Title: CDR modeled in MAGICC to return to preindustrial temperatures by 2100.

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The enclosed paper, ‘CDR modeled in MAGICC to return to preindustrial temperatures by 2100’ is a non-peer reviewed preprint and submitted to EarthArXiv. It has not been previously submitted to any journal. All data is available at https://github.com/hsbay/CDRMEx, with the Creative Commons Attribution 4.0 International open source license. Referenced software is licensed by their respective licenses and listed as such.

CDR modeled in MAGICC to return to preindustrial temperatures by 2100.

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Abstract

Scenario pathways greatly inform the opportunity space of possible future climates. The multistep experiment tests the Alternative Method to Determine a Carbon Dioxide Removal Target's thesis by simulating the novel pathway '300x2050,' SSP1-2.6, and SSP1-1.9 comparing within green growth development in MAGICC 6.8 by removing all cumulative anthropogenic CO_2 over 80 years and phasing out anthropogenic GHGs. Contrary to the previous theory, the experiment removed carbon equal to accumulated fossil fuels and land-use change emissions, realizing a final temperature of 0.07ºC relative to 1720-1800, 0.14ºC to the 1850-1900 mean, and CO_2 concentration of 278.82 ppm by 2550. The vast CDR needed to approximate the speculation of Anthropocene reversal by 2100 justifies utmost urgency and maximally scaled sustainable (zero-carbon intensity) green growth development.

Introduction

This article explores hypothetical climate modeling in MAGICC[1,2,3] to generate temperatures roughly matching preindustrial by 2100 through scaled Carbon Dioxide Removal (CDR or carbon removal). Although the novel large-scale CDR emissions pathway '300 x 2050' is highly implausible with current technology, state of the clean energy industry, and know-how, the resulting modeling through scaled CDR generates temperatures far lower than the marker Shared Socio-economic Pathway (SSP) 1.9[5,6,7,8] within the 'development under a green-growth paradigm' SSP 1 storyline[6]. To better understand the scope of what's needed to reach the lower bound of 300 ppm midcentury and 0ºC by 2100, the novel pathway constrained the total amount of carbon removed from the climate-carbon cycle, quickly reaching net zero by mid-2020s, followed by scaled fossil fuel free CDR and decades-long phaseout of all greenhouse gasses excluding ammonia.

The article's genesis attempts to answer the theme of achieving Anthropocene reversal: What would it take to return to a preindustrial climate or Anthropocene reversal? What requires removing and phasing out? How much carbon are we talking about? Is only the carbon in the atmosphere our problem, or must we also consider anthropogenic ocean carbon? Can we reverse the Anthropocene in less than a century? Can we do it before setting off climate tipping points[9,10] and with the least ecological damage? Can we limit future sea level rise (after our existing lock-in)? With limited funding and resources, and despite existing irreversible climate damage: effectively locked-in sea level rise and climbing extinction rates, is there a way to ballpark what it takes to achieve complete Anthropocene reversal by century's end?

These broad themes are highly underrepresented in the literature, given present-day implausibility. Speculations chart opportunity space increasing the potential for plausibility by providing estimated qualities and quantities to further scientific research and aid engineering solutions. This work is the first attempt to quantify how much carbon removal it would take to match the preindustrial global mean temperature by 2100.

As it's highly difficult to gauge the likelihood of activating tipping elements, unknown feedbacks, and irreversible damage from rising seas and extinction rates, the novel pathway was created to have the quickest peak emissions, quickly followed by zero emissions, then deeply negative, regardless of present industry and political infeasibility. As CO_2 emissions have the greatest contribution to effective radiative forcing and global temperature (from preindustrial to the present)[11], the paper's majority, experiment protocol, and data analyses focus on CO_2 and its removal. To greater assess open-ended speculation and limit the discussion to the magnitude and scale of CDR, CO_2 removals in this text are agnostic to the type of implementation and solution portfolio building and not prescriptive of a technology or set of technologies.

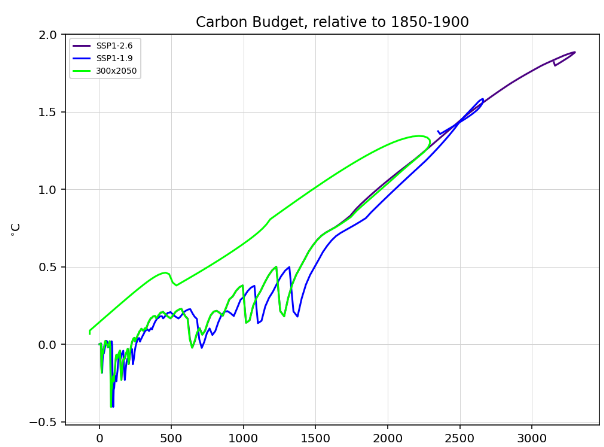

Figure 1: Carbon Budget showing CDR from 2024-2100 for IMAGE SSP 1 2.6[5,6,7], IMAGE SSP 1 1.9[5,6,7,8], and the novel experimental pathway 300 x 2050.

