TRAJECTORY SENSITIVITY OF THE TRANSIENT CLIMATE RESPONSE TO CUMULATIVE CARBON EMISSIONS

JOHN P. KRASTING[1], JOHN P. DUNNE[1], ELENA SHEVLIAKOVA[2,1], and RONALD J. STOUFFER[1]

[1]NOAA/Geophysical Fluid Dynamics Laboratory , [2]Princeton University - Princeton, New Jersey, USA

ABSTRACT

The robustness of Transient Climate Response to cumulative Emissions (TCRE) [Allen et al. 2009, Matthews et al. 2009] is tested using an Earth System Model (Geophysical Fluid Dynamics Laboratory-ESM2G) forced with seven different constant rates of carbon emissions (2 GtC/yr to 25 GtC/yr), including low emission rates that have been largely unexplored in previous studies. We find the range of TCRE resulting from these varying emission pathways to be 0.76 to 1.04 °C/TtC. This range, however, is small compared to the uncertainty resulting from varying model physics across the Fifth Coupled Model Intercomparison Project ensemble. TCRE has a complex relationship with emission rates; TCRE is largest for both low (2 GtC/yr) and high (25 GtC/yr) emissions and smallest for present-day emissions (5–10 GtC/yr). Unforced climate variability hinders precise estimates of TCRE for periods shorter than 50 years or for emission rates near or smaller than present day values. Even if carbon emissions would stop, the prior emissions pathways will affect the future climate responses.

MODEL DESCRIPTION & EXPERIMENTAL DESIGN

The GFDL-ESM2G model used in this study is a fully-coupled Atmosphere-Ocean-General Circulation Model (AOGCM) with an interactive carbon cycle. GFDL-ESM2G uses a ~2º resolution for the atmosphere and land components and a ~1º resolution for the ocean component.

Atmosphere:	AM2 (Same as GFDL CM2.1)
Land:	LM3 with dynamic vegetation
Ocean:	Generalized Ocean Layer Dynamics (GOLD) model (63-layer density-based coordinate)
Ocean Carbon:	The Tracers Of Phytoplankton and Allometric Zooplankton (TOPAZ) model (including biogeochemistry and primitive ecology).

A full description of the models and their validation are presented in two papers by Dunne et al. [2012, 2013].

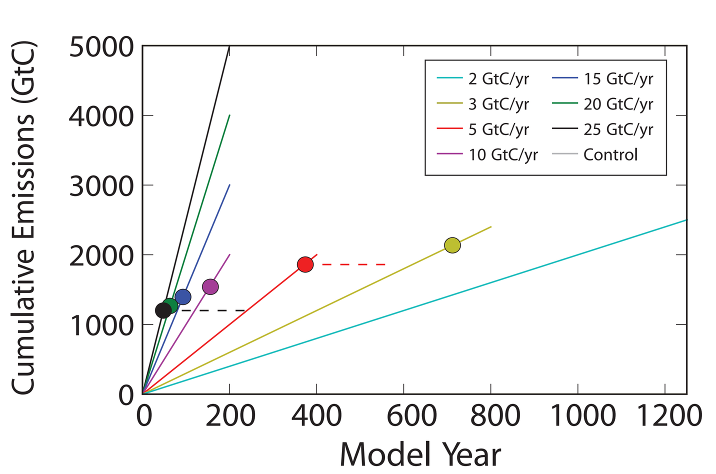

Figure 1: Seven scenarios used in this study based on constant carbon emission rates ranging from 2 GtC/yr to 25 GtC/yr. Dots represent the timing of atmospheric CO_2 doubling (572 ppm) from pre-industrial levels. Dashed lines represent a second set of experiments where the emission source was removed at the time of CO_2 doubling (i.e. "zero-emissions" extensions). (The zero-emissions extensions were also performed for the 2 GtC/yr scenario but are not shown in this figure.)

