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

Author: Shannon A. Fiume, Autofracture, shannon@autofracture.com,

https://twitter.com/safiume, https://github.com/safiume

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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.

S. A. Fiume
shannon@autofracture.com

Abstract

Scenario pathways greatly inform the opportunity space of possible future climates. To increase any likelihood of better matching preindustrial temperature by 2100, I simulate a what-if pathway: '300x2050' that removes all cumulative anthropogenic carbon dioxide and phases out anthropogenic greenhouse gases. The multistep experiment tests the thesis in an Alternative Method to Determine a Carbon Dioxide Removal Target by simulating the novel scenario pathway '300x2050' and markers SSP1-2.6 and SSP1-1.9 within the context of green-growth development exploring large-scale linear carbon dioxide removal over 80 years. The experiment calibrates and tunes the reduced complexity model MAGICC 6.8, managed by pymagicc, to recent global temperatures and CO_2 concentration through 2020, generates and simulates the '300x2050' pathway calibrated to recent historic emissions through 2020, phases out all non-CO_2 greenhouse gases, excluding ammonia, completing by the late 2070s, removes all cumulative anthropogenic carbon dioxide ending by 2100, and equilibrates the climate through 2550. Contrary to the proposed theory, the experiment removed an equivalent amount of carbon equal to accumulated fossil fuels and land-use change emissions to realize the final temperature of 0.07ºC relative to the 1720-1800 mean and 0.14ºC to the 1850-1900 mean and a final CO_2 concentration of 278.82 ppm by 2550.

Introduction

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

The article's genesis attempts to answer the following questions: What would it take to return to a preindustrial climate? What would it take to get back to before the Anthropocene? How much carbon are we talking about? Can we do it in less than a century? Can we do it before setting off climate tipping points[9,10]? Can we do it with the least amount of ecological damage? Can we limit future sea level rise? 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 would take to achieve complete Anthropocene reversibility by century's end?

These broad themes are highly underrepresented in the literature. This work is the first attempt to answer what it would take to lower global temperature to the preindustrial global mean temperature by 2100.

As it's highly difficult to gauge the likelihood of activating tipping elements and other 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 mean surface air temperature (from preindustrial to the present)[11], most of the paper: model mechanics and data analyses are focused on CO_2 and negative emissions. To greater assess open-ended speculation and also limit the discussion to the magnitude and scale of carbon dioxide removal, 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.

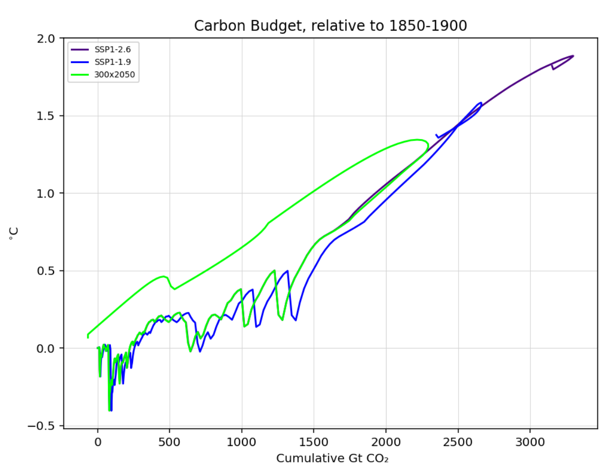

Figure 1: Carbon Budget showing CDR from 2024-2100 for IMAGE SSP 1 2.6[5,6,7], IMAGE SSP 1 1.9[5,6,7,8], and the novel experimental pathway 300 x 2050.

