Earth's Future

Supporting Information for

Integrated Assessment of Carbon Dioxide Removal

W. Rickels[1], F.Reith[2], D. Keller[2], A. Oschlies[2], and M.F. Quaas[3]

[1]Kiel Institute for the World Economy, Germany.

[2]GEOMAR Helmholtz Centre for Ocean Research Kiel, Research Division Marine Biogeochemistry, Germany.

[3]Kiel University, Department of Economics, Germany.

Corresponding author: Wilfried Rickels (wilfried.rickels@ifw-kiel.de)

Contents of this file

Additional Supporting Information (Files uploaded separately)

2017EF000724_SupplementaryInformation_Data.rar

Introduction

Additional information with respect to the linear carbon cycle box models and the validation with BEAM and UVic ESCM are provided in Text S1 (including Table SI.T1 to SI.T3) and Text S2. Figure SI.F1 corresponds to Figure 1 in the main text. While Figure 1 in the main text displays cumulative CDR and cumulative net emissions as function of the convexity of the CDR cost function for the two mitigation frameworks, CBA and 2C, Figure SI.F1 provides the same information but for the two mitigation frameworks, CBA and 2C2100. The comparison between Figure 1 and Figure SI.F1 indicates that there is only a very small difference between the mitigation frameworks 2C and 2C2100 when it comes to cumulative CDR and cumulative net emissions as function of the cost. Figure SI.F2a, SI.F2b, and SI.F2c correspond to Figure 2 in the main text. Figure 2 shows the time profile for cumulative CDR as function of the convexity of the CDR cost for the *CBA* and *2C* mitigation framework and the long-term carbon cycle and climate response in *CC16*. Figure SI.F2a provides the corresponding information for the 2C2100 mitigation framework in *CC16*. Figure SI.2b and SI.2c provide the corresponding information for all three mitigation frameworks (*CBA*, *2C*, and *2C2100*) in *CC13* and *CCGL*, respectively. Table SI.T5 displays the social cost of carbon (in 2010 USD) for all three mitigation frameworks (*CBA*, *2C*, and *2C2100*) in all three carbon cycles for cumulative CDR in the order of 0, 100, 500, 1000, and 1500 Gt C in the years 2015, 2020, 2025, 2030, and 2050 (to facilitate comparison with Nordhaus et al. 2017). The additional compressed file DICE_AMPL_IAM_CDR.rar includes all model files, the required run files to execute the different model files in AMPL, the required data to run the models (either included for single parameters in the model files or for time series of parameters as txt files which are automatically imported into the model upon execution), and a readme.txt file with additional information on the content. Furthermore, DICE_AMPL_IAM_CDR.rar includes csv files with results with respect to cumulative CDR and the time profile for CDR for different costs.

S1. Linear Carbon Cycle Models and Implementation of CDR in DICE

The carbon cycle model in DICE2016R (Nordhaus 2017), DICE2013R (Nordhaus and Sztorc 2013), and (Gerlagh and Liski 2017) are three-box models:

$$\begin{pmatrix} S_1(t) \\ S_2(t) \\ S_2(t) \end{pmatrix} = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix} \begin{pmatrix} S_1(t) \\ S_2(t) \\ S_2(t) \end{pmatrix} + \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix} E(t-1) + \begin{pmatrix} w_1 \\ w_2 \\ w_3 \end{pmatrix} CDR(t-1).$$

In DICE2016R and DICE2013R, S_1, S_2, and S_3, correspond to the atmosphere (MAT), upper ocean (MUP), and lower ocean (MLO), respectively. In Gerlagh and Liski (2017), they correspond to upper box containing atmosphere and upper ocean at constant fractions , terrestrial biosphere, and lower ocean, respectively. Consequently, in two DICE models the parameters σ_{13} and σ_{31} are zero because there is no direct exchange between atmosphere and deep ocean, while this parameters are non-negative in Gerlagh and Liski (2017). Table S1.1 below displays the parameter values of the transition matrix for the three models (for 5 year time steps).

	σ_{11}	σ_{12}	σ_{13}	σ_{21}	σ_{22}	σ_{23}	σ_{31}	σ_{32}	σ_{33}
CC16	0.8800	0.1200	0	0.1960	0.7970	0.0070	0	0.0015	0.9985
CC13	0.9120	0.0880	0	0.0383	0.9592	0.0025	0	0.0003	0.9997
CCGL	0.8351	0.1199	0.0151	0.1104	0.8771	0.0008	0.0545	0.0030	0.9841

Table S1.T1. Parameter values of the transition matrix for the three carbon cycle models for 5 year time steps (displayed here rounded to 4 decimal places).