Instead of applying specified CO_2 concentrations, we applied carbon emissions to the atmosphere over the nonglacial land points in GFDL-ESM2G and allowed the model to predict atmospheric CO_2 concentrations (C_A) with its full suite of physical and carbon interactions and feedbacks. All other forcing (i.e., well-mixed GHGs, aerosols, and solar) was held at CMIP5 preindustrial values. Instead of applying a compounding trajectory (i.e., 1pctCO2) that has been used previously to evaluate TCRE, we applied seven constant emission rates (Figure 1; 2, 3, 5, 10, 15, 20, and 25 GtC/yr). This design avoids the imprint of the prescribed exponential growth of C_A onto the model's response and facilitates investigation of variability of response to emission rates. Three ensemble members of each experiment were integrated for 200 years (400 years in the 5 GtC/yr case and 1300 years in the 2 GtC/yr case) in order to achieve at least a doubling of C_A as lower emission rates lead to longer and longer doubling times of C_A.

CLIMATE-CARBON CYCLE RESPONSES TO IDEALIZED CARBON EMISSIONS

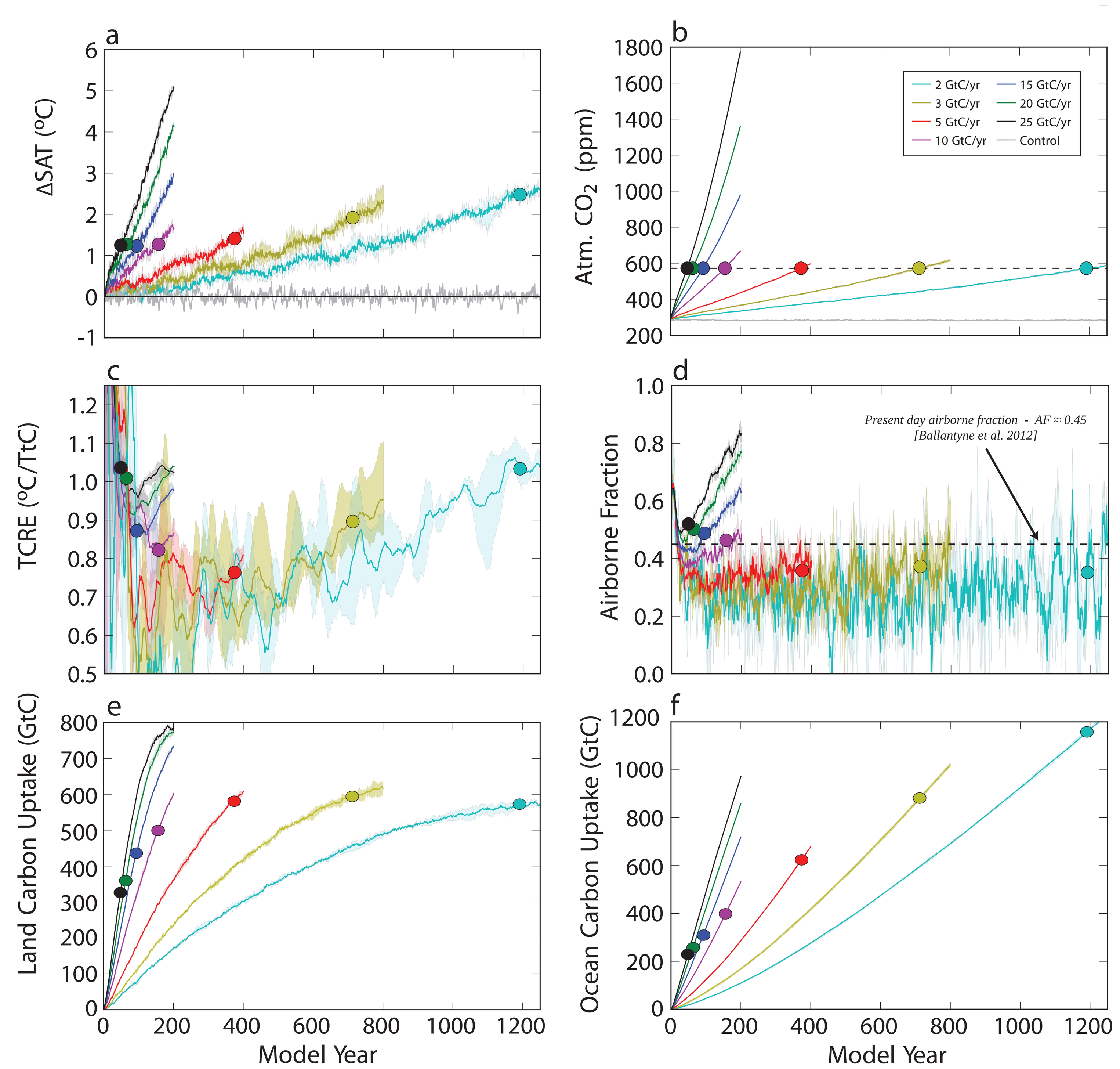

Figure 2: Ensemble mean (solid line) and range (envelope) vs. time for: (a) Global surface air temperature response (ºC); (b) Model- predicted atmospheric CO_2 concentration (ppm); (c) 20- yr smoothed TCRE (ºC/TtC); (d) 20-yr smoothed airborne fraction of carbon emissions; (e) cumulative land carbon uptake (GtC); (f) cumulative ocean carbon uptake (GtC). Dots indicate the time of atmospheric CO_2 doubling.

Table 1. Ideaized Emissions Experiment Results at the Time of CO_2 Doubling[a]

	Year of 2 × CO_2	E_T	Land Uptake	Ocean Uptake	τ	ΔT	TCRE	S:N_{50}
2 Pg/yr	1178 / 1204 / 1190	2356 / 2408 / 2380	565 (7.3)	1157 (21.4)	887 (182.1)	2.48 (0.126)	1.04 (0.064)	0.41
3 Pg/yr	706 / 724 / 707	2118 / 2172 / 2121	594 (15.1)	880 (18.0)	549 (47.9)	1.92 (0.127)	0.9 (0.068)	0.53
5 Pg/yr	370 / 376 / 371	1850 / 1880 / 1855	579 (8.0)	620 (6.1)	384 (61.8)	1.41 (0.096)	0.76 (0.054)	0.99