Results

The novel '300 x 2050' emissions pathway comprised of front-loaded CDR emissions and a phase-down of the other fossil-fuel and agricultural greenhouse gases, when simulated in the calibrated and tuned model, realize a carbon dioxide concentration of 302.83 ppm by 2050, dives sharply to 237.37 by 2100 and recovers to 278.82 by 2550. Surface temperature evolves to .0692ºC at 2100 and .0674ºC at 2550 relative to the preindustrial mean of 1720-1800[12, 9] or 0.1422ºC relative to 1850-1900 mean by 2100 and 0.14ºC at 2550, additional pathway results listed in Table 1. The carbon budget in Figure 1 shows all pathways calculated from the tuned and calibrated model output, including CDR illustrated in the uppermost curves moving right to left and overall decreasing temperature. The '300 x 2050' pathway's carbon budget shows the removal of cumulative anthropogenic carbon emissions totaling about 2.3TtCO_2 (644.99 GtC). The '300 x 2050' pathway removed roughly 237.85 GtC or 871.48 GtCO_2 for fossil-fuel sourced CO_2 emissions by 2050 and 71.44 GtC or 261.76 GtCO_2 of Land-use change emissions by 2050. The emissions pathway then continues to remove all fossil-fuel sourced CO_2 totaling 481.90 GtC or 1765.7 GtCO_2 by 2100. It also removes all anthropogenic land-use change emissions totaling 162.16 GtC or 594.16 GtCO_2 by 2100. As shown in Figure 2, the descent from peak emissions in the early 2020s is swiftly followed by net zero in the mid-2020s (shown when the '300 x 2050' pathway crosses zero yearly emissions by mid-2024), then steeper cuts of negative emissions are increased until 2030 when the annual rate of negative emissions of Fossil Fuel emissions added to AFOLU reach a total of 47 GtCO_2 yr^{-1} by 2030 and continuing until 2050, then lowered to total to 25.03 GtCO_2 yr^{-1} until 2100.

The experiment lists for comparison the marker SSPs for the SSP 1 storyline of high development of green-growth paradigm: IMAGE SSP1 2.6[5,6] and IMAGE SSP 1 1.9[5,6,7,8]; SSP data from the IIASA Explorer[8]. Due to model calibration differences, the shared-socioeconomic pathways exhibit model variation (and normalized to the tuned model), which resemble but do not directly replicate the temperature and forcing provided by the IIASA despite being generated from the same twenty-three greenhouse gas emissions data respective to each pathway. This variation propagates to all subsequent data analyses, tables, and graphs, such as the Carbon Budget in Figure 1. See the supplemental data section and code repository for raw input files.

scenario	unit	variable \ time	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].

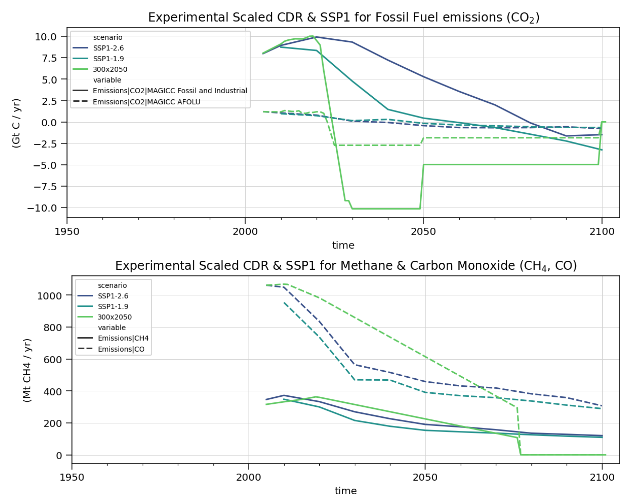

Figure 2 (a-b): Pathways SSP1 2.6[5,6], SSP1 1.9[5,6,7,8], and 300 x 2050 show CO_2, CH_4, CO emissions and emissions reductions starting in 2010 through 2125. Historical emissions through 2020 are included in the pathway '300 x 2050'.

