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Earth 2075—CO2

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Earth 2075—CO_2
II. Targeting 0°C Global Warming, Ocean pH 8.2, and an Early Return to 280 ppm

Robert Fry, Madeline Ison, Sambhudas Chaudhuri, Steven Fry, Kenneth Klabunde, Michael Routh, Gregory Fry, Barry Wroobel, Steven Hughes, Jeramy Hughes, Grant Gower, Climate Restoration Technologies, Inc. (CRT), USA

Abstract: In this second paper of CRT's EARTH 2075—CO_2 series, revised emissions targets take into account fossil fuel combustion and cement production trends, global change inertia, and developing countries' future energy needs. Global CO_2 emissions are currently ~10 GtC/yr. A 12 GtC/yr cap is recommended by 2023. A realistic schedule for subsequently reducing emissions is recommended—returning to 10.5 GtC/yr by 2030 and cutting to 6 GtC/yr by 2050, 3 GtC/yr by 2062, and 1 GtC/yr by 2078. Our forecasting model assumes developing countries (DC) would moderately burn fossil fuels through 2062 while today's industrial nations compensate with high-impact atmospheric carbon capture, plus offsetting emissions reductions of their own—sufficient to cap global emissions by 2023 and enable the above-targeted reductions through 2062. Developing countries would begin or accelerate their emissions cuts in 2063. Our forecasting model projects emissions cap and reduction impact on the accumulated mixing ratio (ppm) for atmospheric CO_2. Emissions cuts alone are no longer likely to prevent CO_2 from reaching 450 ppm tipping levels. More drastic emergency intervention is required to forestall tipping level crossings and prevent disastrous future consequences, including ≥ 2°C warming accompanied by mega-drought, superstorms, partial polar ice collapse, and abrupt catastrophic sea rise. A new approach involving massively amplified safe capture of atmospheric CO_2 at sea is proposed. This paper establishes open-ocean amplified capture targets and forecasts the beneficial impacts of meeting them. Recommended high impact targets for mid-ocean capture and sequestration of atmospheric CO_2 include contingency for delays and energy to drive multi-stage (land/sea) amplified capture plus extra contingency to offset feedbacks, outgassing, and permafrost thaw-release, which the model didn't anticipate. CRT recommends starting multi-stage short-cycle ocean-amplified carbon capture (OACC) in 2019 and ramping it up to net 10 GtC/yr average CO_2 capture by 2025 across vast mid-latitude, mid-ocean expanses—far out at sea and well away from coastal waters—plus simultaneously compounding benefits of the 12 GtC/yr 2023 emissions cap and above-targeted post-2023 emissions reductions, culminating in 92 percent reduction by 2078. With the sum of OACC plus natural sinks matching capped emissions by 2023 and substantially exceeding reduced post-2023 emissions, accumulated atmospheric CO_2 may be capped at ≤ 425 ppm by 2023 and reduced to 350 ppm by 2050, with an option to restore 280 ppm by 2075 and reduce twenty-first century warming to 0°C. High-impact ocean-amplified carbon capture (OACC) at the rate of 10 GtC/yr could enable DC emissions leniency and still turn 280 ppm atmospheric CO_2, $\Delta T = 0°C$, and ocean pH 8.2 into viable twenty-first century targets that can be met approximately 250 years earlier than with emissions reduction alone—if tropospheric aerosol pollution is concurrently reduced.

Keywords: Climate, Oceans, CO_2, Capture-amplification, Targets, Impacts

Introduction

The first paper of this EARTH 2075 series (Fry et al. 2016) applied a carbon-cycle extrapolation model to forecast atmospheric CO_2 levels assuming neither course correction nor intervention. The model projected 450 ppm CO_2 being reached by 2029, exactly matching IPCC-AR5/RCP8.5 Integrated Assessment Model (IAM) projections (Stocker et al. 2013). If CO_2 rises to, or long exceeds, this projected 450 ppm tipping level, Hansen et al. (2008, 2013) and Cao and Caldeira (2008) anticipate catastrophic climate and ocean impacts, respectively. IPCC, COP21, and Climate Action Tracker (CAT) advocate and/or project temperature-based end-of-century warming limits of ΔT = 1.8°C, ≤ 2°C, or 2.7°C, respectively. Hansen et al. (2015, 2016) offer evidence that these are unsafe targets that would lead to accelerated polar ice collapse, abrupt sea-level rise, and future coastline devastation.

This second paper of our EARTH 2075 series uses the same carbon cycle model (Fry et al. 2016), but proposes a course correction strategy that sets fossil fuel combustion and cement

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production CO_2 emissions cutting targets that are less stringent than those advocated by IPCC, COP21, and Hansen et al. (2015, 2016). Nevertheless, restoration of atmospheric CO_2 to 280 ppm by 2075 and concurrent restoration of preindustrial temperature ($\Delta T = 0°C$) are envisioned here—by implementing a new EARTH 2075 high-impact, short-cycle ocean-amplified carbon capture (OACC) concept while simultaneously reducing emissions.

The combination of emissions control and carbon capture via OACC could enable benefits that substantially exceed targets and aspirations of IPCC (RCP2.6) and the United Nations (COP21, Paris-2015). High-impact mid-ocean OACC capture, ramping up by 2025 and led by today's industrial countries, could safely enable 350 ppm atmospheric CO_2 restoration by 2050, while offsetting and allowing developing countries to burn fossil fuels in moderation to meet energy needs and support economic expansion through 2062. If the developing countries (DC) finally curb their emissions in 2063, combined global emissions control plus ocean-amplified carbon capture could restore 280 ppm CO_2 and ocean pH 8.2 by 2075 and enable restoration of the preindustrial temperature ($\Delta T = 0°C$) before century's end.

This paper sets atmospheric CO_2 capture targets for mid-ocean OACC and models the combined impact of emissions control plus OACC on accumulated atmospheric CO_2, ocean pH, and global surface temperature—illustrating the combined potential to forestall near-term 450 ppm tipping level crossings and setting the stage for preindustrial climate restoration and ocean revitalization before the end of this century. Follow-up papers in the series will detail specific strategies, means, and technology.

Background

The United Nations and COP21 (Paris-2015) have targeted a ≤ 2°C global warming cap, above preindustrial temperature. However, Hansen et al. (2013, 2015, 2016) presented compelling evidence that 2°C warming will not provide safety—in fact, it portends significant danger for future generations. Climate Action Tracker (2015) reported that emissions pledges received by COP21, as of December 2015, would overshoot the 2°C target and result in 2.7°C warming by 2100. Assuming emissions control as a sole course correction, Matthews and Caldeira (2008) calculated that anthropogenic emissions would have to be nearly eliminated for several centuries in order to stabilize global temperature, suggesting that humanity needs something more drastic than emissions control alone.

Emissions from fossil fuel consumption and cement production are approaching 10 GtC/yr (10 billion metric tons carbon per year). Stocker et al. (2013 [IPCC RCP2.6 graph, 94]) recommend reduction of emissions to 3 GtC/yr by 2050. In that case, IPCC's best (RCP2.6) emissions control scenario still peaks at 450 ppm atmospheric CO_2 by midcentury and yields century's-end conditions of 420 ppm atmospheric CO_2, ocean pH 8.05, and 1.8°C of warming (Stocker et al. 2013). IPCC recommends that fossil fuel consumption be eliminated by 2100. Hansen et al. (2008, 2009) and Stone (2013) recommend that coal-fired power plants be even more rapidly replaced with nuclear power by 2030. Hansen et al. (2015, 2016) envision natural sinks and massive reforestation then drawing atmospheric CO_2 down to a "safe" level of 350 ppm by 2100. Targets of 350 ppm and an 0.8°C warming cap were judged achievable by 2100 via stringent emissions control and reforestation. That would provide greenhouse gas (GHG) forcing (warming) deemed necessary to offset anticipated negative forcing (cooling) from tropospheric aerosol pollution projected to develop by 2100. Hansen et al. suggest 350 ppm CO_2 warming will be needed to offset future aerosol cooling and achieve zero net radiative forcing—a condition required for planetary energy balance and climate stabilization.