Results

The novel '300 x 2050' emissions pathway comprised of front-loaded negative CO_2 emissions, anthropogenic greenhouse gas phaseouts, and ammonia phase-down, simulated in the calibrated and tuned model, realizes 302.83 ppm of CO_2 by 2050, dives sharply to 237.37 ppm by 2100 and recovers to 278.82 ppm by 2550. Surface temperature evolves 0.0692ºC at 2100 and 0.0674ºC at 2550 relative to the 1720-1800 preindustrial mean[12,9] or 0.1422ºC by 2100 and 0.14ºC at 2550 of the 1850-1900 mean. Global temperature reaches peak warming of 1.4195ºC over the 1850-1900 mean, keeping below 1.5ºC in 2027, three years after net zero in mid-2024. Additional pathway results, including SSP1 1.9[5,6,7,8] and 2.6[5,6] for comparison, are listed in Table 1. The carbon budget in Figure 1 shows all pathways calculated from the calibrated, tuned model output, illustrating CDR in the uppermost curves moving right to left and decreasing overall temperature. The '300 x 2050' pathway's carbon budget shows CDR totaling about 2.3TtCO_2 (644.99 GtC), equal to cumulative anthropogenic carbon emissions. Emissions are charted in Figure 2, and the resulting climate is simulated in Figure 1, 3-8. The '300 x 2050' pathway removes 1133.2 GtCO_2 (309.29 GtC) to reach approximately 300 ppm; -871.48 GtCO_2 (-237.85 GtC) in Fossil Fuel (FF) and -261.76 GtCO_2 (-71.44 GtC) in Land-Use Change (LUC) CO_2 emissions. Next, the emissions pathway removes remaining accumulated FF-sourced CO_2 totaling 1765.7 GtCO_2 (481.90 GtC) by 2100. Additionally, it also removes all anthropogenic LUC emissions totaling 594.16 GtCO_2 (162.16 GtC) by 2100. See *Discussion: MAGICC 6.8 NE Verification* for inferred ocean outgassing and *Discussion: LUC Emissions Accounting* on land-use counterbalancing removals. Figure 2 shows a 2019 peak emissions swiftly declining to zero in mid-2020s, steeply descending to -47 GtCO_2 per year by 2030 through 2050, finally lowering to -25.03 GtCO_2 per year until 2100. The experiment results depend on highly model-specific tunings and explicit experimental goals affecting all results, including results based on IIASA-provided SSP1 data. See *Methods* and *Discussion* for further details.

scenario	unit	variable	2020-01-01	2100-01-01	2550-01-01
SSP1-2.6	ppm	Atmospheric Concentrations|CO2	419.1408	429.7285	374.5315
	W / m^2	Radiative Forcing	2.7057	2.8538	1.4417
	K	Surface Temperature	1.1880	1.8101	1.2480
SSP1-1.9	ppm	Atmospheric Concentrations|CO2	415.8408	371.8397	344.8451
	W / m^2	Radiative Forcing	2.6656	2.0874	1.0784
	K	Surface Temperature	1.1856	1.3773	0.9568
300x2050	ppm	Atmospheric Concentrations|CO2	421.3218	237.3759	278.8180
	W / m^2	Radiative Forcing	2.7738	-0.4094	0.0068
	K	Surface Temperature	1.2158	0.0692	0.0674

Table 1: Intermediate and evolved CO_2 concentration, Radiative Forcing, and Temperature, for marker SSP 1 2.6[5,6], SSP 1 1.9[5,6,7,8] and novel pathway '300 x 2050', Surface Temperature relative to 1720-1800 mean[12,9].

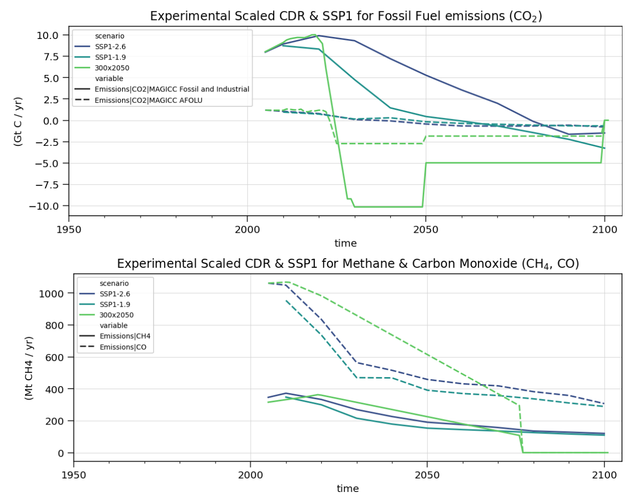

Figure 2 (a-b): Pathways SSP1 2.6[5,6], SSP1 1.9[5,6,7,8], and 300 x 2050 show CO_2, CH_4, CO emissions and emissions reductions starting in 2010 through 2125. Historical emissions through 2020 are included in the pathway '300 x 2050'.