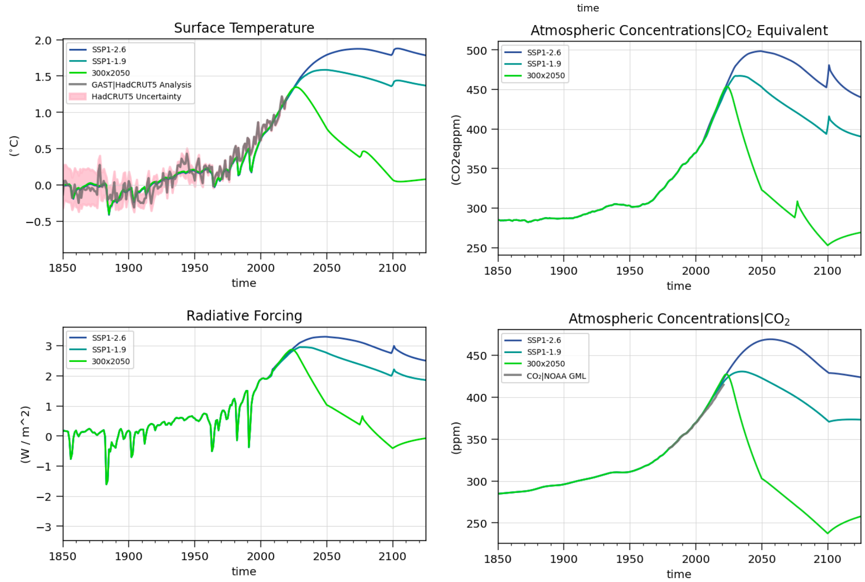

Figure 3 (a-d): Surface Temperature, Radiative Forcing, $CO_{2\text{-eq}}$, and CO_2 for the experimental '300 x 2050', SSP1 2.6 and SSP1 1.9 over the time 1850-2125, also shown in gray are the observational proxies of HadCRUT5 Analysis[14] and the Keeling Curve Global Annual Mean, NOAA GML. [15]All 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 consists of calibrating and tuning MAGICC 6.8[2,3] to match better present near-term temperature, concentration, and emissions data, workaround a land-sink model forcing peculiarity, and run the experiment to generate the novel emissions pathway and simulate it over 1720-2550. Consistent with the SSPs[5,6,7,8], CDR is defined as negative (quantity of) emissions within the experiment parameters and subsequent emissions scenario pathway for model input[2,3]. As MAGICC 6.8 predates large-scale negative emissions, adjunct code was created to demonstrate the CMIP6[17,18] negative emissions tests. The recent anthropogenic carbon dioxide emissions data through 2020 from the Global Carbon Budget 2021[13] was used to calibrate and extend the CO_2 emissions data from 2009 to 2020 and coupled to the novel pathway allowing for 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 average of the last five years, yielding +0.0009ºC for the world region. See *Discussion, Model Temperature Calibration* and *Discussion, Calibration and Regionality* for an in-depth temperature calibration discussion. A rough line-fit to 2015 through 2020 was created from the Keeling Curve Global Annual Mean CO_2 concentration[15], and established error, which under the tuned model yielded +8 ppm above the CO_2 concentration for 2020. These tunings were applied as MAGICC 6.8 was last harmonized with 2010 data. The land-sink workarounds are discussed in *Discussion*, *Accounting of Land Use Change Emissions*. 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 negative emissions test; for more details, see *Equilibrium Climate Sensitivity, Transient Climate Response, and Transient Response to Cumulative CO_2 Emissions.* Negative emissions calibration and verification are covered in *Discussion, MAGICC 6.8 Negative Emissions 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 and 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 decreasing emissions; MAGICC 6.8, which was finalized in 2012, does seem to artificially hold this value high(er than listed[19]) for a few years after a large emissions reduction resulting in 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. To smooth the declining curves for 300 x 2050, all GHGs were declined to phase out by 2077, except ammonia and negative CO_2 (both fossil fuel and land-use change) 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 number 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. Additional details are in the Supplemental Data section.

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, the 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 negative emissions by 2030 that lowers concentration to about 300 ppm by 2050, medium removal to yield a radiative forcing of about 0.0 Wm^{-2} by 2100. The pathway's peak emissions occurred in 2019, where land-use change 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 land use change emissions of -1.36 GtC. The negative emissions rate ramps up to -12.88 GtC by 2030 and held from 2030 to 2050, followed by moderate rates of -6.83 GtC yearly removal until 2100.