Eliminating twenty-first-century emissions or cutting ≥ 5% annually may not be realistic for a population > 7 billion, and even less realistic if population reaches 9 billion and energy demand doubles. Restricting emissions to 1–3 GtC/yr by 2050, as recommended by Hansen et al. (2013) and Stocker et al. (2013), respectively, could stifle energy production and economic growth in developing countries. Failure to consider energy needs for future DC economic expansion may preclude full global compliance, especially since the COP21 Paris agreement and associated INDC pledges are not legally binding and IPCC only assigns a 50% probability that its "best" (RCP2.6) targets will be met.

In our opinion, replacement of coal-fired power plants with renewables and nuclear energy, plus overcoming international resistance to nuclear energy expansion, is unlikely to occur in time to avoid near-term 450 ppm CO_2 tipping levels—suggesting that alternative measures may now be required instead. One lesson that can be taken from recent history is that stringent emissions reductions are easier pledged than accomplished.

Our model anticipates global emissions rising 20% through 2023, with a 2023 cap at 12 GtC/yr. We think lack of an observed rise in 2014 (Le Quéré et al. 2015), plus a slight decline in projected emissions for 2015 (McGee 2016), represents a temporary pause in emissions growth caused by short-term stagnation in global economies. Emissions will likely grow again as economic growth resumes. We will not detail numerous global examples of fossil fuel usage growth and resistance to both clean CCS (carbon-capture-and-storage) fossil power and nuclear initiatives, but we take the long view that conventional fossil-fueled energy may not quickly disappear, renewables and/or nuclear power may not quickly replace it, global atmospheric CO_2 may continue rising to 450 ppm, and warming may exceed 2°C (per CAT [2015] projections) if current IPCC and COP21 plans proceed alone. Realistically achievable intervention and emergency course correction are needed—going well beyond emissions control alone.

A viable approach to emissions cuts based on "Stabilization Wedges" was proposed by Pacala and Socolow (2004) and later revised (Socolow 2011), requiring twelve CO_2 emission stabilization wedges, based on existing technology. An immediate-start assumption toward capping emissions at 8 GtC/yr was made by Socolow in 2011. Unfortunately, emissions rates have continued to rise, and they are currently approaching 10 GtC/yr. In 2012, they reached 9.7 GtC (Rapier 2012; McGee 2013), 9.9 GtC in 2013 (Le Quéré et al. 2014), and 9.8 GtC in 2014 (Le Quéré et al. 2015). McGee (2016) projected a slight decline in 2015 emissions, which is unfortunately being followed by a significant rise in accumulated atmospheric ppm CO_2 for the first half of 2016—suggesting that growth may already be resuming.

Revised Targets for 2020 and Beyond

In developing revised targets, we assumed a later start with a significantly higher 12 GtC/yr emissions cap in 2023 than proposed by others. We then targeted reduction to 10.5 GtC/yr by 2030, 6 GtC/yr by 2050, 3 GtC/yr by 2062, and 1 GtC/yr by 2078. This timeline assumes developing countries would moderately consume fossil fuels while meeting growing energy and transportation needs until 2063. Industrial nations would need to compensate by more aggressively reducing fossil fuel and cement CO_2 emissions to yield a combined global cap of 12 GtC/yr by 2023, plus subsequent reductions as indicated above. By 2062, industrial nations should have switched the brunt of energy and fuel consumption to a combination of large-scale, high-capacity clean energy and a significant fraction of future ground transportation being fueled with ultra-clean fossil hydrogen (H_2) produced by CCS natural gas reformation.[1]

By 2062, industrial nations could convert another substantial fraction of ground transportation to electric vehicles for local traffic—increasing grid capacity as needed to support battery recharging. Growing contributions from renewables, e.g., wind and solar energy, are expected, but they do not produce the concentrated CO_2 front-end driver required for OACC, and their combined global contribution may be limited in a doubled twenty-first-century energy-

[1] A follow-up paper will show that concentrated CO_2 captured from CCS coal and gas power production and CCS natural gas reformation (→ fossil H_2 transportation fuel) can be the front-end driver for multi-stage massive secondary atmospheric CO_2 capture amplification by OACC in this new fossil-fueled EARTH 2075 concept.

demand scenario (Stone 2013). We envision CCS fossil energy developing and playing a prominent role through 2070.

Post-2023 emission reductions targeted by this paper would offset the reality of a late start and higher 2023 global emissions cap, yielding emissions similar to Pacala and Socolow's projection of 4 GtC/yr by 2057 (Socolow 2011). We estimate that it will take until 2023 for the largest emissions contributors in today's industrial nations' energy, manufacturing, transportation, and agricultural sectors, combined with global economic, governmental, and consumer will, to find the CO_2 "brakes" and apply them with sufficient force to meet these emissions targets. Massive public education and awareness campaigns, political lobbying, international diplomacy, global planning, and technical and infrastructural preparations will be needed in advance of that start. The COP21 Paris-2015 agreement represents a good beginning towards required emissions control. However, even with determined industrial nations' effort and energy industry cooperation, we believe capping global fossil fuel and cement emissions at 12 GtC/yr, 20% higher than today, may be the best that can be realistically accomplished by 2023.

Matthews and Caldeira (2008) calculated that non-zero emissions scenarios will not stabilize global temperature if emissions reduction is pursued alone. Timely climate restoration requires extraordinary intervention—well beyond emissions control. We, therefore, propose development of a high-impact mid-ocean short-cycle ocean amplified carbon capture (OACC) capacity of 17 GtC/yr atmospheric CO_2 by 2025. This target includes a 40% contingency allowance for foul weather, delays, interruptions, and energy expended to ensure an average net 10 GtC/yr rate of actual OACC capture of atmospheric CO_2 across vast mid-latitude, mid-ocean expanses—far out at sea and well away from coastal waters. If this OACC capture capacity and mid-ocean storage can be safely developed, and our CO_2 emissions cap and reduction targets and schedules are also met, 450 ppm tipping levels can be avoided and atmospheric CO_2 restored to 280 ppm, with ocean pH = 8.2 and $\Delta T = 0°C$ by 2075. These are decidedly more ambitious goals offering greater benefits than other recommendations and consensus targets. Specific means and strategies exhibiting potential for safely meeting these OACC targets will be summarized in a follow-up paper.

Calculations and Assumptions

CRT's forecasting model, based on carbon-budget-cycle trend analysis and extrapolation using successive approximations within a limited CO_2 range, was described earlier and applied to an unchecked (business-as-usual) scenario (Fry et al. 2016). It is applied again here under new modeling parameters that reflect emissions control and high-impact OACC intervention, with empirical CO_2 target selection and iterative target refinement.

Parametric modeling function components are reviewed below, in which PACE is projected annual CO_2 emissions (GtC/yr) from fossil fuel combustion and cement production, N = number of years after 2005, *CSE* is annual combined surface exchange (GtC/yr), and PACA is projected atmospheric CO_2 accumulation in parts-per-million (ppm), by volume. Extrapolation Function-1 only applies to PACE for the unchecked scenario and/or initial series-extrapolation segments in which neither OACC intervention nor emissions reduction is applied. It ignores essentially flat emissions in 2014–2015 (Le Quéré et al. 2015 and McGee 2016), but assumes lower annual acceleration (2.6 percent) than the 3 percent value listed by Hansen et al. (2013). Future *CSE* and PACA are projected by successive approximations using Function-3 or Function-4 and data of the third figure of our earlier paper (Fry et al. 2016). *LASTPPM* is previous year's atmospheric CO_2 accumulation in ppm mixing ratio for a given year in a projection series, iterating forward annually and beginning from the Mauna Loa (Keeling et al. 2013) value of 379.64 ppm in 2005. Function-3 is for the unchecked scenario, or for emissions cap-only, or cap-and-reduce-only scenarios. In Function-4, *CAPT* is the annual OACC capture amount in GtC/yr. Function-4 is for course correction and intervention scenarios involving a combination of emissions cap-and-reduction plus high-impact CO_2 capture by OACC.