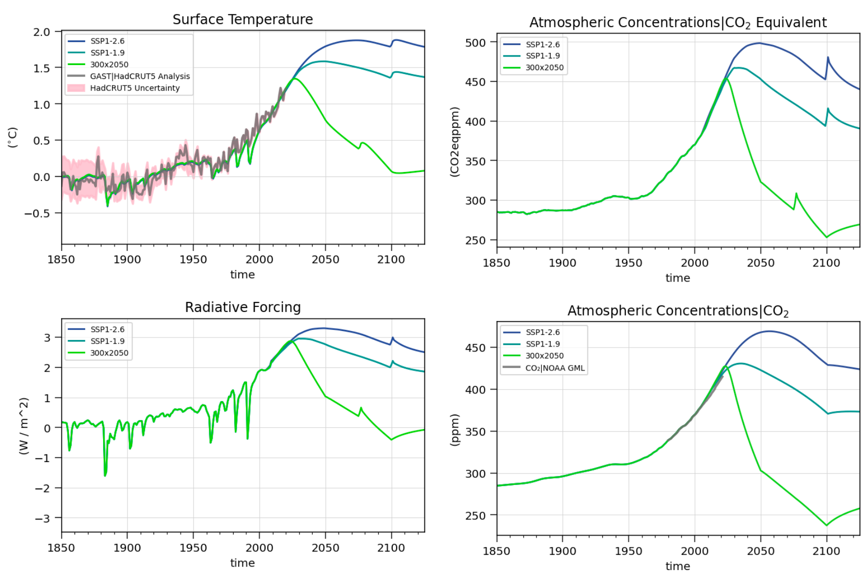

Figure 3 (a-d): Surface Temperature, Radiative Forcing, $CO_{2\text{-eq}}$, and CO_2 for the experimental '300 x 2050', SSP1 2.6 and SSP1 1.9 over the time 1850-2125, also shown in gray are the observational proxies of HadCRUT5 Analysis[14] and the Keeling Curve Global Annual Mean, NOAA GML.[15] All temperature data normalized to the mean of 1720-1800[12,9].

Methods

The multistep experiment protocol and results are in the Jupyter Python ONC CDRMEx notebook running MAGICC 6.8 managed by Pymagicc (2.0)[4]. See Data Availability and Supplement Information for links to the primary notebook and software repository. The experiment protocol calibrates and tunes MAGICC 6.8[2,3] to match better present near-term temperature, concentration, and emissions data, workarounds a land-sink model forcing peculiarity and runs the experiment generating the novel emissions pathway, and simulates it over 1720-2550. The experiment additionally lists for comparison markers IMAGE SSP1 1.9[5,6,7,8] and 2.6[5,6] (Table 1, Figure 1-3, 5-8) generated from each pathway's twenty-three GHG emissions data provided by the IIASA Explorer[7]. Due to the experiment's model calibration, the experiment's SSPs results resemble and vary from temperatures and forcings at IIASA despite being generated from the same data. This variation propagates to all subsequent data analyses, tables, and graphs. See the Supplemental data section and code repository for raw input files.

CDR is defined as Negative Emissions (NE) within the experiment parameters, emissions scenario pathway, and model input and results[2,3], consistent with the SSPs[5,6,7,8]. As MAGICC 6.8 predates large-scale NE, adjunct code was created to demonstrate CMIP6[17,18] lowered CO_2 concentration tests and additional baseline testing (Figures 12-13).

The recent anthropogenic CO_2 emissions data through 2020 from the Global Carbon Budget 2021[13] was used to calibrate and extend CO_2 emissions data from 2009 to 2020 and coupled to the novel pathway allowing a closer near-term fit for peak CO_2 concentration and temperature. To emulate CMIP and present-day temperature evolution in MAGICC, the HadCRUT5 2020[14] temperature data analysis was used to line-fit the mean of the last five years, yielding +0.0009ºC for the world region. A rough line-fit to 2015 through 2020 was created from the Keeling Curve Global Annual Mean CO_2 concentration[15] and established error, whereby the tuned model yielded +8 ppm above the CO_2 concentration for 2020. These tunings were applied as MAGICC 6.8 was last harmonized through 2010.

See Discussion, Model Temperature Calibration and Discussion, Calibration and Regionality for an in-depth temperature calibration discussion. The land-sink workarounds are discussed in Discussion, LUC Emissions Accounting. The Transient Climate Response (TCR) and transient climate response to emissions forcings (TCRE) with respect to model tunings are in the adjunct prerequisite code for the CMIP6 NE test; for more details, see Climate Response Metrics. NE calibration and verification are covered in Discussion, MAGICC 6.8 NE Verification.

Experiment Settings

Tuned Settings

The following settings were changed: climate sensitivity, ratio to land-ocean, heat exchange and amplification, north-to-south heat exchange, CO_2 fertilization, year start, land sink pools and fluxes, and soil feedback factors to allow the model to better line fit the HadCRUT5[14] temperature analysis, GCB 2021[13] emissions data, and Keeling Curve Global Annual Mean[15]. Given the tunings to the land sink pools and fluxes, to simplify curve fitting and minimize overfitting, only the soil feedback was modified, and the other land feedbacks were disabled.