Declining emissions rates from the most common twenty fossil-fuel based greenhouse gases[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. Only the industrial GHG 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 Availablity* and *Supplement Information* sections.

Discussion

With high levels of model customization and emissions pathway constraints, the experiment simulated a return to 300 ppm of CO_2 by midcentury and reached radiative forcing (RF) of 0 Wm^{-2} by century's end. To project a high-development sustainable green-growth (zero carbon intensity energy system and economies and ecosystem rehabilitation, preservation and expansion), non-carbon dioxide industrial GHGs emissions (anthropogenic increases over natural ecosystem cycles), including industrial and land-use methane, except ammonia, were fully phased out by 2077. The intermediate target of 300 ppm of CO_2 by midcentury was chosen as it is highly likely to allow a high chance for ecosystems recovery and high quality of life for all of Earth's ecosystems. Earth was last at 300 ppm of CO_2 in about 1913[21]. The novel pathway 300x2050 was designed to achieve a colder global temperature primarily through front-loaded high-scaled removal to 300 ppm of CO_2 followed by moderate removal of all accumulated anthropogenic carbon to reach RF 0 Wm^{-2}, while also nearly linear phase-outs non-CO_2 GHGs. Even highly scaled removal still needed to be applied over decades to completely remove all anthropogenic CO_2 emissions. Linear removal and phaseouts to anthropogenic non-CO_2 GHG completing a couple of decades before (CO_2 removal ends at) 2100 were found to have the least perturbation post-2100. Simulating with calibration, net zero occurs mid-2024; three years later, is peak warming of the global surface mean temperature reaching 1.4195ºC above 1850-1900, keeping below 1.5ºC.

The available computer resources limited the modeling to a reduced complexity model and precluded testing on a more comprehensive Earth System Model (ESM) with a full Atmosphere-Ocean General Circulation Model (AOGCM). Although an ESM model emulator, the reduced complexity model MAGICC was chosen since it has more physics calculations for the atmosphere and ocean, and its results are historically warmer than FAIR's. The simulation was designed to test over the maximum model timeline, which allows a greater extent of reaching equilibrium. The land-sink workaround heuristic tuning specific to MAGICC and land feedback choices set the temperature (to 0.0674ºC) at 2100 and temperature separation post-2100 and before full equilibrium. Given the state of climate modeling and CMIP ESM variability, the rise was seen as an adequate balance to the experiment's previously listed constraints. See *Discussion: Model Temperature Calibration, Calibration and Regionality, ECS, MAGICC 6.8 Negative Emissions Verification and Calibration, Accounting of Land Use Change and Negative Emissions and Asymmetry* for an in-depth discussion on each topic and how they shaped the customizations and constraints to the results.

Extending the experiment '300 x 2050' out to the model limits would evolve an eventual convergence to about 0.07ºC if negative emissions have a nearly symmetrical climate-carbon cycle response [22] and if the simplified feedback was properly tuned. The shading indicates the experiment run with a lower ECS of 2.1ºC and a higher ECS of 4.4ºC, including the medium uncertainty region splitting.

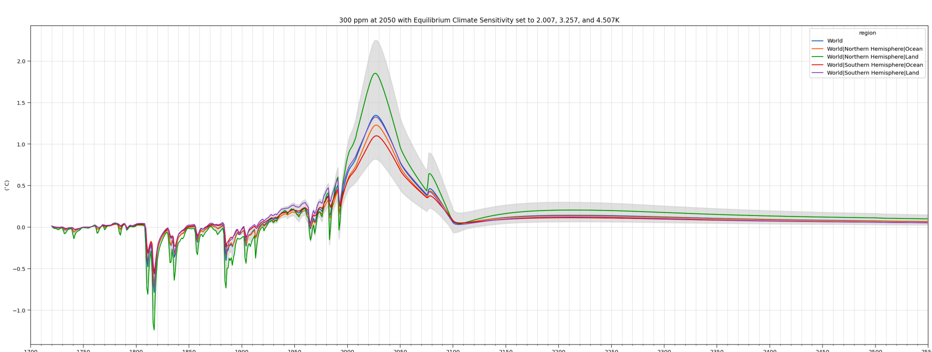

Figure 8: '300 x 2050' pathway with various Equilibrium Climate Sensitivities: 2.01ºC, 3.3ºC, and 4.4ºC from 1720 to 2550 relative to the mean of 1720-1800.

