Climate Change Status Check

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Summary

The recently signed COP 21 Paris Agreement calls for all nations to work towards keeping the global temperature rise this century to well below 2°C above pre-industrial levels and to strive to limit the temperature increase to 1.5°C. But if the current atmospheric concentration of greenhouse gases (about 450PPM CO2e) were to be maintained as coal use declined to zero, we would very likely see about 2°C of warming. So the only way to meet the "well below 2°C" target is to remove the CO2 equivalent of all future greenhouse gas emissions from the atmosphere. And to meet the 1.5° C target would require removing enough CO2 to reduce the atmospheric content of CO2 to about 350 PPM. The prevailing assumption is that we will be willing (and able) to spend whatever it costs to meet the Paris Agreement targets because anything more than that will likely be disastrous for our civilization. Giving up on that goal is then equivalent to condemning future generations to a planet that is inhospitable to civilization as we know it, and this may be the reason that very few people openly acknowledge our predicament. But a closer look expected costs (likely over $200 Trillion this century) shows that we have a very daunting (and almost certainly insurmountable) problem.

A "back of the envelope" calculation shows that $200 Trillion is in the right ballpark: multiplying an optimistic lower bound of the expected dioxide removal costs for CO2 in 2050 ($100/ton – about ¼ of what the Natural Resource Council predicts for the lower bound of direct air capture (DAC) costs, see "J. Carbon Dioxide Removal Costs" below) by the 2010 greenhouse gas emissions (about 52 GTCO2e) shows future generations would need to spend about $5.2 Trillion ($100 * 52 / 1000) to remove the CO2e for the 2010 greenhouse gas emissions. Since emissions will not come down any time soon, we can expect that future greenhouse gas emissions will be more that 2,000 GTCO2e, resulting in CDR costs in excess of $200 Trillion.

Given that

- We can already expect about a 2°C temperature increase based on the greenhouse gases currently in the atmosphere
- The temperature increase since 1970 has been about .16°C per decade. If the temperature continues to increase at the same rate (which is a low estimate), the temperature increase by the end this century will be about 2.5°C
- There will be significant future anthropogenic greenhouse gas emissions for any realistic mitigation scenario
- There will be both significant future natural greenhouse gas emissions and significant albedo changes from the feedbacks from a warming world
- The costs of removing CO2 from the atmosphere at the scale and speed required to limit the temperate increase in 2100 to 2°C are prohibitive
- Most climate change damage will happen before the two-degree warming threshold
- Long-term sea level rise will exceed 40 feet
- Ocean acidification will be catastrophic

it is almost impossible to see how we can prevent very serious climate disruption. We should not give up hope on solving climate change as it is always possible that some technological "miracle" may be discovered. But the prudent thing to do is to assume that very serious climate disruption will occur before 2100. We then have two main choices – we can either (1) use albedo modification for thousands of years to reduce the Earth's average temperature, or (2) start planning for catastrophic climate change. If we really want human civilization to survive for at least another thousand years the sooner we can start having realistic conversations about our likely future the greater the chances of survival will be.

Background

What is not generally understood (or appreciated) is that most of the analyses of our abilty to meet the "2° C challenge" rely on data provided in the IPCC's AR5, which itself relied on our understanding of climate science prior to 2011. Since then there have been significant improvements in our understanding of our climate system, so some of the AR5 assumptions and other basic assumptions need to be examined in detail so that realistic plans for meeting the COP 21 commitments can be made based on our current knowledge. The following lists some of these underlying assumptions and comments about each assumption:

1. Significant CO2 emissions will not be caused by natural feedbacks from a warming world.

    A. "It [(permafrost melt)] was first proposed in 2005. And the first estimates came out in 2011." Indeed, the problem is so new that it has not yet made its way into major climate projections, Schaefer says." …"None of the climate projections in the last IPCC report account for permafrost," says Schaefer. "So all of them underestimate, or are biased low." … "It's certainly not much of a stretch of the imagination to think that over the coming decades, we could lose a couple of gigatons per year from thawing permafrost," says Holmes…. But by 2100, the "mean" estimate for total emissions from permafrost right now is 120 gigatons [440 GTCO2], say Schaefer. http://www.washingtonpost.com/news/energy-environment/wp/2015/04/01/the-arctic-climate-threat-that-nobodys-even-talking-about-yet
    B. Since there are warming feedbacks other than permafrost (see "C. Feedback Factors" below), a reasonable (and probably low) estimate of the contribution from these feedbacks is 500 GTCO2e from 2050 to 2100 (about 10 GTCO2e/year - about 20% of current emissions and 50% of the 1000 GTCO2 UNFCCC budget)

2. We are capable of significantly reducing non-CO2 greenhouse gas emissions (from methane (CH4), nitrous oxide (NO2), etc.)