N_2O data caused a noticeable spike after severely decreased emissions; MAGICC 6.8, which was finalized in 2012, does seem to artificially hold this value higher than listed 120 vs. 109 years[19, 11] for a few years after a large emissions reduction contributing to the artifact around the year 2079 for the '300 x 2050' pathway or in 2100 for the standard scenarios visible in the N_2O, $CO_{2\text{-eq}}$ and Surface Temperature graphs. (Supplement Figures g, Figures 3a-c) To smooth the declining curves for '300 x 2050,' all GHGs were declined to phase out by 2077, except ammonia and negative CO_2 (FF and LUC) emissions. It is left to further study under models not subject to this same N_2O artifact if GHG phase-outs can happen closer to 2050 and would lower the total amount of removal necessary to reach 0ºC. See the Supplemental Data section of the Supplementary Information to show all tuned MAGICC configuration settings.

Preindustrial Baseline, 1720-1800

A baseline of 1720-1800 was chosen per *Estimating Changes in Global Temperature since the Preindustrial Period, 2017*[12], as mentioned in *Trajectories of the Earth System in the Anthropocene, 2018*[9], which resulted in temperatures 0.073ºC warmer than the 1850-1900 baseline. The earlier baseline choice also avoids hysteresis if the model time series starts after 1765. A post-1765 start never reached a temperature of about 0ºC by 2500. See supplement figures *a-f* for additional details.

Table 2: CO_2 concentration and temperature means for various year spans.

unit	variable	mean of 1720-1800	mean of 1850-1900	mean of 1861-1900	mean of 1880-1900	mean of 1951-1980	mean of 1961-1990
ppm	Atmospheric Concentrations|CO2	278.6233	289.8765	291.0738	293.9143	322.3647	333.5193
K	Surface Temperature	-0.0000	-0.0730	-0.0805	-0.1440	0.1753	0.2177

Novel Pathway 300 x 2050

The experimental emissions pathway named '300 x 2050' consists of twenty-three GHGs emissions rates per year spanning 2010 to 2100. To remove all accumulated historical and projected anthropogenic carbon by 2100, carbon dioxide emissions include the following: modern emissions rise for the years 2010 to 2020[13], a short rise through the early 2020s, a steep decline in the mid-2020s reaching a high state of NE by 2030 that lowers concentration to about 300 ppm by 2050, medium NE to yield a radiative forcing of about 0.0 Wm-2 by 2100. The pathway's peak emissions occurred in 2019, where LUC of 1.1GtC was added to 10.02 GtC. The pathway reaches zero emissions part way through 2024 and ends with positive fossil fuel emissions of 0.93

GtC and LUC emissions of -1.36 GtC. The NE rate ramped to -12.88 GtC by 2030, continuing until 2050, followed by moderate rates of -6.83 GtC yearly removal until 2100.

Declining emissions rates from the most common twenty fossil-fuel-based GHGs[19]: methane, carbon monoxide, N_2O, NOx, SOx, black carbon, organic carbon, and ozone-depleting Montreal Protocol[20] controlled gases: chlorofluorocarbons, hydrofluorocarbons, SF_6 were also evolved till 2077. Emission rates per gas followed a linear decline, except when they declined more aggressively than rates listed in the Kigali agreement to the Montreal Protocol. The emissions from the twenty GHGs were completely phased out in 2077. Although phased down, only ammonia remained past 2100. For full reproducibility, constructing the pathway is fully open source; see Build Experiment '300 x 2050' and sections 9-26 written in Python within the main Jupyter notebook, in Data Availability and Supplement Materials Data sections.

Discussion

With high levels of model customization and emissions pathway constraints, the experiment was successful at reaching about CO_2 300 ppm midcentury, 0.14ºC (above 1850-1900) by 2100, and RF (Radiative Forcing) 0 Wm^{-2} post-2140. The non-CO_2 GHG phaseouts and ammonia phase-down project transitioning to a highly scaled sustainable green growth development (redefined as zero-carbon intensity energy and economic systems, zero-waste circular global economy, ecosystems rehabilitation, preservation, and expansion, extending sustainable development). The experiment protocol defined the intermediate target of 300 ppm of CO_2 by midcentury to allow a greater chance of recovery and higher quality of life for all Earth's ecosystems. Earth was last roughly at a CO_2 of 300 ppm in 1915[21]. Even highly scaled carbon removal still needed application over decades to completely negate cumulative anthropogenic CO_2 emissions. Linear removal and nearly linear phaseouts to anthropogenic non-CO_2 GHG completing a couple of decades before CO_2 removal ending at 2100 were found to have the least temperature perturbation post-2100.

The available computer resources limited the modeling to a reduced complexity model (RCM) or Earth System Model (ESM) emulator and precluded testing on a more comprehensive ESM. MAGICC was selected over RCM FaIR given its complex modeling, generating slightly warmer results than FaIR, and its broad use in the literature[5, 6, 11].