In DICE2016R and DICE2013R, emissions enter only the atmosphere, implying that q_2 and q_3 are zero, in Gerlagh and Liski (2017) it is assumed for time steps larger than one year, part of the ambient carbon exchange between reservoirs is captured by non-negative values for q_2 and q_3, implying that a certain fraction directly enters other reservoirs. Accordingly, we have followed their approach for the calibration of w_1, w_2, and w_3 by using these parameters to obtain a closer fit of the 5 year time step calibration with the given 1 year time step calibration (where the three parameter values are zero). Consequently, the parameter w_1 displays the fraction of carbon removed which has returned to the atmosphere within a five year time period. Table S1.2 below displays the parameter values for the distribution of emissions and CDR.

	q_1	q_2	q_3	w_1	w_2	w_3
CC16	1	0	0	0	0	1
CC13	1	0	0	0	0	1
CCGL	0.9318	0.0460	0.0221	0.0062	0.0002	0.9936

Table S1.T2 .Parameter values of the distribution of emissions and CDR for the three carbon cycle models for 5 year time steps (displayed here rounded to 4 decimal places).

Both, DICE2013 and CCGL have been simulated with “historical emissions” such that they have the same initial conditions for atmospheric carbon stock as DICE2016R (i.e., 851 GtC) in the year 2015. Table S1.3 below displays the initial values for the three carbon cycles.

	$S_1(0)$	$S_2(0)$	$S_3(0)$
CC16	851.000	460.0	1,740.00
CC13	851.000	1,541.0	10,010.50
CCGL	290.836	159.4	158.34

Table S1.T3. Initial values for the three carbon cycle models in 2015 in GtC.

For CCGL, the constant fraction 0.904409 of S_1 corresponds to the atmospheric carbon stock. Furthermore, in CCGL the carbon stocks are measured in deviation to the preindustrial values, implying that in order to obtain the initial value for atmospheric carbon stock of 851 GtC one needs to add the preindustrial value of 588 GtC.

All other equations with respect to the climate module (i.e., forcing equation and temperature equation) and assumptions with respect to exogenous land-use emissions and exogenous forcing are specified like in DICE2016R.

S2. Validation with BEAM and UVic ESCM

The parameter values for the non-linear three-box Bolin and Eriksson Adjusted Model (BEAM) are obtained from Glotter et al. (2014) and validated with the documentation of webDICE (http://webdice.rdcep.org/). Like with the linear carbon cycles models, we derived "historical emission" up until the year 2015 such that the atmospheric carbon stock is as DICE2016R (i.e., 851 GtC).

To insure that the carbon cycle models in the IAMs and UVic ESCM are initialized with nearly the same mean annual atmospheric CO2 and temperature conditions, we first prescribe all forcing, following historical observations, to reach the same year 2015 conditions as in the IAMs. Then, we diagnose compatible CO2 emissions and use these to force the model until the year 2015. The model has been spun-up for 10,000 years and then run from 850 to 2005, where historical atmospheric CO2 forcing is prescribed along with known natural (orbital, volcanic, and solar) and other anthropogenic forcing (greenhouse gases, sulfate aerosols, and land cover change), following the Paleoclimate Modelling Intercomparison Project Phase 3 (PMIP3) and the Coupled Model Intercomparison Project Phase 5 (CMIP5)-recommended datasets (Taylor et al. 2011).

From the year 2006 until the year 2015 simulations continue with prescribed historical CO2 forcing, which is then held constant from 2014 to 2015 at 2014 levels. From 2006 onwards, natural forcings as well as land cover change are held constant at 2005-levels. Non-CO2 greenhouse gases and aerosols follow the RCP 8.5 specifications from 2006 to 2015 (Meinshausen et al. 2011). Further, prescribed, monthly varying, National Center for Environmental Prediction (NCEP) reanalysis winds are used together with a dynamical feedback from a first-order approximation of geostrophic wind anomalies associated with changing winds in a changing climate (Weaver et al. 2001).