10 Pg/yr	154 / 154 / 154	1540 / 1540 / 1540	491 (5.9)	392 (1.7)	213 (5.1)	1.27 (0.09)	0.82 (0.058)	2.3
15 Pg/yr	92 / 94 / 93	1380 / 1410 / 1395	436 (10.0)	309 (3.0)	151 (3.3)	1.23 (0.055)	0.88 (0.033)	6.07
20 Pg/yr	63 / 64 / 63	1260 / 1280 / 1260	362 (10.8)	259 (2.7)	115 (3.9)	1.27 (0.056)	1.0 (0.052)	8.96
25 Pg/yr	48 / 48 / 48	1200 / 1200 / 1200	326 (2.3)	229 (0.5)	96 (2.8)	1.25 (0.038)	1.04 (0.032)	17.12
1%/yr to 2 times	70	1184	327	239	119	1.14	0.96	
1%/yr to 4 times	70	1194	339	238	103	1.26	1.05	

[a]The year at which atmospheric CO_2 reaches a doubling from preindustrial values is shown for each ensemble member. E_T (GtC) represents the cumulative carbon emissions from the start of the simulation to the time of CO_2 doubling. The total amount of uptake by the land and ocean are also in units of GtCΔT (ºC) is the global annual average temperature change based on a 20 year average centered on the year of CO_2 doubling. TCRE is shown in units of ºC/TtC. The signal-to-noise ratio (S:N50) was evaluated at year 50 of the experiment (TCRE ×50 years × emission rate)/(2σ ΔT)). Values for the CMIP5 1pctCO_2 to 2 times and 1pctCO_2 to 4 times concentration forced experiments are also given as reference.

Table 2. Climate and Carbon Cycle Response 100 and 200 Years after the Imposition of Zero Emissions at the time of CO_2 Doubling[a]

	Land Uptake		Ocean Uptake		ΔT		TCRE	
	+100 years	+200 years	+100 years	+200 years	+100 years	+200 years	+100 years	+200 years
2-to-0 GtC/yr	542 (7.6)	511 (9.6)	1242 (19.6)	1310 (20.2)	2.37 (0.032)	2.41 (0.041)	0.99 (0.003)	1.01 (0.025)
5-to-0 GtC/yr	567 (10.6)	534 (11.7)	741 (6.5)	829 (6.9)	1.40 (0.046)	1.74 (0.095)	0.75 (0.018)	0.94 (0.057)
25-to-0 GtC/yr	444 (10.8)	423 (9.3)	369 (1.3)	451 (1.8)	0.8 (0.047)	0.78 (0.103)	0.66 (0.039)	0.65 (0.086)

[a] Land and ocean carbon uptake (GtC) are cumulative from year 1 of the experiments. ΔT (ºC) computed as a 20 year average (years 81–100 and 181–200). Values represent a mean across ensemble members and the 1σ standard deviation is given in the parenthesis.