The simulation was designed to test over the maximum model timeline, allowing anomaly detection post-removal and reaching equilibrium (Figures 4,6, and 9). The MAGICC land-sink workaround heuristic tuning and land feedback choices set the temperature to 0.0674ºC at 2100 and slight temperature rise post-2100 before equilibrium. The tunings are valid if NE have a nearly symmetrical climate-carbon cycle response[22] and the simplified feedback emulates a CMIP land sink. Examining the calibrated results in Figure 4, the shading serves as a proxy illustrating greater uncertainty in the extremes diverging from the central temperature at an ECS of 3.257ºC, with shading from lowered ECS of 2.1ºC and raised ECS of 4.4ºC. Given the state of climate modeling and CMIP ESM variability, the slight rise above 0ºC is a sufficient balance of the experiment's previously listed constraints. See *Discussion: Model Temperature Calibration, Calibration and Regionality, Climate Response Metrics, MAGICC 6.8 NE Verification, LUC Emissions Accounting, and NE and Asymmetry* for an in-depth discussion of how they shaped the customizations and modeling constraints affecting the results.

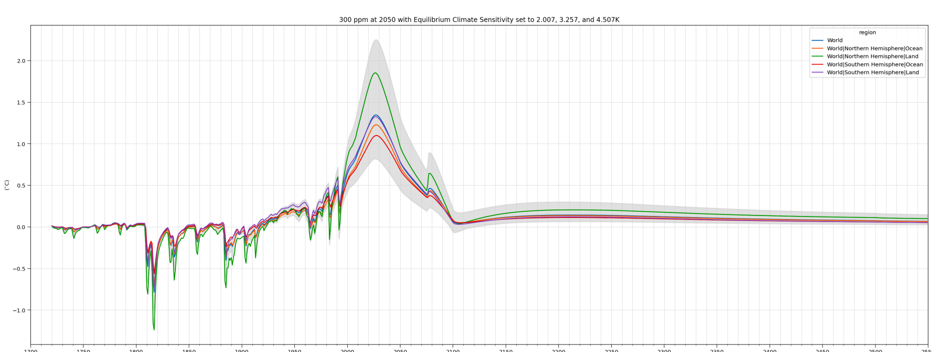

Figure 4: '300 x 2050' pathway with various Equilibrium Climate Sensitivities: 2.01ºC, 3.3ºC, and 4.4ºC from 1720 to 2550 relative to the mean of 1720-1800.

Model Temperature Calibration

The experiment was tuned and calibrated to the recent temperature increases from 2015-2020 Global, Northern, and Southern hemispheres temperature mean from the HadCRUT5 analysis[14] evolving global temperature, achieving a delta of +0.0009ºC and nearly ±0.18ºC for the hemispheres. See Table 4 for temperature data. Calibration to recent temperature and emissions increases through 2020 expanded the graphed temperatures' amplitude over an untuned configuration. Presumably tuning to recent temperature increases, the model would replicate those temperature ranges with higher confidence, irrespective of baseline. The calibration additionally attempted to match 412.44 ppm global CO_2 concentration for 2020[15]. The experimental pathway '300 x

2050' for 2000-2020, with added GCB emissions, CO_2 concentration, and temperature, reflects a closer but not exact match for the near future: 2021 predicted CO_2 of 423.97±8 ppm and 1.25ºC temperature rise. The combined effects of prescribing historical emissions, temperature, and CO_2 tunings are visually noticeable by the divergence of '300 x 2050' from the harmonized SSP1 2.6 and 1.9 starting about 2015 (Figure 2-3, 5-7). Although CO_2 concentration was eight ppm higher than the global mean for 2020, ΔQ_{2xco2}, the RF conversion factor see *Appendix A*[2]*,* eq *A36*, was kept to the default of 3.71 Wm^{-2} as a trade-off given the calibration and constraints (*Discussion*, *LUC Emissions Accounting, Methods, Experimental Settings, Tuned Settings*), while unfortunately increasing uncertainty for the CO_2 concentration data extremes. To better match the present-day climate in modeling, in-depth calibration incorporating the latest emissions, recent temperatures, and CO_2 concentration data is highly recommended.

Calibration and Regionality

The calibrated experiment predicts a 0.15ºC lower regional temperature (Figure 5) than the mean of 2015-2020 from CRUTEM5[16]. Listing the regions from warmest to coolest, the northern hemisphere, with the most developed land, experiences the majority of the warming well beyond the other regions; then the southern hemisphere land, the northern hemisphere ocean, and the southern hemisphere ocean. The resulting ordering is common to all graphed pathways. The regional temperature projections were compared but not tuned to the CRUTEM5 2021 dataset or ESM data. The northern hemisphere mean temperature was 1.64ºC for 2015-2020 (from 1850-1900) for the '300 x 2050' pathway and 0.14ºC less than the CRUTEM5 2021 dataset mean (1.78ºC) over the same duration. The southern hemisphere mean temperature was 1.21ºC for 2015-2020 (from 1850-1900) for the '300 x 2050' pathway and 0.15ºC less than the CRUTEM5 2021 dataset mean for 2015-2020 relative to 1857-1900 (1.361ºC).

Given the heat exchange and temperature effects spreading to each region, despite the '300 x 2050' pathway temperature evolution estimated at a high uncertainty, and yet how long it takes to recover with a high removal rate, these next two decades are critical to lowering global temperatures.