Compatible CO2 emissions from 850 to 2015 are diagnosed in the prescribed CO2 run presented above and then used to conduct an emission driven simulation until the year 2015. All other forcing remains the same. From the year 2016 onwards, the UVic simulations follow the same forcing as used in the respective IAM simulations. Table S2.1 below displays the initial values for BEAM and UVic ECSM in 2015, showing for the latter the initial values for atmosphere, land, and total ocean.

	$S_1(0)$/ Atmosphere	$S_2(0)$/Land	$S_3(0)$ / Total Ocean
BEAM	851	727	35,646.00
UVic ECSM	850.89	1789.02	37391.18

Table SI.T4. Initial values for BEAM and UVic ECSM in 2015 in GtC.

Like in the carbon cycle models in the IAMs, CDR/deep ocean CO2 injections are simulated by adding carbon to the lower box, $S_3(t)$. In UVic ESCM, deep ocean CO2 injections in the respective CDR scenarios is simulated, in terms of the locations of the injections sites and the general deployment methodology, based on the OCMIP carbon sequestration protocols (Orr et al. 2001) and carried out in an idealized manner by adding CO2 directly to the dissolved inorganic carbon (DIC) pool (Orr et al. 2001). Thus, we neglect any gravitational effects and assume that the injected CO2 instantaneously dissolves into seawater and is transported quickly away from the injection point and distributed homogenously over the entire model grid box with lateral dimensions of a few hundred kilometers and many tens of meters in the vertical direction (Reith et al., 2016). Consequently, the formation of CO_2 plumes or lakes as well as the potential risk of fast rising CO_2 bubbles are neglected (IPCC 2005; Bigalke et al. 2008).

Following Orr et al. (2001) and Reith et al. (2016) CO_2 is injected at seven separate injections sites, which are located in individual grid boxes near the Bay of Biscay (42.3°N, 16.2°W), New York (36.9°N, 66.6°W), Rio de Janeiro (27.9°S, 37.8°W), San Francisco (31.5°N, 131.4°W), Tokyo (33.3°N, 142.2°E), Jakarta (11.7°S, 102.6°E) and Mumbai (13.5°N, 63°E) (Reith et al., 2016; their Figure 1). Direct CO_2 injections are carried out at 2900 m depth to minimize leakage and maximize retention time. At this depth, liquid CO_2 is denser than seawater, which has the additional advantage that any undissolved droplets would sink rather than rise to the surface (e.g., IPCC, 2005).