    A. The RCP 2.6 pathway has .143 GTC of CH4 emissions in 2100, compared to RCP 8.5 pathway emissions of .380 GTC of CH4 emissions in 2015 (or a reduction of about 62% from current emission levels); and in RCP 2.6 atmospheric concentration of CH4 for 2100 (1.25 PPM) was about 30% below current values (1.78 PPM) and about 67% below the RCP 8.5 2100 value (3.75 PPM)
    B. With both an increasing population and an increasingly affluent population it is likely that methane emissions will continue to rise through 2100, not decline significantly as many optimistic temperature increase projections assume
    C. Non-CO2 (CH4, NO2, etc) greenhouse gas emissions were equivalent to about 27.2% of all greenhouse gas emissions in 2010. So if CO2 emissions since 1870 have added about 170 PPM, the equivalent non-CO2 emissions would be about 46 PPM, again putting us close to 450 PPM of CO2e (https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf, and see "K. Global Greenhouse Gas Emissions (1970-2010) below)
    D. If non-CO2 greenhouse gas emissions can be reduced to the point where their total concentrations are ½ of the current levels, they would still contribute about 23 PPM CO2e. At 18 GTCO2 emissions/PPM (7.8 GTCO2 per PPM of atmospheric CO2 / .43 "airborne fraction" of emitted CO2 which stays in the atmosphere), this would mean that about 400 GTCCO2 would not need to be removed, reducing the CDR costs by about $40 Trillion, resulting in a total of about $150 Trillion for 2°C world.

3. The 2° C target will be breached when atmospheric concentrations of CO2 exceed 450 PPM for a sustained period of time

    A. That would be true if the climate sensitivity of CO2 was about 3 and CO2 were the only greenhouse gas whose concentrations had increased since preindustrial times. But when all major greenhouse gases are included we are already at about 480 PPM CO2e (see #2.C above and http://globalchange.mit.edu/files/2014%20Energy%20%26%20Climate%20Outlook.pdf, which is excerpted below in section "E. Greenhouse Gas Concentrations and Climate Implications")

   B. The aerosols from burning coal significantly dampen the temperature increase caused by CO2 emissions. According to Dr. Michael Mann, since the burning of coal must be ended to meet any meaningful temperature increase target, a more realistic target of atmospheric CO2 is 405 PPM, which will be reached in a few years (http://ecowatch.com/2015/12/24/dangerous-planetary-warming/2/ and see "F. Limit CO2 to 405 PPM" below)
   C. The temperature increase at the end of 2015 was about 1.0°C and an additional .1°C increase is expected for 2016. In addition, the aerosols from the burning of fossil fuels are masking another .5°C of temperature increase. And the Earth's current energy imbalance will likely lead to another .5°C increase over the coming decades based on the greenhouse gases already in the atmosphere. (If we can reach "net zero" anthropogenic CO2 emissions, the oceans will absorb significant amounts of CO2, but this will likely offset by natural emissions from global warming feedbacks (permafrost thawing, etc.)). Assuming that we will be able to stabilize the non-CO2 greenhouse gases (CH4, NO2, etc.) at their current levels (because reducing them will be really difficult in a more affluent and more populous world), it is quite likely that we are already committed to a temperature increase around 2°C.
   D. With all of the weird weather that we have been getting from 1.0° C temperature increase and with another .5°C to 1°C "baked in", it would seem that current atmospheric concentrations of greenhouse gases are already too high, implying the need to remove the CO2 equivalent of all future greenhouse gas emissions from the atmosphere.
   E. So we may very close to 2° C target with the current atmospheric concentration of CO2 at 400 PPM.