Model Temperature Calibration

When calibrating the Northern and Southern regions for the HadCRUT5 analysis, the model evolved the four basic partitions: Northern and Southern Hemisphere Land and Ocean regions. The model was calibrated to achieve a delta of +0.0009ºC for the world and a little over ±0.18ºC for the northern and southern hemispheres. See *Supplement Data Table 3* for temperature data in tabular form. The calibration to recent temperature forcing and emissions as of 2020 changed the amplitude of the temperature graphs over an untuned configuration. The calibration exercise additionally line fit global CO_2 concentration for 2020 in an attempt to reach 412.44 ppm and match CO_2 concentration per Dlugokencky et al. (2021)[15]. The experimental pathway 300 x 2050 for 2000-2020 reflects a closer match to the temperature and CO_2 evolution for near future dates, such as 2021 was predicted to reach 1.25ºC and a CO_2 concentration of 423.97±8 ppm. This is visually noticeable (see Figure 2) by the divergence of 300 x 2050 from the harmonized SSP1 2.6 and SSP1 1.9 starting about 2015. For an accounting of real-life emissions and temperature modeling, calibrating to the latest emissions, recent historical temperature, and CO_2 concentration data is highly recommended.

Calibration and Regionality

Combining the HadCRUT5 calibration for the world, the regions split between hemispheres, and the CRUTEM5 land dataset[16], MAGICC predicts a temperature evolution lower than the mean of 2015-2020 in CRUTEM5 by +0.15ºC. The northern hemisphere, with the most developed land, experiences the majority of the warming well beyond the other regions; next is the southern hemisphere land, followed by the northern hemisphere ocean, and finally, the southern hemisphere ocean. This ordering is common to all graphed pathways. The regional splitting of these temperature projections has only been compared but not tuned to the CRUTEM5 2021 dataset and not to other ESM data. The northern hemisphere mean temperature for 2015-2020 relative to 1850-1900 for the 300 x 2050 pathway in MAGICC was 1.64ºC and 0.14ºC less than the CRUTEM5 2021 dataset mean (1.78ºC) over the same duration. The southern hemisphere mean temperature for 2015-2020 relative to 1850-1900 for 300 x 2050 pathway in MAGICC was 1.21ºC and 0.15ºC less than the CRUTEM5 2021 dataset mean for 2015-2020 relative to 1857-1900 (1.361ºC).

Given the effect of heat exchange and temperature splitting in each region, and even though temperature evolution for the 300 x 2050 pathway is estimated with high uncertainty and given how long it takes to recover with a high rate of removal, it follows that these next two decades are critical to lowering global temperatures.

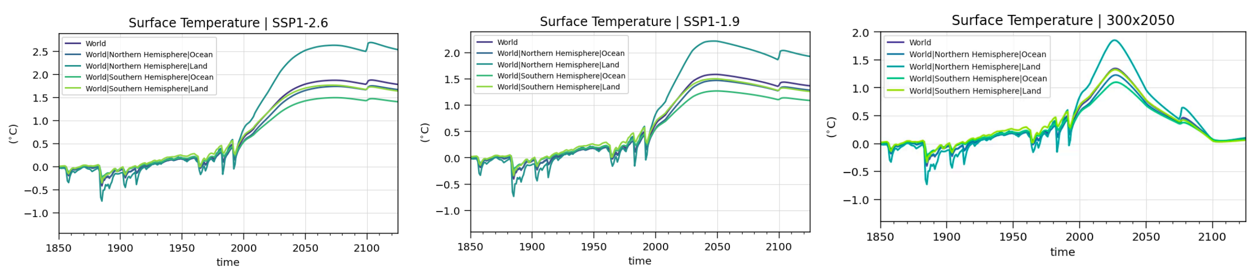

Figure 4 (a-c): Surface Temperature for SSP 1 2.6, SSP 1 1.9, and 300 x 2050, listing the northern, southern, land, and ocean regions, including the world region.