Additional Figures

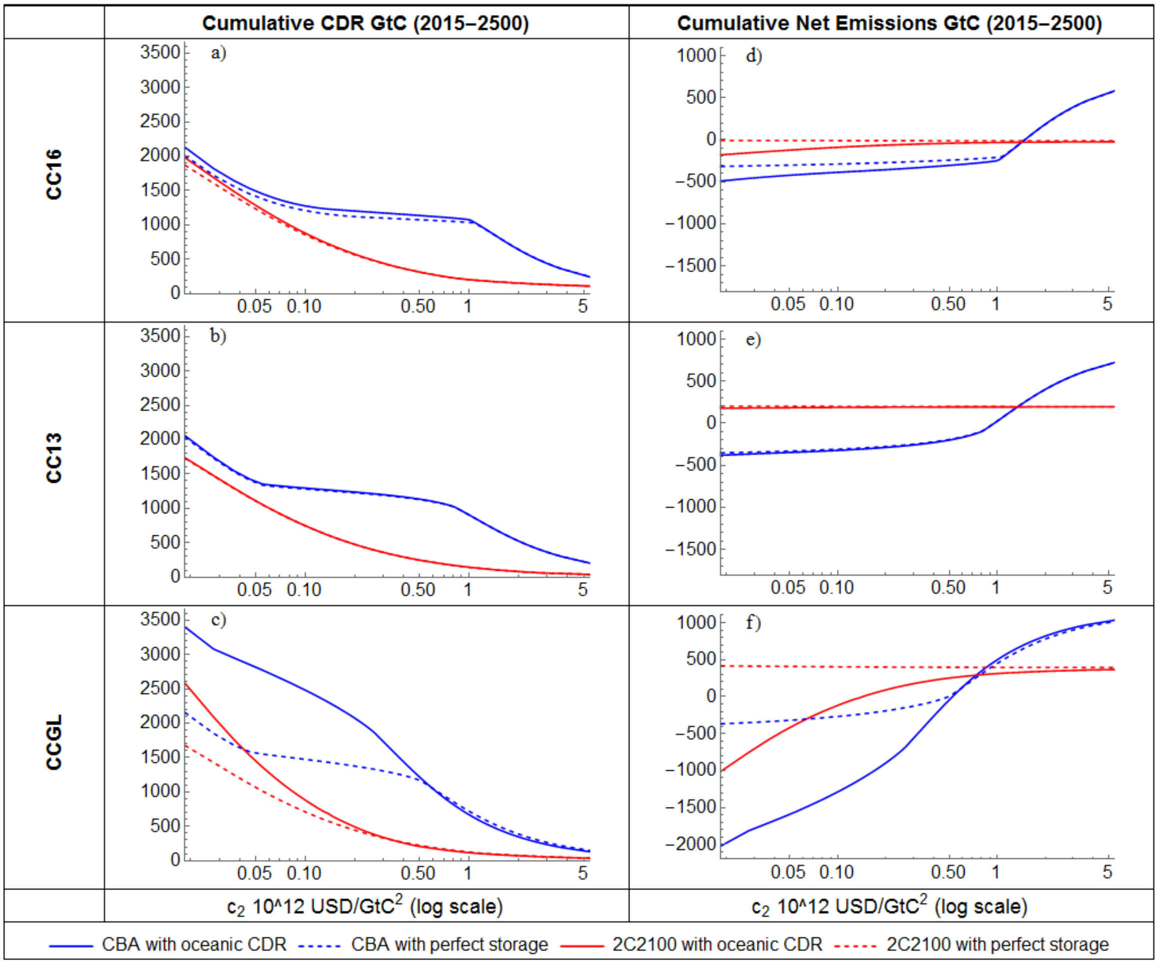

Figure SI.F1. Cumulative CDR and Net Emissions as Function of Convexity of CDR cost for the CBA and 2C2100 Mitigation Framework. The figure shows the cumulative optimal amount of CDR (left panel) and cumulative optimal amounts of net emissions (right panel) as function of c_2, the slope of the marginal CDR cost curve. The upper panel corresponds to CC16 (the carbon cycle model from DICE2016R), the middle panel corresponds to CC13 (the carbon cycle model from DICE2013R), and the lower panel corresponds to CCGL (the carbon cycle model from Gerlagh and Liski (2017)). Each box displays the optimal amounts for CBA (blue lines) and 2C2100 (red lines) for two CDR options, oceanic CDR (solid lines) and perfect storage (dashed lines).