PACE = 8.11 x 1.026^N (1)
CSE = (Ocean sinks) + (Land sinks) – (Land-use change emissions) (2)
PACA = (*PACE – CSE*)/2.12 + *LASTPPM* (3)
PACA = (*PACE – CSE – CAPT*)/2.12 + *LASTPPM* (4)

In Functions 3 and 4, *PACE* was redefined to be our revised DC-lenient target values for fossil fuel and cement emissions after 2016, for all except the unchecked emissions scenario. *CSE* values from successive approximation iterations were CSE-II values (see Fry et al. 2016), unless otherwise noted. The corresponding Functions 1–4 above were iterated annually within each projection series.

A CO_2 emissions forecast (curve A) was generated using Function-1 iteratively for $N = 1$ through $N = 52$ for the period 2005–2057 to project the unchecked emissions scenario. An abbreviated section of curve A was plotted in Figures 1 and 2.

An emissions target-cap curve (B) in Figure 1 was generated by retaining the first segment of curve A in the curve B data file to simulate rising fossil fuel and cement emissions through 2016. From 2017–2023, an initially small but progressively increasing deceleration was applied, leveling target projections at the 2020-A value of 12 GtC/yr—flattening at that level by 2023 in curve B. Emissions rise unabated at first to allow time for industrial nations to develop a full global cap on targeted CO_2 emissions by 2023. Given the likelihood of economic recovery, rising energy demand, and impending nuclear plant closures, we believe 12 GtC/yr is a realistic 2023 target.

For post-2023 fossil fuel and cement emissions targets, we propose reductions to 10.5 GtC/yr by 2030, 6 GtC/yr by 2050, 3 GtC/yr by 2062, and 1 GtC/yr by 2078, regardless of future energy demand. These are DC-lenient targets that reflect developing nations' future energy needs. A revised emissions target curve (C) was created for Figures 1–4 by transferring curve B projections into the curve C data file through 2023, entering reduced target values of 10.5, 6, 3, and 1 GtC directly into the curve C data file at 2030, 2050, 2062, and 2078, respectively, and filling in interpolations of interim CO_2 emissions for the years 2024–2077. Constant maintenance target values of 1 GtC/yr were filled in from 2079–2100 and beyond.

Curve C contains target values for fossil fuel and cement CO_2 emissions for the rest of this century and beyond, reflecting rising energy demand to be satisfied through numerous sources with a broad range of carbon footprints before nuclear energy can resume expansion to assume a larger share of emissions reduction as curve C approaches 2065. While we expect renewable energy contributions from wind and solar, Stone (2013) points out that they won't likely absorb doubled energy demand, which is anticipated to develop in the twenty-first century. A combination of nuclear and CCS fossil energy would likely need to play the dominant role in cleanly satisfying doubled energy demand.[2]

For atmospheric CO_2 capture targets, we assume a short-cycle OACC fair-weather capture capacity of 17 GtC/yr, ramped up by 2025 and maintained through 2070, which includes a 40% contingency allowance in order to ensure 10 GtC/yr of actual average net impact OACC capture (*CAPT* in Function-4) and permanent safe storage—a subject to be discussed in our follow-up paper.

Average net impact OACC capture target curve D (Figure 4) was generated by entering the value 10 GtC/yr for *CAPT* as a constant from 2025–2066 into a data file with ramp-up from 2019–2024 and ramp-down from 2067–2076 to an unamplified maintenance capture level of 1

[2] In our follow-up paper, captured CO_2 from CCS fossil energy is proposed as the concentrated front-end CO_2 driver required for multi-stage, massively amplified secondary OACC capture of net 10 GtC/yr atmospheric CO_2 at sea. Means of meeting curve C emissions targets have already been listed in part by Pacala and Socolow (2004) and Socolow (2011).

GtC/yr thereafter, with *PACE* emissions also capped at 1 GtC/yr by 2078. This would allow cement production and fossil fuel combustion to continue, without further planetary warming, within a global limit of 1 GtC/yr emissions through the end of this century and beyond.[3]

In the figures, projected annual CO_2 emissions (PACE) from fossil fuel combustion and cement production are plotted either as curve A for the unchecked emission scenario (Function-1), or curve B for the 2023 emissions cap alone, or curve C for the emissions cap-and-reduction scenario. Unless otherwise noted, the plotting range for projected emissions was from 2010–2100 on the x-axis and 0–17 GtC/yr on the left y-axis, with plot truncation above 17 GtC/yr where that value is exceeded. Targeted short-cycle OACC capture curve D is plotted as absolute-values on the same scale in Figure 4. For curves A–C, we plotted uncorrected point-of-exhaust (POE) fossil fuel and cement emissions in GtC/yr without subtracting *CSE*.

For projections of atmospheric CO_2 accumulation (PACA—mixing ratio [PPM]), we used Function-3 (with Function-1 PACE values) to plot curve A_1 for the unchecked scenario of Figure 2, and with curve-C *PACE* values to plot curve C_1 for the emissions cap-and-reduce-only scenario (Figures 2 and 3)—in both cases with *CSE* and PACA iterated in successive approximations between trial values from the third figure of our previous paper (Fry et al. 2016) and computed Function-3 PACA values related to A_1 or C_1. Atmospheric accumulation projections (PPM CO_2) for curves A_1 and C_1 determined in this manner were plotted for 2010–2100 in the right y-axis range 200–500 ppm CO_2.

For the final emissions cap-and-reduce plus high-impact OACC atmospheric CO_2 capture scenario (Figure 4), we used Function-4 with curve-C *PACE* values to plot curve CD_1—with *CSE* and PACA iterated in successive approximations between trial values from the third figure of our previous paper (Fry et al. 2016) and computed Function-4 PACA values for CD_1, using *CAPT* from curve D. Atmospheric accumulation projections (PPM CO_2) for curve CD_1 determined in this manner were plotted for 2010–2100 in the right y-axis range 200–500 ppm CO_2.

Multiple plots of CD_1 were made as key parameters of its component short-cycle OACC capture curve D were varied with *PACE* emissions maintained at the curve C target condition. Curve D variations of the OACC capture starting year, ramp-up rate, capture amount (*CAPT*), capture duration, capture termination year, and ramp-down curve were iterated until PACA (CO_2 accumulation PPM curve CD_1) peaked early-on with a reasonable margin of safety beneath the 450 ppm tipping level and then steadily diminished to a "soft landing"—stabilizing at 280 ppm CO_2 ppm, and thereby restoring ocean pH 8.2 along with the preindustrial climate, if there is concurrent reduction in tropospheric aerosol pollution—all before 2100. A final forty-five-year curve D plateau value of *CAPT* = 10 GtC/yr net impact from 2025–2070 was selected as the high-impact OACC capture target.

Though a variety of plots were made, and many more are possible, only our optimal target selections for curves C, D, and PPM accumulation impact curve CD_1 (mixing ratio) are plotted here. Owing to a fixed 450 ppm CO_2 tipping level, curve C and D targets should be viewed as inflexible requirements that should be met, regardless of rising energy demand. These targets are deemed achievable and DC lenient, but growing population and rising energy demand will make meeting them a significant challenge—one that will require public acceptance of OACC plus CCS fossil energy and a significant expansion of nuclear energy, in addition to further growth in renewables.