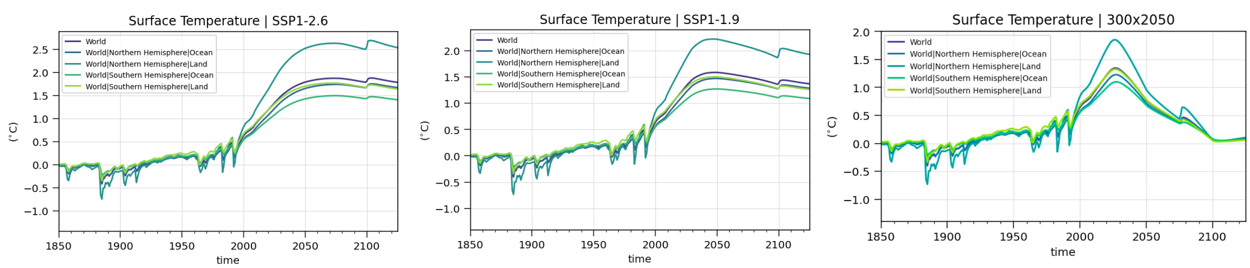

Figure 5 (a-c): Surface Temperature for SSP 1 2.6, SSP 1 1.9, and 300 x 2050, listing the northern, southern, land, and ocean regions, including the world region.

Climate Response Metrics

```
MAGICC ECS setting: 3.257K, MAGICC ΔQ2xCO2 setting: 3.71K
Calculating ECS from abrupt-2xCO2.
Calculating TCR & TCRE from 1pctCO2.
TCR is 2.0882, ECS is 3.2376 kelvin and TCRE is 2.420048 K / 1000 GtC
Calculating ECS from abrupt-0p5xCO2.
Calculating TCR & TCRE from 1pctCO2-cdr.
TCR is 2.0882, ECS is 3.2555 kelvin and TCRE is 2.420048 K / 1000 GtC
```

Figure 9: MAGICC output listing ECS, TCR, TCRE results, and CMIP6 experiments.

The Equilibrium Climate Sensitivity (ECS) is defined as the rise in temperature from a doubling (or for NE calibration, halving) of CO_2 concentration until global temperature equilibrates. Calibrating and tuning yielded a core climate sensitivity (ΔT_{2x}) raised from the MAGICC 6.801[2,3] 3ºC default to 3.257ºC, evolving ECS over 2500 years to 3.24+0.02ºC. The effect of tuning to the present-day temperature mean also lowered Transient Response to Cumulative CO_2 Emissions (TCRE) to 2.4ºC and Transient Climate Response (TCR) to 2.1ºC. Although the calibration to the present-day mean temperature trended initially hotter than SSP 1 1.9 and 2.6, overall, ECS didn't trend significantly hotter. This effect is likely given the shorter duration of increased emissions from the '300 x 2050' pathway. For a more in-depth discussion, see Section 3.1[2].

MAGICC 6.8 NE Verification

The NE Verification of MAGICC 6.801 was performed by augmenting the pymagicc program to utilize the CMIP6 abrupt-0p5xCO2[18] and 1pctCO2-cdr tests. The experiment generates ECS, TCR, and TCRE via NE adjunct code by evaluating the abrupt doubling of emissions (CMIP abrupt-2xCO2) and the 1% continual increase in CO_2 concentrations (CMIP 1pctCO2) and CMIP6 abrupt halving in CO_2 concentration and CMIP6 1% increase then negative 1% (1pctCO2-cdr) tests. The absolute value of the pairs of the TCR and TCRE were equal, and ECS resulted in a slight difference of about 0.0194ºC, yet an acceptable demonstration of NE given the tests equilibrate over 2500 years. Figure 9 shows NE verification by comparing ECS, TCR, and TCRE for carbon additions and removals. The experiment calibrating MAGICC running the abrupt drop test[18] (Supplement

Figure *i-m*) yielded -2.59ºC after 150 years in line with IPSL-CM6A-LR (-2.85ºC)[23] and HadGEM3-GC31-LL (-2.210ºC)[24]. Additional CMIP6 abrupt drop in CO_2 concentration results from several CMIP6 ESMs[18,23,24,25,26,27,28,29,30,31] are shown in Supplement Figure *n*.

Ocean outgassing is inferred as all FF emissions need to be removed instead of only atmospheric emissions. A removal realizing about 302.83 ppm of CO_2 by 2050 (237.85 GtC modeled, removing only the atmospheric anthropogenic increase 415 ppm - 302.83 ppm then multiplied by 2.124 GtC/ppm to obtain carbon by weight) still needed an additional removal of 244 GtC to counterbalance the effect of the ocean reestablishing pCO_2 equilibrium, all of which completed by 2100. The continued removal allowed temperature to recover slowly and finally converge to match preindustrial. CO_2 concentration does drop significantly to 237 ppm; however, $CO_{2\text{-eq}}$ only drops to 252.99 ppm, while global temperature never drops below 0.04ºC. The '300 x 2050' pathway results predict ocean upwelling will return to baseline by 2100; see supplemental Figure *h*. The ocean heat exchange, drop in concentration from emissions forcings, N_2O artifact (discussed in Methods: Experiment Settings, Tuned Settings), and GHGs phaseouts introduce enough varying factors to complicate modeling on RCM meriting a more comprehensive understanding of the present-day emissions and removals, temperatures and future evolution to justify modeling on an ESM ensemble.