Equilibrium Climate Sensitivity, Transient Climate Response, and Transient Response to Cumulative CO_2 Emissions

```
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 5: MAGICC output listing ECS, TCR, TCRE results, and CMIP6 experiments.

The Equilibrium Climate Sensitivity (ECS) is defined as a doubling or halving of CO_2 concentration over the time global temperature equilibrates. The MAGICC setting for core climate sensitivity (ΔT_{2x}) was raised from the MAGICC 6.801[2,3] initial defaults of 3ºC to 3.257ºC and evolved ECS to 3.24+0.02ºC over 2500 years, with heat exchange tunings to allow for a closer proximal distribution to the hemisphere land regions when considering the CRUTEM5 2021 data and HadCRUT5 2020 data analysis. The effect of tuning to the present-day temperature mean also lowered both the Transient Response to Cumulative CO_2 Emissions (TCRE) to 2.4ºC and the Transient Climate Response (TCR) to 2.1ºC. Despite present-day calibration temperature mean trending initially hotter than lower scenarios, SSP 1 2.6 and SSP 1 1.9, ECS didn't trend significantly hotter. This effect is likely given the shorter duration of increased emissions from the least emitting pathway of 300 x 2050. See Section 3.1 of *Introduction of variable climate sensitivities* in *Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration, 2011*[2] for a more in-depth discussion as it pertains to a model emulator MAGICC 6.8x.

MAGICC 6.8 Negative Emissions Verification and Calibration

The negative emissions verification of MAGICC 6.801 was performed by adapting the supplied pymagicc code to utilize the CMIP6 abrupt-0p5xCO2[18] and 1pctCO2-cdr tests. Once integrated as an adjunct to the pymagicc framework, the experiment generates ECS, TCR, and TCRE by evaluating the standard increasing abrupt doubling of emissions (CMIP abrupt-2xCO2) and the 1% continual increase in CO_2 concentrations (CMIP 1pctCO2) compared to CMIP6 1/2 abrupt drop in CO_2 concentration and negative 1% CDR tests. Calibration is valid if the absolute value of the paired tests and subsequent TCR, TCRE, and ECS are found to be equal. The absolute value of the pairs of the TCR and TCRE were equal, and ECS resulted in a slight difference of about 0.0194ºC and is still an acceptable demonstration of negative emissions given the tests equilibrate over 2500 years.

The CMIP abrupt drop in CO_2 concentration test[18] for MAGICC calibrated to the experiment yielded a -2.59ºC after 150 years in line with IPSL-CM6A-LR (-2.85ºC)[23] and HadGEM3-GC31-LL (-2.210ºC)[24]. See Supplemental Figures I-K for the tuned MAGICC 6.8 model output running abrupt-0p5xCO2 and comparison to several abrupt-0p5xCO2 CMIP6 data series [25,18,23,24,26,27,28,29,30].

When removing all anthropogenic emissions from both fossil fuel emissions and land-use change with the '300 x 2050' pathway, the model was able to achieve 0.07ºC over the mean temperature for 1720-1800 or 0.14ºC over the mean temperature for 1850-1900. The inclusion of cumulative land-use change for removal was unexpected and unanticipated in the author's previous theory[32] paper.