[3] We plot curve D as positive capture, but we subtract it (as CAPT) in Function-4. Note the short-cycle OACC capture curve D (Figure 4) could conceivably be designated "negative emissions," plotted here as the absolute value—but we prefer to call it OACC or simply "capture curve D" instead, representing short-cycle mid-ocean-amplified CO_2 capture (OACC) at sea. This curve D capture rate cannot be achieved through single-stage air-capture or by any single-stage, unamplified means. Multi-stage land/sea massive amplification is required instead to achieve a net 10 GtC/yr capture rate for atmospheric CO_2. We, therefore, prefer to distinguish multi-stage short-cycle mid-ocean OACC at 10 GtC/yr from single-stage unamplified capture systems, which are currently designated as potentially enabling "negative emissions" on a more limited scale of about 1 GtC/yr.

Projections of future maximum GHG warming ($\Delta T_{equilibrium}$, abbreviated here as ΔT_{eq}), above preindustrial, were made using a calibration empirically extracted from an essentially linear segment (200–900 GtC) of the IPCC graph of historical ΔT versus cumulative total anthropogenic emissions, with IPCC multi-model composite future ΔT curve extension (Stocker et al. 2013, 28). The following linear approximation for ΔT projection was extracted from the IPCC curve for the limited range 200–900 GtC cumulative total anthropogenic emissions since 1870:

$$\Delta T_{eq} = X/357 - 0.3 \qquad (5)$$

where ΔT_{eq} is the GHG-induced warming increment (projected equilibrium surface temperature above 1870 era—rounded to 0.1°C) and X is the cumulative total anthropogenic CO_2 emissions (GtC) since 1870. X and any applied OACC subtraction are both on the original point-of-exhaust (POE) basis in Function-5, instead of net airborne basis.

Ocean pH was projected via calibrations extracted from the IPCC-AR5 pH graphs (Stocker et al. 2013) in combination with the Mauna Loa CO_2 historical record (Keeling et al. 2013) and/or the RCP2.6-projection of future ppm CO_2 (Stocker et al. 2013), and/or Figure 3- or Figure 4-projected future CO_2 values for curves C_1 or CD_1.

Results

A Realistic Global CO_2 Emissions Cap by 2023

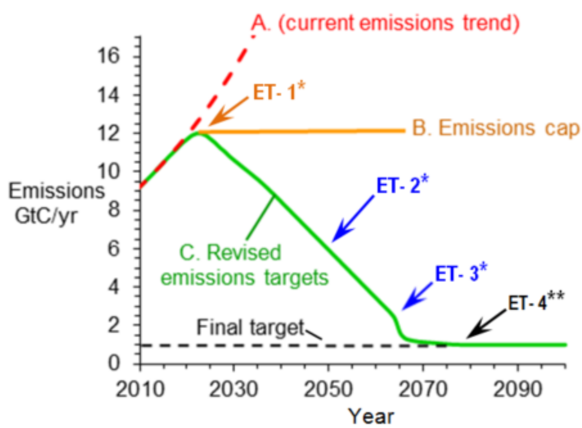

Figure 1: 2023 Emissions Cap (B) and Revised Target Curve (C) for DC-lenient Post-2023 Global CO_2 Emissions Reduction

*ET-1, ET-2, and ET-3 emissions targets to be met primarily by today's industrial nations.
**Final ET-4 target to be met by all nations.

Figure 1 projects rising fossil fuel and cement emissions until 2020 and continued rising emissions in an unchecked scenario after 2020 (curve A). Curve B illustrates one possible cap on fossil fuel and cement CO_2 emissions at 12 GtC/yr. That substantially exceeds our recommended final emissions stabilization target of 1 GtC/yr, but it's a realistic starting point. We, therefore, recommend a 12 GtC/yr cap by 2023 as Emissions Target #1 (ET-1).

Added Course Corrections and a DC-lenient Post-2023 CO_2 Emission Reduction Schedule

Additional control measures that reduce subsequent global CO_2 emissions below the 2023 emissions cap can yield curve C, which decays to 6 GtC/yr by 2050. This is our recommendation for Emissions Target #2 (ET-2).

A massive effort by today's industrial nations (including China), renewables industries, nuclear industries, and future CCS fossil fuel industries will be required to achieve this targeted ET-2 reduction goal for 2050 while permitting developing countries to moderately burn low-cost fossil fuels in the conventional way—during periods of economic expansion through 2062. This ET-2, 2050 milestone (6 GtC/yr) will be especially challenging, in the event of anticipated twenty-first-century doubling of global energy demand (Stone 2013).

Differences between curve C and Pacala and Socolow's (2004) and Socolow's (2011) wedge model are a delayed start, a higher emissions cap (12 GtC/yr) in curves B and C, and faster post-2023 reductions in curve C. Post-2023 reduction enables curve C to match the 4 GtC/yr, 2057 target of Pacala and Socolow. Curve C's 12 GtC/yr cap is also higher than IPCC's RCP2.6 (Stocker et al. 2013) and the preferred scenario of Hansen et al. (2013). Curve C's midcentury ET-2 emissions target of 6 GtC/yr is also less stringent than 3 GtC/yr or 1 GtC/yr—the 2050 requirements of IPCC and Hansen et al., respectively. Curve C targets allow developing nations extra time to reduce carbon emissions.

Humanity's third and fourth CO_2 emissions milestones (see curve C) would be reduction to 3 GtC/yr by 2062 (ET-3) and 1 GtC/yr by 2078 (ET-4). We recommend that ET-1, ET-2, and ET-3 be primarily targeted by today's industrial nations, and we assume developing nations' emissions cuts would begin as late as 2063—nevertheless enabling full global compliance with curve C's ET-4 target of 1 GtC/yr by 2078.

If industrial nations are resistant to the idea of DC-leniency, a viable alternative that would ensure meeting curve C targets would be for the industrial nations to offer sufficient financial and technical assistance to enable CCS conversion of fossil energy technology in developing countries who want to utilize untapped coal and/or gas reserves to support economic expansion. In any case, we believe curve C targets represent the best that can be achieved overall—requiring significant effort and expenditure by all CO_2-emitting countries, especially as the world population grows, economies expand, and energy demand rises accordingly.

Impact of Achieving Targeted Emissions Control on Atmospheric CO_2 Accumulation

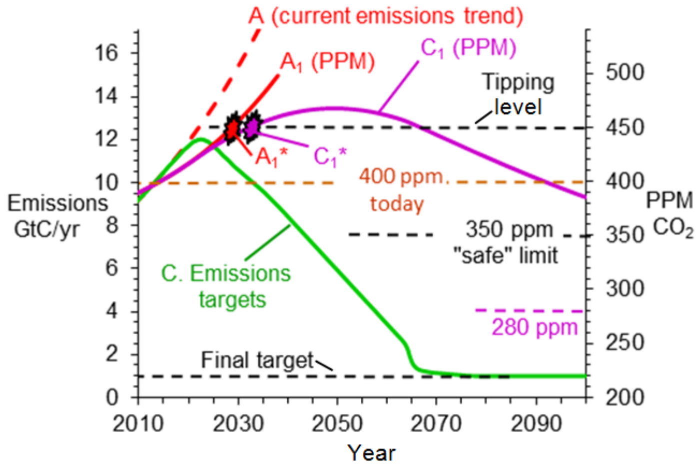

Figure 2: Atmospheric CO_2 Accumulation (ppm, Mixing Ratio) Impact of a Global Emissions Cap and Reduction Program, Alone

Curves A, A_1, and point A_1* are projected emissions (PACE [GtC/yr]), resulting atmospheric CO_2 accumulation (PACA [ppm, mixing ratio]), and the projected 450 ppm tipping level crossing, respectively, for an unchecked scenario. Curves C, C_1, and point C_1* are projected fossil and cement emissions (*PACE* [GtC/yr]), resulting atmospheric CO_2 accumulation (PACA [ppm, mixing ratio]), and the near-term 450 ppm tipping level crossing, respectively, for the revised targeted global emissions cap and DC-lenient emissions reduction initiative alone. (Note: Emissions (curves A and C) are read as GtC/yr from the left y-axis. Accumulated CO_2 (curves A_1 and C_1, plus points A_1* and C_1*) is read as ppm from the right y-axis.)