unit	variable	1750-01-01 00:00:00	1817-01-01 00:00:00	1850-01-01 00:00:00	2023-01-01 00:00:00	2050-01-01 00:00:00	2082-01-01 00:00:00	2100-01-01 00:00:00	2550-01-01 00:00:00	2081-2100 mean	2081-2100 1850mn
ppm	Atmospheric Concentrations|CO2	277.0147	284.1080	284.8000	427.3552	302.8265	262.7444	237.3759	278.8180	249.6460	NaN
W / m^2	Radiative Forcing	0.0052	-0.8239	0.1591	2.8734	1.0329	0.3283	-0.4094	0.0068	-0.0728	NaN
K	Surface Temperature	-0.0022	-0.7863	0.0022	1.2993	0.7769	0.4223	0.0692	0.0674	0.2409	0.3139
	SURFACE_ANNUALMEANTEMP	-0.0151	-0.6849	-0.0117	1.2981	0.7500	0.4007	0.0494	0.0546	0.2181	0.3031

scenario	unit	variable	2023-01-01 00:00:00	2050-01-01 00:00:00	2100-01-01 00:00:00
SSP1-2.6	Cumulative Gt C	Emissions|CO2|MAGICC Fossil and Industrial|Cumulative	487.7882	697.3675	750.6188
		Emissions|CO2|MAGICC AFOLU|Cumulative	160.8537	160.1986	128.0173
SSP1-1.9	Cumulative Gt C	Emissions|CO2|MAGICC Fossil and Industrial|Cumulative	470.3978	549.6581	489.4033
		Emissions|CO2|MAGICC AFOLU|Cumulative	193.9925	198.8223	173.9885
300x2050	Cumulative Gt C	Emissions|CO2|MAGICC Fossil and Industrial|Cumulative	481.8968	244.0495	0.0001
		Emissions|CO2|MAGICC AFOLU|Cumulative	162.1623	90.7213	-0.0022

Table 3 (a-b): '300 x 2050' CDR pathway data at various time points. Cumulative emissions at various at peak, 2050 and 2100 SSP1-2.6, SSP 1-1.9 and '300 x2050'.

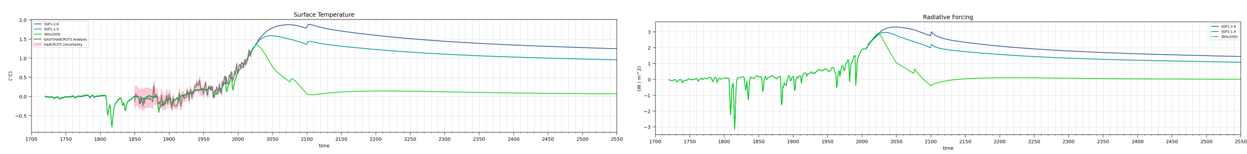

Figure 6 (a-b): Full graphs for Surface Temperature of '300 x 2050' and Radiative Forcing to show '300 x 2050' convergence of about 0.07ºC and Radiative Forcing 0 Wm^{-2}.

LUC Emissions Accounting

Cumulative increases to the land sink since preindustrial also needed to be removed to achieve equilibrium. The inclusion of cumulative LUC for removal was unexpected and unanticipated in the author's previous theory[33] paper.

By including the 2010-2020 GCB 2021 data in the '300 x 2050' pathway, '300 x 2050' LUC emissions diverged from SSP 1 1.9 before 2020, shown in Figure 7, d. The divergence was unexpected as the model's initial settings harmonized all emissions through 2005. Extensive tunings to heat, hemispheres, and soil feedback were applied in addition to a workaround removing 42.4 GtC of AFOLU to match MAGICC evolved emissions data. The soil carbon feedback was tuned to allow positive growth in CO_2 concentration and subsequent minimal non-linear concentration and temperature evolution in the near-term mid-2020s, 2100, and through 2550. Given the mixed effects on land sinks in the ESM results in ([32]) but slight decreases modeled on UVIC ESM in ([22]), a very slight, positive rise above 0ºC was selected for the post-2100 temperature calibration. This temperature target remained slight to model NE properly. The additive effects of tuning and the workaround increased the Northern/Southern temperature divergence, and non-linear rate changes graphed as more rounded curves.

MAGICC 6.8 doesn't allow durable storage from below-ground mineralization of CO_2 removed from the natural climate-carbon cycle (or a setting to mimic this behavior). It is unknown if a minimal portion of the land sink should have turned into durable storage beyond temporal land sink feedbacks. Natural conversion to more permanent storage is a topic open for further investigation.