4. Significant use of carbon capture and storage (CCS) or carbon dioxide removal (CDR) is not required since many of the Web sites that show "2 degree pathways" do not mention CCS or CDR

   A. For example, the Web page for "Climate Interactive" scenarios (https://www.climateinteractive.org/tools/scoreboard/scoreboard-science-and-data/ and excerpted below in "A. Climate Interactive "ratcheting" scenarios") not only does not mention CCS or CDR but also shows a two degree pathway where the CO2 emissions are almost triple the UNFCCC budget . The chart also indicates impossibly low values for GTCO2e for the 1.8° and 1.5° scenarios – in the latter the GTCO2e is less than the GTCO2 value and in the former the GTCO2e value is only 5 PPM above the GTCO2 value with no explanation as to how this was derived as it implies that CO2 is virtually the only non-condensing greenhouse gas in the atmosphere in 2100)
   B. However, "Under the IEA Energy Technology Perspectives 2012 2°C Scenario (2DS), CCS contributes one-sixth of total CO2 emission reductions required in 2050 [, about 8,000 MTCO2]." (http://www.iea.org/publications/freepublications/publication/technology-roadmap-carbon-capture-and-storage-2013.html) . Costs in 2050 were estimated to be about $400 Billion/year.

5. Sea level will rise two to three feet by 2100 and the damage from sea level rise can be contained by limiting the temperature increase to 2° C or 1.5° C.

   A. The ice sheets in Greenland and Antarctica are destabilizing much faster than anticipated and expectations for sea level rise by 2100 are being increased. In addition, over long periods of time, sea level rise will very like be at least 20 feet per degree C. It is very doubtful that long-term catastrophic sea level rise can be prevented no matter how much emissions are reduced.
   B. Because tens of feet of sea level rise are already "locked in" with a 1° C rise in temperature, limiting future greenhouse gas emissions will not be able to keep sea levels from rising more than three feet, which will be catastrophic. The best that we can do is to slow the rate of the sea level rise, but it is difficult to determine how much the rate would slow for a .5° C change in the expected temperature increase

6. The worst affects of climate change will occur after 2° C of warming, so we'll be OK as long as the temperature rise can be limited to 2° C

    A. Most climate change damage will happen before the two-degree warming threshold (http://www.newsweek.com/earth-resources-ruined-two-degrees-warming-threshold-404406 and see "H. Climate Impacts vs. Temperature Increase" below)

7. The 66% chance of meeting the UNFCCC's 1000 GTCO2 budget is consistent with the climate sensitivity that most climate scientists expect

    A. The 1000 GTCO2 budget results in a climate sensitivity of 2.8
    B. The actual climate sensitivity is likely closer to 3 or 3.1, which would require a decrease in the UNFCCC's 1000 GTCO2 budget of about 150-200 GTCO2
    C. Do we really want only a 66% chance of meeting a budget? If we want a 90% chance of staying below 2°C, the entire budget has already been used (http://media.wix.com/ugd/148cb0_bb2e61584dbb403e8e33fd65b1c48e30.pdf and see "G. 2°C Carbon Budget" below)

8. The UNFCCC's 1000 GTC budget provides a 66% chance of limiting the temperature increase to 2°C

    A. The budget needs to be reduced by about 150-200 GTCO2 because the budget resulted in a climate sensitivity of about 2.8 for a 66% chance of staying under 2°C, while a better planning estimate for climate sensitivity for CO2 is 3 .0-3.1.
    B. Non-CO2 greenhouse gas emissions are likely playing a much more major role that anticipated; taking this into account reduces the budget by at least another 400 GTCO2.
    C. The UNFCCC budget did not take into account the expected emissions from the positive feedbacks from a warming world (permafrost thawing, albedo changes from an ice-free Arctic Ocean, etc.), which would likely reduce the budget by at least another 500 GTCO2. (If net CO2 emissions were to approach zero, the oceans would continue to absorb CO2 at close the current rate, thus reducing the atmospheric concentration of CO2. But it is assumed that this was taken into account in developing the 1000 GTCO2 budget).
    D. A more realistic carbon dioxide budget for the rest of the century is about zero.