Figure 2 forecasts the impact of emissions reductions from Figure 1 on atmospheric CO_2 accumulation. Curves A and A_1 closely resemble near-term IPCC-AR5/RCP8.5 projections (Stocker et al. 2013) and show near-term emissions and CO_2 accumulation from an unchecked emissions scenario. Curve C_1 shows the curve C emissions reduction impact on CO_2 accumulation—a significant reduction in long-term ppm CO_2 accumulation (vs. A_1), but unfortunately still quickly exceeding the 450 ppm tipping level (at C_1*) and remaining above it until at least 2067.

Curves C and C_1 loosely resemble IPCC-AR5/RCP2.6 (Stocker et al. 2013) but some disparity arises from IPCC's 9.0 GtC/yr RCP2.6 emissions cap assumption, which is already exceeded. Curves C and C_1 instead assume a 12 GtC/yr cap, to account for recent and pending US nuclear plant closures (with replacement by natural gas [Brinton and Freed 2015]) and our expectation that fossil emissions will likely resume rising as global economies resume expansion following the brief pause observed in 2014–2015 (Le Quéré et al. 2015; McGee 2016).

At 2100, curve C_1 projects 385 ppm CO_2, compared to 420 ppm for IPCC-AR5/RCP2.6. Post-2065 curve C_1 disparity (vs. RCP2.6) may be partly due to differences in projecting longer term CSE, and partly because our model doesn't correct for amplifying feedbacks—thereby possibly exaggerating the post-2065 decline rate of curve C_1.

Otherwise, general resemblance of Figure 2 curves A and A_1 to IPCC RCP8.5 and curves C and C_1 to RCP2.6 suggests that our less sophisticated model yields CO_2 results in proximal agreement with IPCC RCP projections through about 2065—allowing for differences in the assumed emissions caps, allocated emissions targets, and emissions reduction schedules, especially for developing countries.

Whereas the IPCC-RCP2.6 emissions curve yields projected end-of-century warming of 1.8°C above the 1870 temperature (see Stocker et al. 2013, 28, Figure SPM.10), adding the cumulative total emissions that we project from curve C to the historical accumulation (1870–2010) reported in IPCC Figure SPM.10 enables Function-5 to project end-of-century warming of

2.2°C for curve C emissions control alone. This end-of-century differential (2.2°C vs. 1.8°C) might initially be viewed as the "warming price" of DC leniency in the case of emissions control alone. However, adding short-cycle high impact OACC, to dramatically reduce late-century warming to 0°C, will later be seen to justify this leniency and to validate our use of this short-range carbon-cycle extrapolation model through 2075 (in Figure 4)—without need of amplifying feedback correction.

Figure 3 extends the C_1 accumulation plot another fifty years to show that CSE-II sinks won't draw atmospheric CO_2 down to 350 ppm until at least 2135 in a cap-and-reduction-alone scenario. CSE-I sinks would be somewhat more favorable, but a CSE-I scenario seems unlikely (see Fry et al. 2016). Restoring 350 ppm via IPCC-AR5/RCP-2.6 would take far longer than 2135 (Stocker et al. 2013), and the already impending 2020–2030 delayed-start scenarios warned against by Hansen, et al. (2013—see Hansen Figure 5B in "Assessing 'Dangerous Climate Change': Required Reduction of Carbon Emissions to Protect Young People, Future Generations, and Nature") could actually push Hansen's preferred century's-end (2100) restoration of 350 ppm CO_2 out as far as 2300–2500, with significant extra warming.

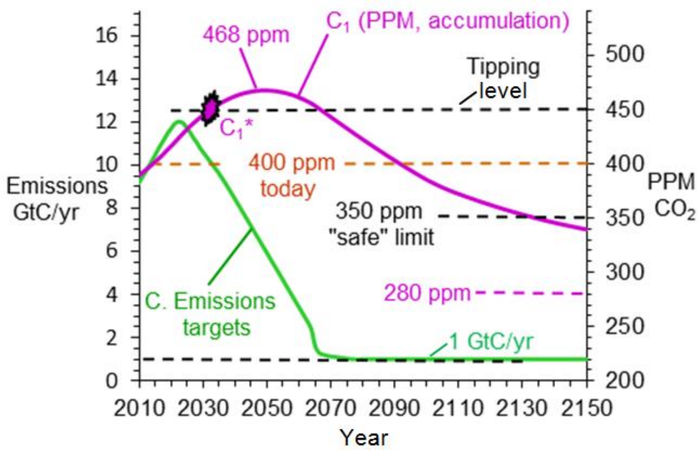

Figure 3: Same as Figure 2 with Time Extension to 2150 (Omitting Curves A and A_1)

Note that PPM accumulation curve C_1 crosses the 450 ppm tipping level by 2034 (see C_1*) and remains above it for thirty-three years for the emissions cap and reduction initiative alone. The "safe" CO_2 level of 350 ppm targeted by Hansen et al. (2008, 2009, 2013, 2015, and 2016) isn't restored until 2135 (under CSE-II sink conditions). Note: The extent of *CSE* extrapolation using successive approximations was limited to 19% for the 450 ppm crossings and 26% for the 468 ppm C_1 peak projection.

Figure 3 suggests that at least another two centuries may be required before the post-2023 emission reductions of curve C alone would enable CSE-II sinks to draw atmospheric CO_2 accumulation (C_1) down to 280 ppm—and perhaps considerably longer yet, if amplifying feedbacks were included. A Function-5 calculation indicates that this curve C and C_1 emissions-control-only scenario would result in 2.2°C maximum warming by 2100.

Emissions-control-only scenarios would likely irreversibly seed catastrophic climate and ocean impacts. With a realistic curve C emissions cap at 12 GtC/yr, Figure 3 forecasts an early (C_1*) crossing of the tipping level, at least 147 years spent above the 350 ppm level (since 1988), and the prospect of extended heat waves, protracted drought, crop failure, famine, partial polar ice collapse, catastrophic sea rise, coastal flood, wildfires, and weather extremes.

Because of a relatively late start applying course corrections, lowering fossil fuel and cement emissions alone while relying solely on natural (CSE) sinks to gradually reduce atmospheric CO_2 accumulation would appear insufficient—now requiring more drastic global course correction and high-impact intervention to avoid tipping levels, restore climate, and revitalize oceans while stabilizing polar ice and the global sea level.

Lowering CO_2 Emissions and Capturing CO_2 at the Same Time

Our model strongly suggests implementation of a large scale atmospheric CO_2 capture strategy, targeting capture and storage of net 10 GtC/yr by 2025, in concert with meeting emissions cap and reduction targets discussed earlier.

Figure 4 combines our recommended CO_2 emission cap-and-reduction targets (curve C) with a mid-ocean short-cycle ocean-amplified carbon capture (OACC curve D) target of 10 GtC/yr. Figure 4 curve CD_1 modeling projection of the impact of implementing both items concurrently suggests that the combination of OACC plus emissions control would act fast enough to narrowly avoid the near-term 450 ppm tipping level and then complete CO_2 drawdown to 280 ppm, achieving climate restoration before 2075—a time frame and CO_2 range where forecasting errors due to amplifying feedbacks would likely be minimized.