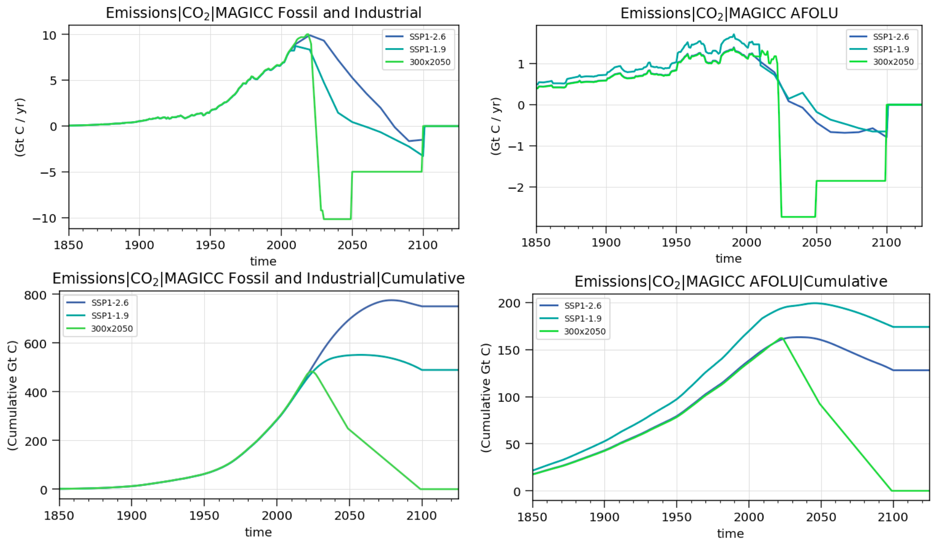

Figure 7 (a-d): Anthropogenic and Land-Use Change Emissions and cumulative emissions data, and CDR decreasing in green.

Negative Emissions and Asymmetry

The ‘300 x 2050’ pathway has NE totaling 644.99 + 42.2 GtC to match the cumulative anthropogenic emissions. If more LUC emissions are permanently contained within the land sink and cumulative emissions fall to roughly 500GtC, removal falls within natural sink uptake model variability([17,22,32]). Yet, if all anthropogenic NE (644.99 + 42.2 GtC or totaling 2520.4 $GtCO_2$) are needed to reach 0ºC over preindustrial, although not exhibited within this highly customized work, it’s possible the removal amount needs to be slight increased beyond cumulative emissions since preindustrial. The amount over 500GtC to determine the CDR magnitude necessary to match preindustrial temperatures by 2100 is open for in-depth investigation.

Conclusion

This text outlines future investigation starting points to better approximate a preindustrial climate by 2100. Having a team explore the experiment’s thesis yet with increases upwards of 1.55x to 1.7x preindustrial CO_2 concentration([22]) driven by forcings from emissions, and removing between 600 GtC (2198.4 $GtCO_2$) to about 775GtC (2839.6 $GtCO_2$), matching up to present-day temperatures, and on a model ensemble would best provide more accurate projections of temperature, holding below 1.5ºC, and additional data: regional temperatures, below ground CO_2 mineralization, sea-level rise, AMOC, ENSO, and jet-stream turnover([9,10]) evolve over time.

This work often indirectly and directly indicates the link between the magnitude of cumulative anthropogenic carbon and critical solution first step of maximally scaling zero carbon intensity sustainable development (redefined in the Discussion). The accumulated anthropogenic carbon magnitude and annual accrual require massive remediation efforts for net zero, holding well below 1.5ºC and seeking preindustrial temperature by 2100. To not exacerbate the existing anthropogenic carbon burden, massive remediation efforts necessitate the fastest path to the smallest net zero with practically zero carbon intensity, then zero emissions. Given the vast quantity of removal needed in the least amount of time, near-term emissions are radically limited. Such tremendous remediation efforts are only achievable if we limit emissions to stay well within the carbon budget. Even though removals and phaseouts are agnostic to technology and implementation, the dual conditions of massive CDR and achieving 0ºC by 2100 require a complete phaseout of fossil fuels over the century. A continued dependency on fossil fuels is unable to yield phaseouts in emissions or the deep carbon removals necessary to achieve the scale and scope to match the preindustrial temperature.

Although this article alone couldn’t answer these questions: Can we have the climate of our childhood, our parent’s generation, or the climate of 1750 by 2100, this decade — the 2020s is paramount for climate ecosystem restoration and maximally scaled sustainable green growth development. Moonshots’ efforts in mobilizing the most expansive near zero-carbon intensity resources with maximal urgency are pivotal to limiting global warming and subsequent irreversible climate damages while opening the widest door for follow-on restoration finishing by century’s end. Human potential is often quoted as limitless; harnessing this audacity can shape the mindset to better elucidate what’s required to achieve the near impossible required for Anthropocene reversal. The possibility of eventually matching the preindustrial climate should help inform the debate of maximally scaled sustainable green growth development for the fastest path to net zero, phaseout of anthropogenic emissions sources, and scaled carbon removals with zero-carbon intensity to develop a more equal future world.

Data Availability

The experimental setup, data and results are fully open source, https://github.com/hsbay/CDRMEx, see Supplementary Materials for additional details.

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Competing Interests

None.

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