg C)
?		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 esmHistorical (1850–2005) and esmrcp85 (2006–2008)*

Model	Realization	Ocean Inventory (Pg C)	Ocean Uptake (Pg C y^{-1})
?		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 esmHistorical (1850–2005) and esmrcp85 (2006–2008). For models, values in parentheses are computed residuals; other land accumulation values come from models. 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
?			1.8 (1.3–2.3)	0.3 (−0.3–0.8)		2.0 (1.4–2.6)	1.1 (0.5–1.8)		2.3 (1.7–2.9)	1.1 (0.4–1.8)
IPCC AR4			1.8 (1.0–2.6)	0.3 (−0.6–1.2)		2.2 (1.8–2.6)	1.0 (0.4–1.6)		2.2 (1.8–2.6)	1.3 (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

References

S. Khatiwala, F. Primeau, and T. Hall. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature*, 462(7271):346–349, Nov. 2009. doi:10.1038/nature08526.

C. L. Sabine, R. A. Feely, N. Gruber, R. M. Key, K. Lee, J. L. Bullister, R. Wanninkhof, C. S. Wong, D. W. R. Wallace, B. Tilbrook, F. J. Millero, T.-H. Peng, A. Kozyr, T. Ono, and A. F. Rios. The oceanic sink for anthropogenic CO_2. *Science*, 305(5682):367–371, July 2004. doi:10.1126/science.1097403.

D. W. Waugh, T. M. Hall, B. I. McNeil, R. Key, and R. J. Matear. Anthropogenic CO_2 in the oceans estimated using transient time distributions. *Tellus B*, 58 (5):376–389, Nov. 2006. doi:10.1111/j.1600-0889.2006.00222.x.

Acknowledgment

Research sponsored by the Climate and Environmental Sciences Division (CESD) of the Office of Biological and Environmental Research (OBER) within the U.S. Department of Energy's Office of Science (SC). This research used resources of the National Center for Computational Sciences (NCCS) at Oak Ridge National Laboratory (ORNL), which is managed by UT-Battelle, LLC, for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.