Ocean outgassing is inferred as all fossil fuel emissions had to be removed instead of only the emissions that currently reside in the atmosphere. A removal to roughly realize 302.83 ppm of CO_2 by 2050 (237.85 GtC modeled, compared to (415 ppm - 302.83 ppm) * 2.124 (GtC/ppm) = 238.27 GtC) needed additional removal of 244 GtC to counterbalance the effect of the ocean reestablishing pCO_2 equilibrium (resulted in outgassing), all of which was completed by 2100. The continued removal allowed temperature and CO_2 to recover slowly and finally converge to match preindustrial. CO_2 concentration does drop well below 237 ppm; however, CO_{2eq} only drops below 252.99 ppm, while the global temperature mean never goes lower than 0.04ºC. Ocean upwelling is predicted to return to baseline by 2100 in the '300 x 2050' pathway; see supplemental figure h. The ocean heat exchange, drop in concentration from emissions forcings, N_2O artifact, and GHGs phaseouts introduce enough varying factors to complicate modeling on a reduced complexity model software to merit a more comprehensive understanding of the present-day emissions and temperatures and future evolution of the experiments to be modeled in an entire ESM ensemble.

unit	variable \ time	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
K	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 \ time	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'.

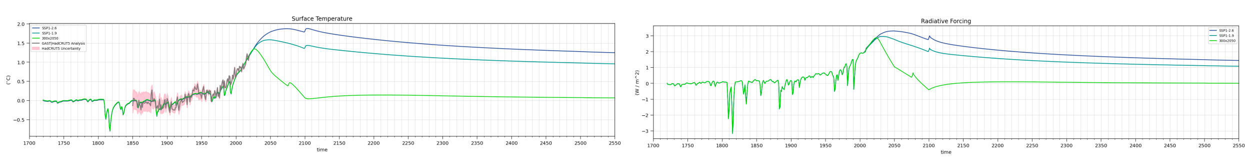

Figure 6 (a-b): Full graphs for Surface Temperature of '300 x 2050' and Radiative Forcing to show '300 x 2050' convergence of about 0.07ºC and Radiative Forcing 0 Wm^{-2}.

Accounting of Land Use Change Emissions

By including the Global Carbon Budget 2021 emissions data, the land-use change emissions forcings diverged from SSP 1 1.9 before 2020, as shown in Figure 7, d. The divergence was unexpected as all emissions data ought to be harmonized by the model to 2005. To work around this modeling behavior, extensive tunings to the heat, hemispheres and soil feedback were applied in addition to removing 42.4 GtC of AFOLU (Land-use change carbon) to match the MAGICC evolved emissions data. The soil carbon feedback was enabled and tuned to allow for positive growth in CO_2 concentration to allow for minimal non-linear evolution to concentration and temperature in the near-term mid-2020s, 2100, and through 2550. The combined effect of tunings and workaround increased the Northern/Southern temperature spread.

Given the mixed effects on the land sinks in the ESM results in *Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2, 2020*[31], but yet slight decreases with the UVIC ESM in *Asymmetry in the climate-carbon cycle response to positive and negative CO_2 emissions, 2021*[22] a very slight, positive rise (0.0674ºC) above 0ºC relative to 1720-1800 was chosen for the post-2100 temperature calibration. This temperature target remained slight to model negative emissions properly.

The author was unable to find guidance on increasing the land sink or a MAGICC 6.8 setting to allow more below-ground mineralization of anthropogenic land-use change CO_2 to remove it from the climate-carbon cycle by removals to the ocean or atmosphere sinks. The author doesn't know if there should be a portion of the cumulative land-use emissions that should have turned over into durable storage of CO_2 in a mineralized form. It was suspected and thus written as such in the theory paper[32] that land-use change emissions shouldn't need to be removed as they are fully in balance, as it were, with the cumulative increases to the land sink since preindustrial. In lack of evidence, this seems in error. However, natural conversion to more permanent storage is a topic open for further investigation.

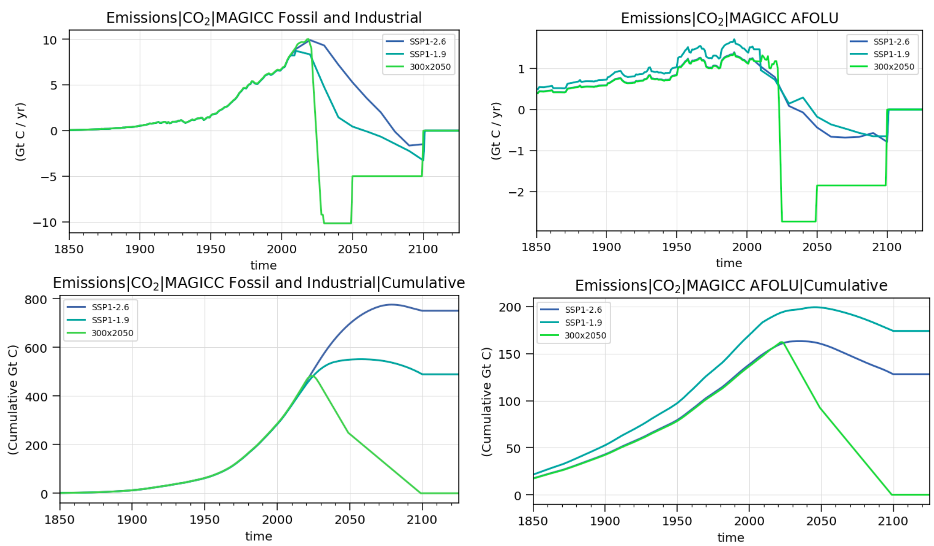

Figure 7 (a-d): Anthropogenic and Land-Use Change Emissions and cumulative emissions data, and CDR decreasing in green.