Likely Future Emissions Based on INDCs

The following table shows projected greenhouse gas emissions (GTCO2e) based on the INDCs (data for 2010-2030 from Climate Interactive)

Emissions for Specific Years					**Cumulative Emissions**		**Decline 3%/year**	**Decline 2%/year**	**Decline 3%/year**	**Decline 2%/year**
2010	2015	2020	2025	2030	2016-2025	2016-2030	2025-2058	2025-2075	2030-2063	2030-2080
50.7	57.2	58.4	57.1	57.3	580	866	942	1427	945	1433

CO2 Capture and Removal Requirements

Since we are likely very close to the 2°C target at the end of 2015, a rough estimate of CO2 removal costs can be done be assuming that the CO2 equivalent of all greenhouse gase emissions emitted after 2015 will need to be removed from the atmosphere. Based on the above "Likely Future Emissions Based on INDCs" it is easy to calculate rough values for the amount of CO2 that would need to be removed to limit the temperature increase to either 2.0° C or 1.5° C:

GTCO2e	Source
1522	Net of all of the greenhouse gases emitted after 2015, assuming they peak in 2025 and are reduced linearly at 3 percent per year (net zero in 2058) (=580 for 2015-2025 + 942 for 2025-2058) (There will likely need to be significant CCS to meet the "net zero" goal, but the associated costs are not included here)
320	Greenhouse gases emissions from 2058-2100 that need to be captured and sequestered (8*40) (IEA – see 4.B above – assumes the annual amount of CCS needed is stabilized in 2050, whereas it is likely to increase)
500	GHG equivalent emissions from climate feedbacks from 2020-2100 (440 GTCO2e from permafrost and 60 GTCO2e from other sources)
-450	CO2 absorbed by the oceans from 2050-2100 as net CO2 emissions approach zero. Oceans currently absorb 30-50% of CO2 from fossil fuel emissions (http://www.gdrc.org/oceans/fsheet-02.html) . Assuming that there are "net zero" fossil fuel emissions in 2058 and using a 40% absorption rate of 2010 emissions in 2050 of about 12 GTCO2, which would be reduced in half by 2100, the total CO2 absorbed by the oceans from 2050 would be 50 * (12 + 6) /2, or 450 GTCO2 (this is just a "swag" but is probably in the right ballpark)
1892	**Total CO2 to be sequestered for a 2 degree world**
1000	CO2 to be removed for 350 PPM (="Carbon content of 1 PPM of Atmospheric CO2" * "Conversion factor CO2->C "* "50 PPM to be removed" / "Percent of emitted CO2 that ends up in the atmosphere": 2.12*3.664*50/ 0.42)
2892	**Total CO2 to be sequestered for a 1.5 degree world**

The following table gives the additional greenhouse gases that must be sequestered if emissions peak later and/or are reduced at a different rate:

GTCO2e	Scenario	% Change to meet 2° C goal	% Change to meet 1.5° C goal
289	Peak in 2030 and reduce 3%/year	15	10
485	Peak in 2025 and reduce 2%/year	26	17
774	Peak in 2030 and reduce 2%/year	41	27

Carbon Dioxide Removal (CDR) Costs

The future costs of CDR are very difficult to predict. In the recently published book "Climate Intervention – Carbon Dioxide Removal and Reliable Sequestration" the National Resource Council (NRC) estimated costs for "bio-energy with carbon capture and storage" (BECCS) at about $100/ton CO2 and for "direct air capture" (DAC) at $400-$1000/ton CO2 (Table 2.2 in the report – see "J. Carbon Dioxide Removal Costs" below). Other CDR methods are available but may also be of little use given the magnitude of the problem. Due to the likely limited availability land for of BECCS and because of the really large quantities of CO2 that must be removed, DAC removal will likely need to be used most widely.

Given an optimistic CDR cost of $100/ton CO2 (the lower bound estimate of the NRC for BECCS), the cost to meet the 2.0° C target would be about $190 Trillion this century and about $290 trillion to meet the 1.5° C target.