OACC capture would match net airborne emissions (not shown) by 2023, ten years prior to the point where curve D capture matches uncorrected emissions curve C in 2033. High-impact short-cycle OACC capture would actually surpass net airborne emissions after 2023 and surpass uncorrected emissions after 2033.

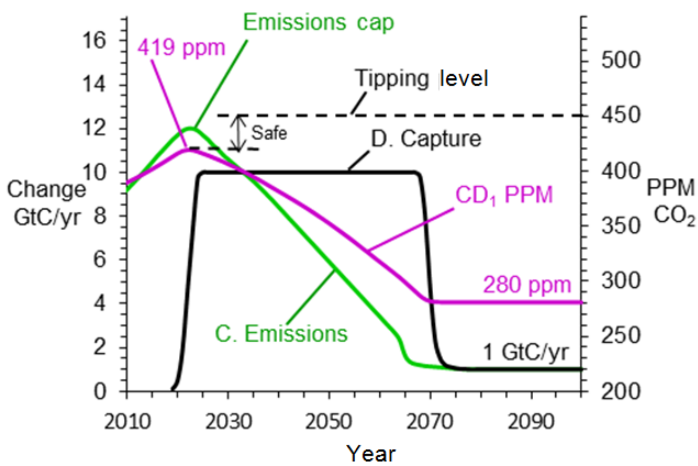

Figure 4: Recommended Mid-ocean Short-cycle OACC, CO_2 Impact Capture Target Curve D (GtC/yr—Absolute Value Plot) and Its Atmospheric Accumulation Impact Curve CD_1 (PPM) of Performing CO_2 Emission Cap and Reduction According to Target Curve C While Concurrently Capturing CO_2 by OACC According to Curve D.

Figure 4 assumes an ideal world with repetitive mid-ocean short-cycle OACC capture and no unexpected problems or delays. Accordingly, curve D is net impact capture of CO_2 at the amplified rate of 10 GtC/yr. Curve C is illustrated as uncorrected global CO_2 emissions (GtC/yr) because readers may be most familiar with those terms. CSE extrapolation via successive approximations for 419 ppm CO_2 was limited to 11 percent. Curve CD_1 (PPM) represents our final recommended target and schedule for reduction of ppm atmospheric CO_2.

Atmospheric CO_2 Accumulation Impact of Doing Both Simultaneously

Figure 4 forecasts the impact on CO_2 accumulation (curve CD_1) of directly capturing and storing CO_2 with a massively amplified mid-ocean short-cycle OACC capacity of net 10 GtC/yr of atmospheric CO_2 (per curve D) while concurrently capping and reducing fossil fuel and cement CO_2 emissions according to curve C.[4] Atmospheric CO_2 accumulation curve CD_1 is the differential between a net-airborne-corrected version (not shown) of curve C and curve D, expressed in ppm, essentially subtracted from the previous year's accumulation (after 2023), and

[4] It is important to note that the entirety of curve CD_1 in Figure 4 remains below 425 ppm CO_2 and stabilizes at 280 ppm by (or before) 2075. This means the extent of CSE extrapolation using successive approximations in generating Figure 4 was less than 13%, and amplified feedbacks may be safely neglected in this EARTH 2075 curve CD_1 (OACC + emissions control) scenario.

iterated annually using Function-4 and CSE/PACA successive approximations (see Fry et al. 2016).

Curve CD_1 indicates atmospheric CO_2 accumulation would be capped at 419 ppm by 2023 and reduced to 280 ppm by 2075—by combining DC-lenient emissions reduction, CSE-II natural sinks, and net 10 GtC/yr mid-ocean short-cycle ocean-amplified CO_2 capture (OACC). After rising to 419 ppm by 2023, atmospheric CO_2 accumulation would return to today's level of 400+ ppm by 2033 and to Hansen et al.'s recommended 350 ppm "safe limit" by 2050. It would reach our 280 ppm target by 2075. Combined with emissions control, global scale OACC capture makes 280 ppm atmospheric CO_2 a viable twenty-first-century target (see curve CD_1).

ΔT_{eq} and Ocean pH for OACC-based Curve CD_1—and the Case for DC Leniency

Curve CD_1 suggests that OACC would mitigate the "warming price" otherwise (earlier) suggested as the cost of DC leniency in the case of emissions control alone. The Function-5 end-of-century accumulated warming projection for the Figure 4 combination of OACC + DC-lenient emissions control is $\mathbf{\Delta T_{eq} = 0°C}$. That's well below ΔT_{eq} = 2.2°C as projected for emissions control alone in Figures 2 and 3. It's also well below Hansen et al's preferred ΔT_{eq} = 0.8°C, IPCC's RCP2.6-projected ΔT_{eq} = 1.8°C, COP21-targeted $\Delta T_{eq} \leq 2°C$, and CAT-projected ΔT_{eq} = 2.7°C.

Our calculations also suggest that OACC-accelerated restoration of 280 ppm CO_2 would yield ocean pH 8.2 restoration by 2075, about two centuries sooner than emissions control only scenarios, and substantially better than the IPCC-RCP2.6 best-case forecast of ocean pH 8.05 in 2100, or ocean pH 8.12 corresponding to the 350 ppm CO_2 target of Hansen et al. (2008, 2009, 2013, 2015, 2016).

The case for DC-lenient emissions control—allowing developing countries extra time to reduce carbon emissions, and/or requiring financial assistance enabling them to develop and utilize CCS fossil energy—is based on GHG sourcing and accumulation history, plus international economic realities. However, our model suggests that implementing OACC and DC-lenient emissions control would also enable near-term 450 ppm CO_2 tipping level avoidance, 350 ppm restoration by 2050, 280 ppm and ocean pH 8.2 restoration by 2075, and a GHG warming projection of ΔT_{eq} = 0°C by the end of this century—considerably more desirable outcomes than the emissions-control-only scenarios/projections of IPCC, COP21, and CAT, or remediation scenarios of Hansen et al. (2013).

Short-cycle Ocean-amplified CO_2 Capture (OACC) Could Sharply Accelerate Climate Restoration and Ocean Revitalization

The benefits of combining emissions cap-and-reduction plus high-impact short-cycle ocean-amplified carbon capture are compelling—restoring 350 ppm CO_2 at least eighty-five years sooner than emissions cap-and-reduction alone, and restoring 280 ppm more than 250 years sooner. Early restoration of 280 ppm atmospheric CO_2 and ocean pH 8.2, plus lowering the accumulated GHG warming component to ΔT_{eq} = 0°C could have profound beneficial implications for stabilizing polar ice, sea level, and climate, plus revitalizing oceans. Mega-drought and an era of superstorms might also be minimized or forestalled by combining emissions control and OACC capture.

Should the Twenty-first-Century Target be 350 ppm or 280 ppm CO_2?

Hansen et al. (2008, 2013, 2015, 2016) detailed a planetary radiant energy balance argument in support of a 350 ppm CO_2 target, proposing to restore 350 ppm by 2100 via a 100 GtC reforestation drawdown of atmospheric CO_2 plus 6% annual emissions cuts starting in 2013. While acknowledging positive twenty-second-century radiative forcing (residual warming) from 350 ppm CO_2, Hansen et al. also forecast offsetting negative forcing (cooling) from tropospheric aerosol pollution. They suggest 350 ppm CO_2 would provide warming needed to offset cooling from future aerosol pollution, thereby eliminating planetary energy imbalance, yielding zero net radiative forcing, and stabilizing climate by 2100—assuming 6% annual emissions cuts had actually begun in 2013 as Hansen et al. target.

We believe targeting 350 ppm restoration by 2100 would be too late for preventing partial polar ice collapse or catastrophic sea rise. That target also neither reflects significant delays in emissions cuts that have already occurred in Hansen et al.'s schedule, nor anticipates significant resistance to stringent emissions cutting targets that is likely to arise in developing countries that were planning to burn fossil fuel reserves to aid their future economic growth.