Negative Emissions and Asymmetry

The 300 x 2050 pathway experiment has a total removal of 644.99+42.2 GtC in negative emissions to match the cumulative anthropogenic emissions. If more land-use change emissions were more permanently contained within the land sink whereby the quantity of negative emissions needed was reduced to about 500GtC, then the removal is within the model ensemble variability of AOGCM model and natural sink uptake studies[22,31,17]. However, if all anthropogenic negative emissions since preindustrial 644.99+42.2 GtC or totaling 2520.4 $GtCO_2$ are needed to reach closer to 0ºC over preindustrial, then a slight quantity more than what was emitted since preindustrial be added to remove all anthropogenic CO_2 emissions. The quantity over 500GtC to determine the magnitude of CDR necessary to match preindustrial temperatures to be completed by 2100 is open for in-depth investigation.

Conclusion

This text outlines starting points for future investigation on pathways more closely matching a preindustrial climate by 2100 over existing literature. Having a team explore the experiment's thesis yet with increases from 1.6x upwards to 1.75x of preindustrial CO_2 concentration[24] driven by forcings from emissions, and removing between 600 GtC or 2198.4 $GtCO_2$ upwards to about 775GtC or 2839.6 $GtCO_2$, with current temperature forcings, and on an extensive model ensemble would best provide more accurate projections of temperature, holding below 1.5ºC, and additional data such as regional temperatures, below ground CO_2 mineralization, sea-level rise and AMOC, ENSO, jet-stream turnover[9,10] evolution over time.

At numerous times, as pointed out in this text, the magnitude of anthropogenic carbon and the present annual accrual rate requires massive remediation efforts, which necessitate the fastest path to net zero, zero emissions, at nearly zero carbon intensity not to exacerbate the existing anthropogenic carbon burden. Given the vast quantity of emissions needed to be removed under such a short time period, it radically limits the amount of near-term emissions allowable and likely is only achievable should we limit emissions to stay well within the carbon budget. Even though removals and phase-outs are agnostic to both technology and implementation, the dual conditions of massive amounts of CDR and achieving 0ºC by 2100 require a total and complete phase-out of fossil fuels over the century. A continued dependency on fossil fuels is unable to yield phase-outs in emissions or the deep removals necessary to achieve the scale and scope to match the preindustrial temperature.

This decade of the 2020s is critical for climate ecosystem remediation and highly-scaled sustainable green growth development, far surpassing previous estimates to limit global warming and associated irreversible climate damages. Human potential is often quoted as limitless; harnessing this audacity can help frame steps required to achieve the near impossible. The possibility of eventually matching the preindustrial climate should help inform the debate to radically accelerate front-loaded, near-term phase-out of anthropogenic emissions sources and scale zero-carbon intensity carbon removals in order 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 Information for additional details.

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Competing Interests

None.

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