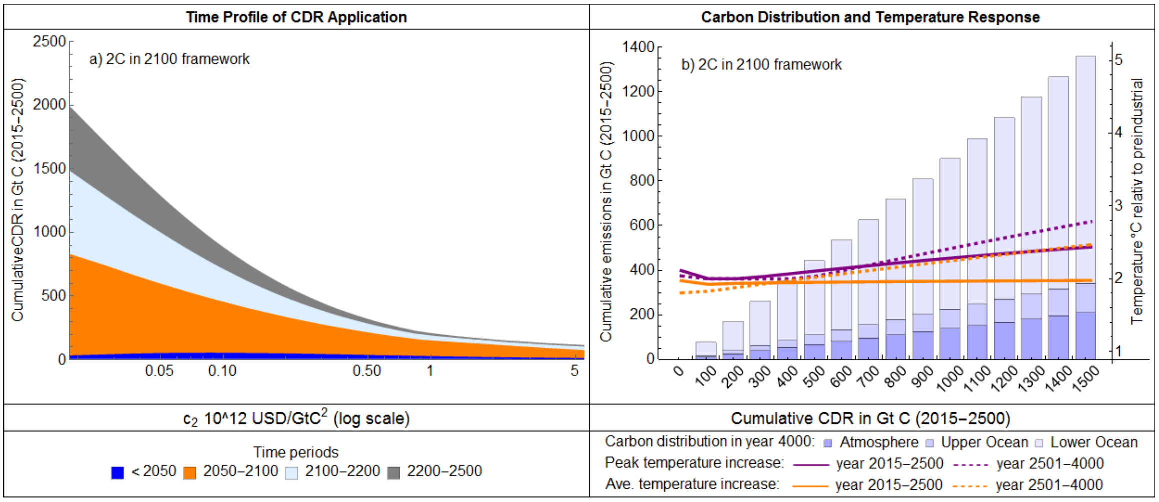

Figure SI.F2a. CDR Time Profile and Cumulative Emissions in *CC16* for the *2C2100* Mitigation Framework. The left panel shows the time profile of CDR utilization as function of c_2, the slope of the marginal CDR cost curve for the *2C2100* mitigation framework (a). The right panel shows the cumulative emissions (from 2015 until 2500) as function of the cumulative amount of CDR for the *2C2100* mitigation frameworks (b). The right panel also includes information about the distribution of the carbon emissions among the different carbon reservoirs in the year 4000 and about peak and average temperature for the period 2015-2500 and 2501 until 4000.