Had 6% annual cuts actually begun in 2013, starting from 9.7 GtC in 2012 (Le Quéré et al. 2015), emissions would have reduced to 8.1 GtC through 2015 as first steps required toward Hansen's targeted reduction to 1 GtC/yr by 2050. Instead, emissions remained ≥ 9.7 GtC/yr (Le Quéré et al. 2015; McGee 2016)—suggesting significant schedule slippage has already occurred in Hansen et al.'s preferred plan. Figure 5B (Hansen et al. 2013) illustrates the projected impact of delaying Hansen's start of reductions until 2020 and reducing annual emissions cuts to 5%—collectively pushing projected 350 ppm restoration to 2300. In our opinion, a > 2020 start delay will likely occur. In fact, our curve C projects a 20% emissions rise through 2023. Delaying Hansen et al.'s remediation start until 2030 pushes 350 ppm restoration out to 2500 in the Hansen Figure 5B. Hansen's current and pending delays unfortunately remind us that global warming reality historically outpaces humanity's best-laid remediation plans and intentions.

Restoring 350 ppm by 2100 via 6% annual emissions reduction appears to be overly optimistic—even assuming improved agricultural practices and 100 GtC worth of reforestation. The best IPCC scenario (RCP2.6) projects 420 ppm by 2100 for emissions-control-only, with only 50% probability of achieving that target. Without feedback correction, our curve C_1 scenario projects 385 ppm at 2100, but it also indicates delay of 350 ppm restoration until at least 2135. Current delays suggest that 350 ppm restoration by 2100 is likely no longer achievable without OACC.

Hansen et al. (2015, 2016) warn that ≤ 2°C warming targets of IPCC and COP21 represent dangerous warming levels that elevate risk of partial polar ice collapse, abrupt catastrophic sea rise, and superstorms similar to those experienced c.a. 120,000 years ago during the Eemian interglacial warm period, when ΔT_{eq} rose to 1.9°C because of orbital forcing. We concur—adding that 350 ppm and ocean pH 8.12 may also be dangerous targets—especially if delayed until 2100, or centuries longer yet—owing to Hansen et al.'s (now impending) Figure 5B start delays. We think a more aggressive goal of 280 ppm CO_2 and ocean pH 8.2 restoration by 2075 is warranted, via the bold combination of emissions control + OACC, yielding ΔT_{eq} = 0°C and restoring preindustrial conditions before 2100.

However, considering Hansen et al.'s (2013, 2015) compellingly-argued importance of restoring planetary energy balance without overshooting in the cooling direction, we suggest periodic reassessment of tropospheric aerosol pollution and residual planetary radiant energy during the curve CD_1 drawdown to 350 ppm CO_2 (by 2050), and curbing aerosol pollution accordingly before proceeding with additional CO_2 drawdown—taking note that reducing tropospheric aerosol pollution and restoring ocean pH 8.2 (corresponding to 280 ppm atmospheric CO_2) represent eminently worthy goals in themselves.

Although we don't dispute the advisability of rebalancing planetary radiant energy, we believe emissions control plus OACC-based climate restoration, lower temperature (ΔT_{eq} = 0°C), more aggressive polar ice stabilization, ocean pH 8.2 restoration, and sea-level stability comprise compelling arguments for 280 ppm as the best target for rebalancing twenty-first-century planetary radiant energy—assuming concurrent reduction in tropospheric aerosol pollution.

We believe these targets and aspirations are appropriate and desirable, provided that humanity is willing to commit resources for implementing CCS fossil energy and OACC capture of 10 GtC/yr, required to drive twenty-first-century restoration of 280 ppm—the preindustrial CO_2 concentration (Etheridge et al. 1996). However, with IPCC or COP21 INDC emissions-cutting pledges alone, 450 ppm tipping levels will not be averted and neither 280 ppm nor 350 ppm can be restored during this century. In that case, it would be unlikely that mankind could prevent partial polar ice collapse and abrupt catastrophic multi-meter sea rise in the late twenty-first or early twenty-second century.

Discussion

What if These Targets Aren't Met?

If humanity only meets the emissions control targets of curve C in Figures 1–3, without implementing OACC, atmospheric CO_2 would exceed the 450 ppm tipping level by about 2034, peak at 468 ppm by 2050, and remain above 350 ppm until at least 2135—essentially the IPCC and COP21 emissions control alone scenario. Corresponding warming would be 1.8°C–2.2°C by 2100, or as much as 2.7°C as projected by Climate Action Tracker (2015), based on INDC pledges received in December 2015 toward the COP21 target. Emissions control alone would increase risk of irreversibly seeding catastrophic climate and ocean impacts with an early crossing of the tipping level, at least 147 years in the energy imbalanced warm range above 350 ppm CO_2, and the prospect of extended heat waves, protracted drought, crop failure, famine, wildfires, and weather extremes—with significant risk of partial polar ice collapse and abrupt multi-meter global sea-level rise in the late twenty-first or early twenty-second century. We review several examples below of why catastrophic impacts would likely occur if these targets aren't met.

Superstorms, Abrupt Sea Rise, Flooded Coastal Cities, and Accompanying Economic Devastation from Missed Targets

Kopp et al. (2009), Dutton and Lambeck (2012), and Hansen et al. (2015, 2016) summarized what happened the last time Earth warmed by 1.9°C about 120,000 years ago during the Eemian interglacial warm period preceding the last ice age. Eeemian warming via orbital forcing, cited by Hansen et al. as warming nominally 1.9°C above Earth's 1870 temperature, essentially matches the twenty-first-century warming caps currently being targeted by IPCC-AR5/RCP2.6 (Stocker et al. 2013) and COP21 (Paris-2015). Eemian-period seas rose gradually at first and then abruptly five to nine meters in several stages—the latter occurring within decades. The resulting high seas lasted thousands of years.

Multi-meter Eemian sea rise was attributed to warming-induced abrupt partial mechanical collapses of ice sheets in Antarctica and Greenland—following earlier extended periods of slower melting. Hansen et al. (2016, 3761) emphasized that "ice mass loss [in response to warming] from the most vulnerable ice, sufficient to raise sea level several meters, is better approximated as exponential than by a more linear response."

This suggests Eemian paleoclimatic history may provide a better predictor of late twenty-first-century warming impact, relating to potential sudden mechanical collapse of vulnerable ice sheets and abrupt several-meter rise in sea levels, as opposed to the gradual linear melt rate that IPCC now extrapolates to project only one foot of sea rise by 2100. Although collapsed Eemian ice sheets later reformed during the last ice age, the same sheets are once again at risk of modern collapse—this time induced by GHG warming. Today's gradual but accelerating polar-ice melting rates and corresponding observations of gradual sea rise are deceptively small, but early warnings of impending nonlinear (abrupt) late twenty-first- or early twenty-second-century ice sheet collapses in Greenland, West Antarctica, and parts of East Antarctica have already been reported (Rasmussen 2014; Rignot 2014; Rignot et al. 2014). These abrupt mechanical collapses would yield multi-meter sea rise paralleling the paleoclimatic Eemian warm period events.

Sparse coastal human populations in Eemian times would have likely responded to rising seas by moving further inland. However, late twenty-first-century adaptation to abrupt sea rise would be difficult, given that approximately 50% of the world's 7-billion-plus population and about 50% of the world's economy currently reside on the coasts. In a crowded industrial world, the modern economic impact of abrupt permanent three to thirty foot sea rises would be devastating—even with the rises occurring in several stages.