PROPORTIONALITY BETWEEN WARMING AND CUMULATIVE EMISSIONS

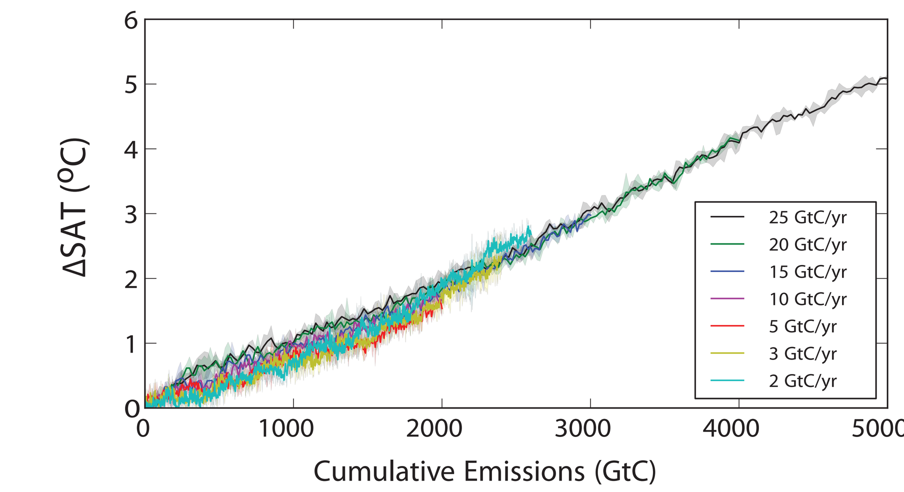

Figure 3: Global surface air temperature response (°C) plotted against cumulative carbon emissions (GtC). Although warming is approximately linear with respect to emissions, there is a separation among the different emission rates.