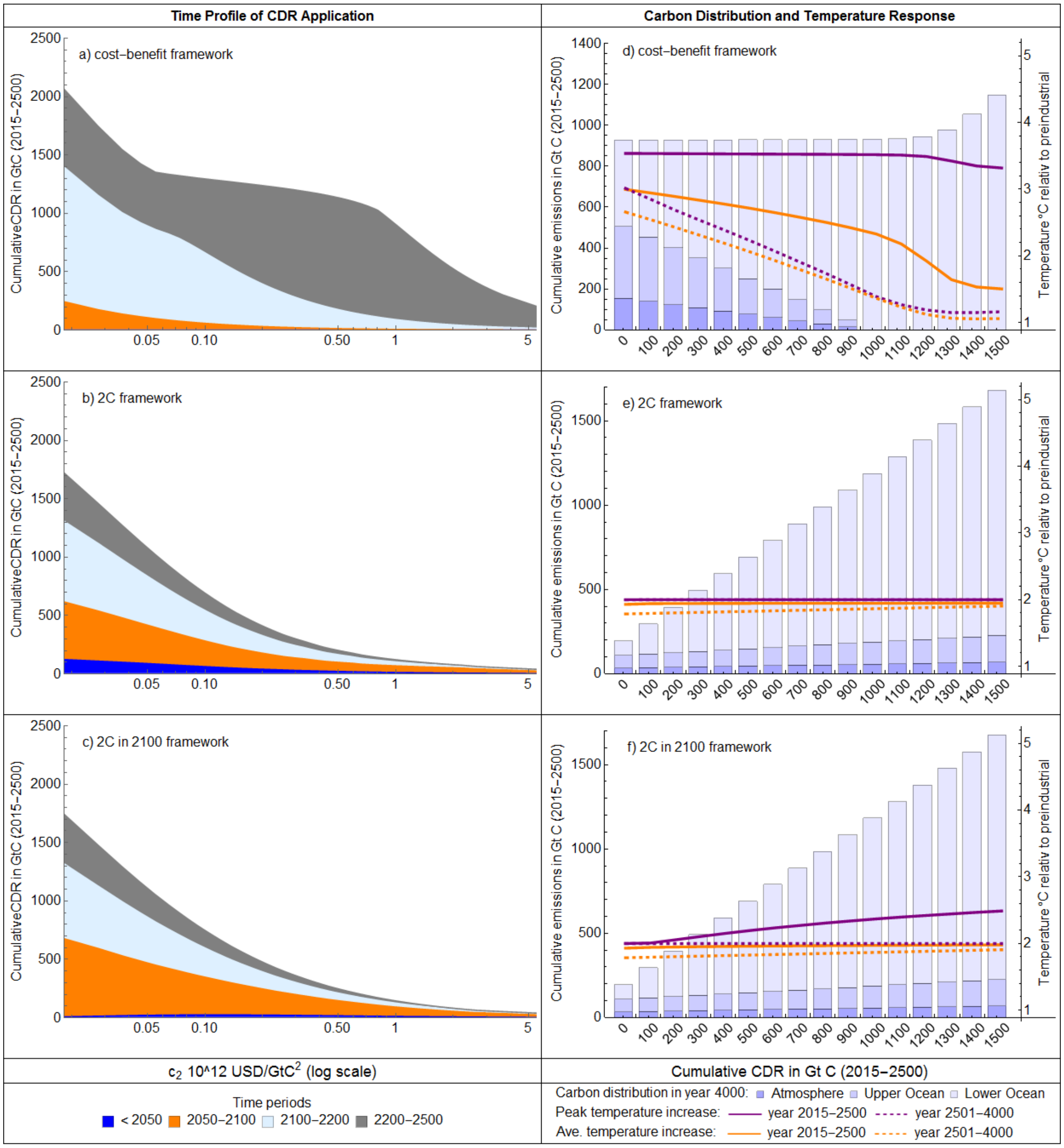

Figure SI.F2b. CDR Time Profile and Cumulative Emissions in *CC13*. The left panel shows the time profile of CDR utilization as function of c_2, the slope of the marginal CDR cost curve for the different mitigation frameworks (*CBA* , *2C*, and *2C2100* in a), b), and c), respectively). The right panel shows the cumulative emissions (from 2015 until 2500) as function of the cumulative amount of CDR for the different mitigation frameworks (*CBA*, and *2C*, and *2C2100* in d), e), and f), respectively). The right panel also includes information about the distribution of the carbon emissions among the different carbon reservoirs in the year 4000 and about peak and average temperature for the period 2015-2500 and 2501 until 4000.