Hansen et al. (2016) also cite evidence of intense Eemian era superstorms. Abrupt stepwise three to thirty foot modern sea rise, submerged coastal cities, superstorms, and associated economic damage could be late twenty-first- or early twenty-second-century consequences of meeting curve C—but failing to meet the OACC-based curve D and CD_1 targets of Figure 4, and of the resulting 1.8°C–2.2°C warming. Hansen et al. (2015, 2016) convincingly argued that IPCC and COP21 targets of 1.8°C–2°C are dangerously unacceptable warming caps. We concur, but we think targeting 350 ppm CO_2, via emissions control alone, would occur too slowly to forestall catastrophic climate and ocean impacts.

Contingency

Ocean-amplified carbon capture and its beneficial impact on curve CD_1 atmospheric CO_2 accumulation assume 10 GtC/yr of net impact capture, yielding a total OACC capture of 475 GtC by 2075. To achieve that, our follow-up paper will recommend global-scale mid-latitude mid-ocean nutrient supplementation plus species-selective short-cycle, high-density, mid-latitude ocean algal seeding, with seeding initiated at an unusually high point on the nonlinear algal growth curve to collectively, and selectively, accelerate heavier-than-water algal species blooming. Seeding would take place far out at sea—well away from coastal waters to safely achieve the required massive OACC amplification effect. Those conditions are projected to avoid a variety of classic problems such as inadequate bloom rate, neurotoxic blooms, persistent floating light blockage by mature (or dead) blooms, and post-bloom anoxia (only observed in coastal waters)—plus alleviating other concerns associated with fertilized ocean blooming.

Assuming 100% success with no schedule slippage wouldn't be realistic for a global-scale endeavor. A substantial contingency margin that addresses and offsets delays, interruptions, foul weather, planetary feedbacks, outgassing, permafrost thaw release, extra land-use change emissions offsets, and other unexpected influences is, therefore, required. Extra CO_2 capture allocation is also needed to offset project-related consumption of conventional fossil transportation fuels during early (pre-H_2 fueling) years of mid-ocean short-cycle OACC seeding.

Accordingly, three levels of contingency are envisioned for successfully implementing OACC. The first is development of a 17 GtC/yr "fair weather" OACC capture capacity—to ensure net 10 GtC/yr of actual capture. The second optionally adjusts timing of the trailing edge of curve D to create a 10–30 year extra OACC capture duration beyond the curve D period in Figure 4. At 10 GtC/yr of net OACC capture, an extra thirty years would yield 300 GtC of additional (optional) CO_2 capture capacity to compensate for unexpected outgassing, permafrost thaw release, and other amplifying feedbacks. The third contingency level provides up to 3 GtC/yr unamplified post-2070 maintenance capture following the 10 GtC/yr OACC period—thereby anticipating emissions reduction schedule delays. These three levels add up to a planned overall OACC contingency of approximately 80%.

Conclusions

Continuing on an unchecked (business-as-usual) emissions path would lead to atmospheric CO_2 rising to 450 ppm tipping levels by 2029, with a very high risk of irreversibly seeding catastrophic impacts. We think the lack of observed emissions rises in 2014–2015 was a temporary pause in emissions growth. We believe emissions growth will resume as economic expansion resumes. Capping CO_2 emissions by 2023 and implementing curve C reductions would merely delay the 450 ppm tipping level crossing by five years, if it's the only course correction applied, and it would not prevent adverse climate change, partial polar ice collapse, or catastrophic multi-meter sea rise. Without OACC, Hansen et al. have shown that even a massive reforestation drawdown would not restore 350 ppm until about 2300, or even 2500, if accompanying stringent 5% or 6% annual emissions cuts alone are delayed until 2020 or 2030, respectively—which seems likely.

Hansen's pioneering assessment of future climate risk has inspired and guided our thinking, as we are sure it has for many others. However, humanity has delayed implementing his insightful solutions to the point where, in our opinion, the risk of continued start delay (according to Hansen's Figure 5B projections) grows too great and his timeline for correspondingly delayed CO_2 drawdown then becomes unacceptably long, with impending catastrophic consequences already appearing more likely with each passing year that extends delayed start for Hansen's plan. The 6% annual emissions reduction rate Hansen et al. recommend is also increasingly untenable, in our view, in a twenty-first-century economic expansion scenario, clearly suggesting the need to implement aggressive atmospheric CO_2 capture to complement more realistic emissions cuts.

Global-scale ocean-amplified CO_2 capture (OACC), in conjunction with realistic DC-lenient emissions control, has the potential to cap Earth's atmospheric CO_2 accumulation at $\leq$ 425 ppm in 2023, avoid the near term 450 ppm tipping level, restore 350 ppm by 2050, and ultimately restore 280 ppm CO_2 by 2075—if tropospheric aerosol pollution is concurrently reduced.

The combination of OACC + DC-lenient emissions control makes 280 ppm atmospheric CO_2, ocean pH 8.2, and $\Delta T = 0°C$ viable twenty-first-century targets. Achieving these targets could have profound implications for revitalizing oceans, stabilizing polar ice, preventing abrupt catastrophic sea rise, and minimizing or forestalling a variety of other potentially catastrophic climate and economic impacts.

The unanswered question is: *Will humanity commit to this challenge?*

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Appendix

A Schedule of Combined CO_2 Emissions, Short-cycle OACC Capture,
Atmospheric CO_2 Accumulation (ppm), Ocean pH, and GHG-related ΔT Milestones

2017	Emissions control begins. GHG warming is currently $\Delta T_{actual} = 1°C$. Ocean pH 8.07
2019	Ocean-amplified carbon capture (OACC) scale-up commences
2023	A. 12 GtC/yr fossil fuel and cement emissions cap → Emissions Target ET-1 B. OACC capture and natural sinks (CSE-II) reach 12 GtC/yr (combined removal) C. ≤ 425 ppm atmospheric CO_2 accumulation (mixing ratio) cap D. Ocean pH 8.05 (lowest average pH in millions of years) E. 450 ppm tipping level crossings *safely forestalled*
2025	A. 10 GtC/yr net impact OACC capture and safe storage achieved B. Amplified capture and CSE sinks (combined) exceed decreasing emissions C. Concurrent tropospheric aerosol pollution reduction begins
2030	10.5 GtC/yr emissions (reduced since 2023)
2035	A. 400 ppm CO_2 (today's value) restored B. Ocean pH 8.07
2050	A. 6 GtC/yr emissions (halved since 2023) → Emissions Target ET-2 B. 350 ppm CO_2 restored C. Ocean pH 8.12 D. Tropospheric aerosol reduction accelerates. (Re-assess before proceeding.)
2062	3 GtC/yr emissions (halved again) → Emissions Target ET-3
2063	Today's developing nations join the global emissions reduction effort
2067	OACC capture program commences ramp-down from 10 GtC/yr[a]
2075	A. 280 ppm CO_2 restored B. Ocean pH 8.2 restored C. GHG warming projection drops to $\Delta T_{eq} = 0°C$ D. Tropospheric aerosol pollution is correspondingly reduced E. Global respiratory distress reduced and public health improved
2078	A. 1 GtC/yr emissions target reached (maintenance level) → Emissions Target ET-4 B. Atmospheric CO_2 capture relaxes to 1 GtC/yr maintenance[a] (no amplification)

These are the combined targets and milestones CRT recommends for climate restoration via elimination of excess atmospheric CO_2. Ocean pH is regulated by atmospheric CO_2. Ideal preindustrial ocean pH 8.2 will automatically be restored as atmospheric CO_2 returns to 280 ppm.

[a]OACC capture duration may be extended, as needed, for up to thirty years more—to offset up to 300 GtC of otherwise uncompensated feedbacks, outgassing, and/or permafrost thaw-release. Recommendations to future generations: Reduce tropospheric aerosol pollution and reassess it (and ΔT) in 2050 before drawing CO_2 down below 350 ppm. Maintain 10 GtC/yr (net impact) OACC capture until atmospheric CO_2 drops to 290 ppm. Then commence ramp-down of capture to 1 GtC/yr maintenance level.

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