ZERO-EMISSIONS EXTENSIONS

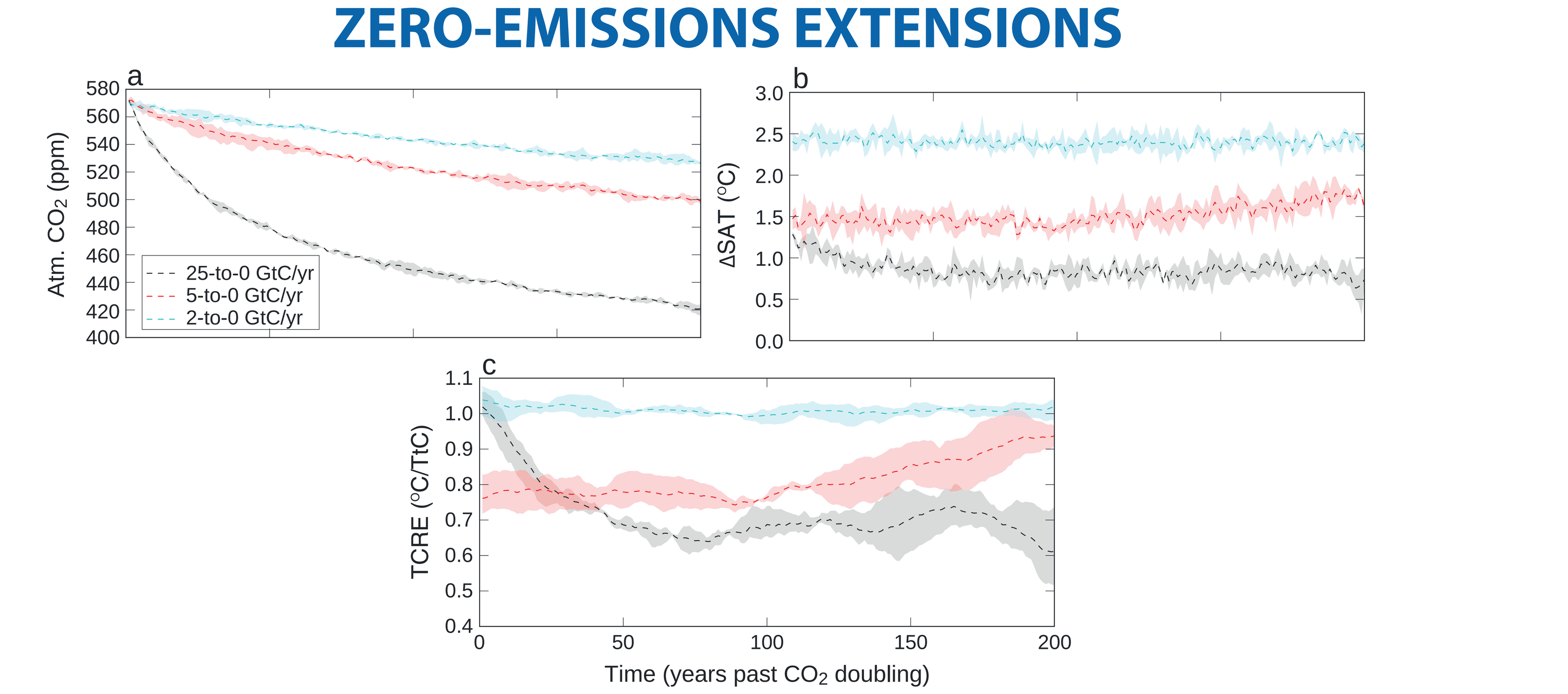

Figure 4: (a) Atmospheric CO_2 concentration (ppm), (b) change in SAT (K) relative to the control run, and (c) TCRE (°C/TtC) with no additional carbon emissions after achieving a doubling of atmospheric CO_2 (i.e., "zero emissions"). The average time to CO_2 doubling for the 2, 5, and 25 GtC/yr scenarios are 1191, 372, and 48 years, respectively. TCRE in the 5-to-0 GtC/yr scenario is approximately constant during the first century and increases during the second century. TCRE in the 25-to-0 GtC/yr scenario decreases during both centuries. The variability of TCRE increases with time for both scenarios.

TAKE HOME MESSAGES

The range of Transient Climate Response to cumulative carbon Emissions (TCRE) has a complex relationship to emission rates; TCRE is largest for both very low emission rates (e.g. 2 GtC/yr) and very high emission rates (e.g. 25 GtC/yr).

The range of TCRE resulting from these varying emission pathways is 0.76 to 1.04°C/TtC. TCRE is lowest for emission rates that are comparable to the present day (5 to 10 GtC/yr). [Ciais et al. 2013]

GFDL-ESM2G produces a TCRE that is consistent with the range from other CMIP5 models (0.8 to 2.4 ºC/TtC) [Gillett et al. 2013].

Structural model uncertainty (i.e. differences in model parameterizations) is larger than emissions pathway uncertainty for TCRE.

The TCRE signal is difficult to detect under low emissions and on short time scales.

The climate response once emissions cease depends on prior emission rates.

References

Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen, and N. Meinshausen (2009), Warming caused by cumulative carbon emissions towards the trillionth tonne, Nature, 458(7242), 1163–1166.

Ballantyne, A. P., C. B. Alden, J. B. Miller, P. P. Tans, and J. W. C. White (2012), Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years, Nature, 488(7409), 70–72.

Ciais, P., et al. (2013), Carbon and other biogeochemical cycles, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. Stocker et al., chap. 6, Cambridge Univ. Press, Cambridge, U. K., and New York.

Dunne, J. P., et al. (2012), GFDL's ESM2 global coupled climate– carbon earth system models. Part I: Physical formulation and baseline simulation characteristics, J. Clim, 25(19), 6646–6665, doi:10.1175/JCLI-D-11-00560.1.

Dunne, J. P., et al. (2013), GFDL's ESM2 global coupled climate– carbon earth system models. Part II: Carbon system formula- tion and baseline simulation characteristics, J. Clim., 26(7), 2247–2267, doi:10.1175/JCLI-D-12-00150.1.

Gillett, N. P., V. K. Arora, D. Matthews, and M. R. Allen (2013), Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations, J. Clim., 26, 6844*6858, doi: 10.1175/JCLI-D-12-00476.1.

Krasting, J. P., J. P. Dunne, E. Shevliakova, R. J. Stouffer (2014), Trajectory sensitivity of the transient climate response to cumulative carbon emissions, Geophys. Res. Lett., 41(7), 2520-2527, doi: 10.1002/2013GL059141.

Matthews, H. D., N. P. Gillett, P. A. Stott, and K. Zickfeld (2009), The proportionality of global warming to cumulative carbon emissions, Nature, 459(7248), 829–832.