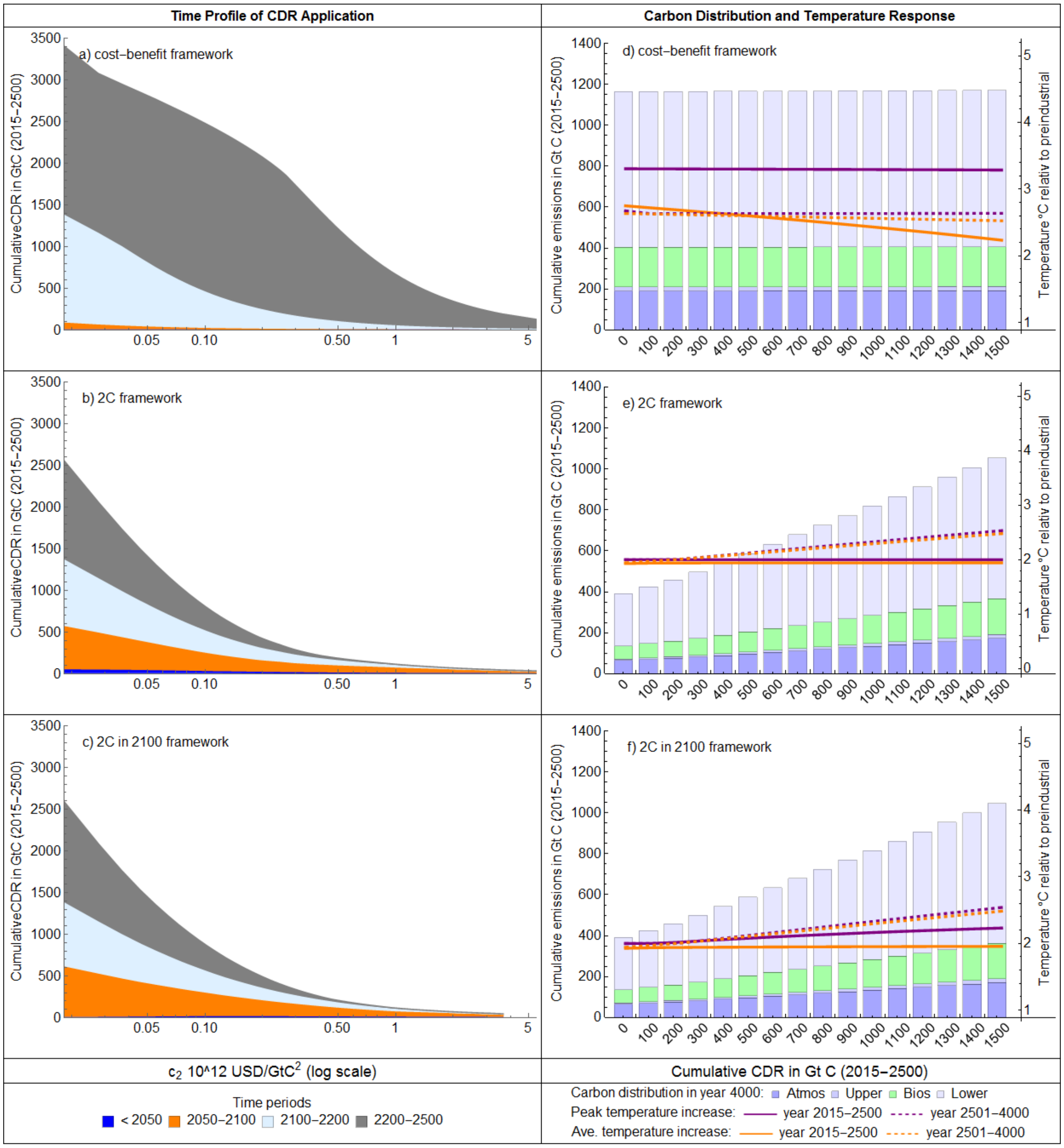

Figure SI.F2c. CDR Time Profile and Cumulative Emissions in *CCGL*. The left panel shows the time profile of CDR utilization as function of c_2, the slope of the marginal CDR cost curve for the different mitigation frameworks (*CBA* , *2C*, and *2C2100* in a), b), and c), respectively). The right panel shows the cumulative emissions (from 2015 until 2500) as function of the cumulative amount of CDR for the different mitigation frameworks (*CBA*, and *2C*, and *2C2100* in d), e), and f), respectively). The right panel also includes information about the distribution of the carbon emissions among the different carbon reservoirs in the year 4000 and about peak and average temperature for the period 2015-2500 and 2501 until 4000.

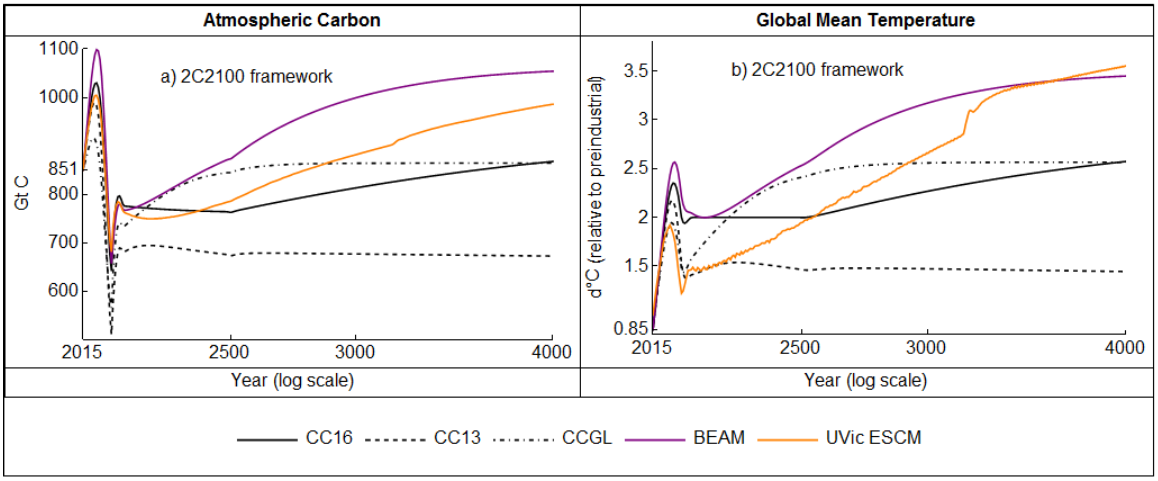

Figure SI.F3. Comparison of carbon cycle models with CDR in the *2C2100* Mitigation Framework. The figure shows atmospheric carbon content (left panel) and global mean temperature increase (right panel) for the *2C2100* framework (a) and b) respectively) for *CC16*, *CC13*, *CCGL*, BEAM, and UVic ESCM. The optimal emission and CDR paths in the three frameworks where derived with *CC16* for a CDR cost scenario which corresponds to cumulative 1200 Gt C.

		CBA					2C					2C2100				
CC	CDR Gt C	2015	2020	2025	2030	2050	2015	2020	2025	2030	2050	2015	2020	2025	2030	2050
CC16	0	30.80	36.83	43.61	51.26	91.25	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	100	30.80	36.80	43.60	51.25	91.24	308.83	385.21	480.25	509.77	460.68	308.83	385.21	480.25	509.77	460.68
	500	30.78	36.79	43.58	51.23	91.19	105.49	132.14	164.41	202.96	427.23	91.13	115.10	144.56	180.37	406.54
	1000	30.75	36.75	43.54	51.17	91.05	79.66	99.68	123.78	152.37	310.79	52.03	66.01	83.25	104.31	239.31
	1500	29.34	35.06	41.40	48.47	84.58	63.53	79.55	98.78	121.53	245.94	34.57	43.95	55.54	69.75	161.83
CC13	0	25.44	30.52	36.28	42.77	76.75	141.54	182.72	234.96	300.72	460.68	141.54	182.72	234.96	300.72	460.68
	100	25.43	30.52	36.28	42.76	76.73	97.35	126.06	162.35	207.62	460.67	95.82	124.29	160.42	205.74	460.68
	500	25.41	30.49	36.25	42.72	76.64	70.24	90.47	115.61	146.35	328.49	46.90	61.137	79.29	102.24	262.91
	1000	25.37	30.44	36.18	42.64	76.43	55.96	72.02	91.90	116.08	255.07	28.01	36.56	47.50	61.38	160.16
	1500	24.46	29.27	34.69	40.73	71.69	44.40	57.13	72.85	91.91	199.09	19.06	24.90	32.37	41.86	110.14
CCGL	0	17.62	21.24	25.34	29.96	54.19	85.28	110.34	142.15	182.20	460.68	85.28	110.34	142.15	182.20	460.68
	100	17.62	21.24	25.34	29.96	54.18	62.39	80.91	104.44	134.08	342.38	62.40	80.93	104.46	134.11	342.44
	500	17.62	21.23	25.32	29.94	54.14	47.53	61.55	79.24	101.34	248.03	38.59	50.15	64.85	83.42	215.12
	1000	17.60	21.22	25.31	29.91	54.08	40.97	53.05	68.28	87.27	212.03	27.76	36.11	46.73	60.15	156.09
	1500	17.59	21.19	25.28	29.88	53.98	36.10	46.74	60.13	76.81	185.51	21.68	28.21	36.52	47.02	122.46

Table SI.T5. The global social cost of carbon (SCC) for the different mitigation frameworks across the different carbon cycles in 2010 international US dollars.

References

Bigalke NK, Rehder G, Gust G (2008) Experimental Investigation of the Rising Behavior of CO 2 Droplets in Seawater under Hydrate-Forming Conditions. Environ. Sci. Technol. 42:5241–5246. doi: 10.1021/es800228j

Gerlagh R, Liski M (2017) Consistent climate policies. Journal of the European Economic Association. doi: 10.1093/jeea/jvx010

Glotter MJ, Pierrehumbert RT, Elliott JW, Matteson NJ, Moyer EJ (2014) A simple carbon cycle representation for economic and policy analyses. Climatic Change 126:319–335. doi: 10.1007/s10584-014-1224-y

IPCC (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque J-F, Matsumoto K, Montzka SA, Raper SCB, Riahi K, Thomson A, Velders GJM, van Vuuren DP (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109:213. doi: 10.1007/s10584-011-0156-z

Nordhaus W, Sztorc P (2013) DICE 2013R: Introduction and User's Manual. Cowles Found, New Haven, CT

Nordhaus WD (2017) Revisiting the social cost of carbon. Proc Natl Acad Sci U S A 114:1518–1523. doi: 10.1073/pnas.1609244114

Orr JC, Aumont O, Yool A, Plattner K, Joos F, Maier-Reimer E, Weirig M-F, Schlitzer R, Caldeira K, Wicket M, Matear R (2001) Ocean CO2 Sequestration Efficiency from 3-D Ocean Model Comparison. Greenhous Gas Control Technologies Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies:469–474

Reith F, Keller DP, Oschlies A (2016) Revisiting ocean carbon sequestration by direct injection: A?global carbon budget perspective. Earth Syst. Dynam. 7:797–812. doi: 10.5194/esd-7-797-2016

Taylor KE, Stouffer RJ, Meehl GA (2011) An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society 93:485–498. doi: 10.1175/BAMS-D-11-00094.1

Weaver AJ, Eby M, Wiebe EC, Bitz CM, Duffy PB, Ewen TL, Fanning AF, Holland MM, MacFadyen A, Matthews HD, Meissner KJ, Saenko O, Schmittner A, Wang H, Yoshimori M (2001) The UVic earth system climate model: Model description, climatology, and applications to past, present and future climates. Atmosphere-Ocean 39:361–428. doi: 10.1080/07055900.2001.9649686