Other Assumptions

Based on the cost estimates above two other assumptions need to be reviewed

1. The "costs of inaction" will be much higher than the "cost of action"

    A. When looking at the "costs of action" for this century we should only include the incremental costs of a world with a 3-4° C temperature increase over that of a 2° C increase since the latter costs will be borne no matter what we do (i.e., most of the costs due to 3-4 feet of sea level rise cannot be included in the comparison since sea level rise will be more that 3-4 feet with 2° C of warming). While the "costs of action" will likely run well over $200 Trillion by 2100 (with a significant portion of that having no real economic value), the “incremental cost of inaction” will likely be much less (one “Hurricane Katrina” per month after 2050 would cost only $120 Trillion).

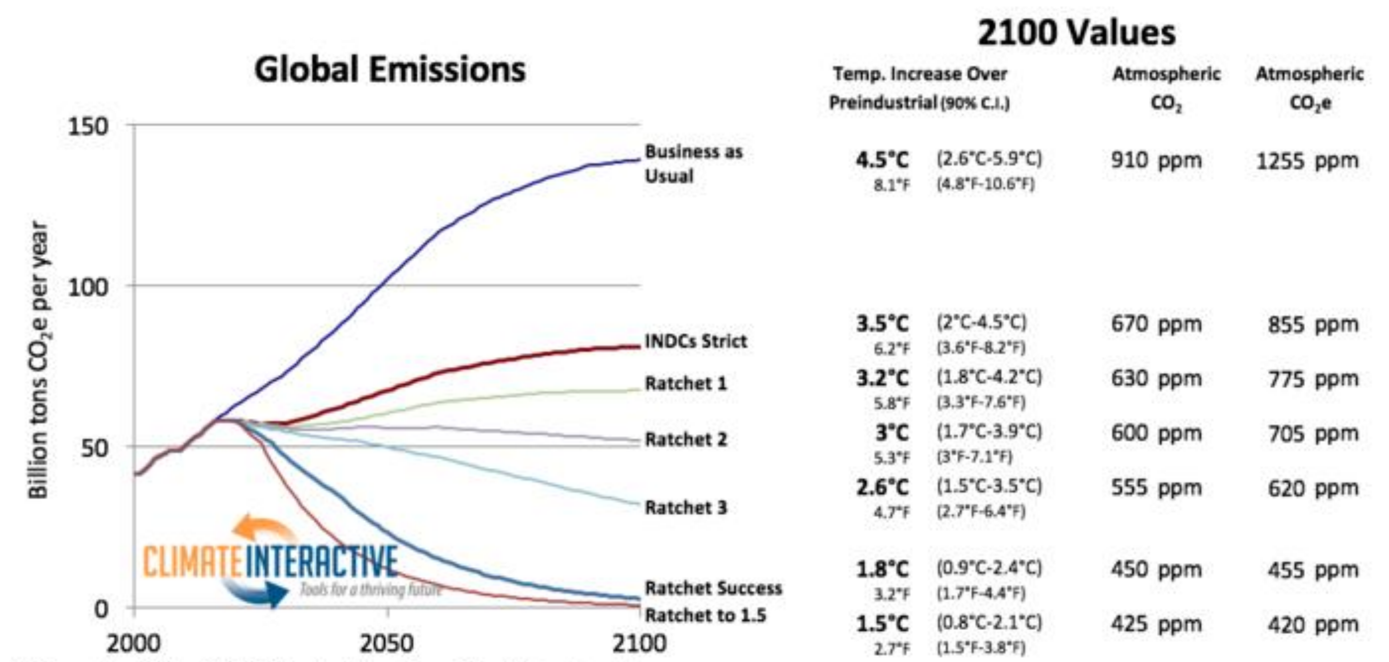
2. We will be willing to pay both the “carbon capture and storage” (CCS) costs and “carbon dioxide removal” (CDR) costs needed to meet the COP 21 temperature targets.
    A. Given an optimistic CDR cost of $100/ton CO2, the cost to meet the 2.0° C target would be about $190 Trillion this century and about $290 trillion to meet the 1.5° C target (see “Analysis” above)
    B. There is very likely an upper limit as to how much we will be willing to pay, particularly since most of the costs of CCS provide no direct economic value but are needed solely to meet the temperature target (see “B. Thoughts on CDR Financing” below)

Adjustments to the UNFCCC’s 1000 GTCO2 budget

There are three basic assumptions on the UNFCCC’s “remaining 1000 GTCO2 budget” which are almost always overlooked or ignored, and when “compensated for”, use up the entire budget:

Budget Reduction (GTCO2)	**Reason for Reduction**
150-200	Adjusting the climate sensitivity from 2.8 to 3.0-3.1. The UNFCCC’s probability of reaching the target is only 66% - we should have better – and more realistic - “odds”.
>500	Feedbacks from global warming. These were not considered in the IPCC analysis; the mean projection for CO2 for permafrost thawing by 2100 is 440 GTCO2 and there are other feedbacks to consider.
> 400	From non-CO2 greenhouse gases currently in the atmosphere. These are currently responsible for about 80 PPM CO2e (MIT, 2014). The IPCC assumed that 20% of the warming would come from non-CO2 sources (e.g., methane, ozone, soot, albedo changes, etc.). Adding 1000 GTCO2 to the atmosphere after 2011 would result in an atmospheric concentration of about 450 PPM CO2, for a total increase of about 180 PPM. If 20% of the warming were non-CO2 sources, then these sources were expected to contribute about 45 PPM CO2e (=180/0.8 – 180), which is about 35 PPM CO2e less than the current value for just the non-CO2 greenhouse gases. Since about 18 GTCO2 of emissions result in about 1 PPM of atmospheric CO2, if a realistic CO2 PPM reduction to account for these gases turns out to be 20 GTCO2e (about ½ the 35 PMM “overage”, to allow for other factors, including an effort to reduce emissions of non-CO2 greenhouse gases), that would mean that about 400 GTCO2 would need to be removed.

A. Climate Interactive “ratcheting” scenarios



Temp. Increase Over Preindustrial (90% C.I.)		Atmospheric CO_2	Atmospheric CO_2e
4.5°C 8.1°F	(2.6°C-5.9°C) (4.8°F-10.6°F)	910 ppm	1255 ppm
3.5°C 6.2°F	(2°C-4.5°C) (3.6°F-8.2°F)	670 ppm	855 ppm
3.2°C 5.8°F	(1.8°C-4.2°C) (3.3°F-7.6°F)	630 ppm	775 ppm
3°C 5.3°F	(1.7°C-3.9°C) (3°F-7.1°F)	600 ppm	705 ppm
2.6°C 4.7°F	(1.5°C-3.5°C) (2.7°F-6.4°F)	555 ppm	620 ppm
1.8°C 3.2°F	(0.9°C-2.4°C) (1.7°F-4.4°F)	450 ppm	455 ppm
1.5°C 2.7°F	(0.8°C-2.1°C) (1.5°F-3.8°F)	425 ppm	420 ppm

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https://www.climateinteractive.org/tools/scoreboard/scoreboard-science-and-data/
Climate-Scoreboard-Output-14Dec2015-to-share.xlsx (link from the above page)

Emissions from 2012-2100:

BAU	INDC Strict	Ratchet 1	Ratchet 2	Ratchet 3	2 deg Pathway	Ratchet Success Pathway	Ratchet Success to 1.5 no CDR
9,333	6,174	5,526	4,919	4,167	2,758	2,206	1,638

B. Thoughts on CDR Financing

Given a realistic CO2 emissions scenario and a realistic carbon budget, the sequestration costs between now and 2100 will be many tens of trillions of dollars (and very likely over $200 trillion).

Money spent on removing CO2 from the atmosphere provides no net economic benefit in the "normal economic sense" as it does not build "useful" infrastructure (roads, buildings, etc) and provides no revenue stream (or return on investment). Even though the money spent on the "energy production side" of a BECCS power plant does provide a "normal economic" investment, the money spent to capture and sequester the CO2 does not.

Governments are expected to contribute $100 billion annually to the UNFCCC's Green Climate Fund, half of which will be used for mitigation and half for adaptation. It will be a "stretch" to even come close to this level of financing, and that level of funding is far short of what is needed for sequestration.

It is generally assumed that private financing will play major role in funding the Green Climate Fund as there are insufficient public funds available. Because there is no "return on investment" for spending on CDR, it is highly unlikely that private financing will provide any money for CDR projects. Because minimal private financing will be available for CDR projects, the only source of funding is likely the public sector. But with current global tax revenues at about $8 trillion per year, the required public sector funding would represent about 10% of total tax revenue.

Greenhouse gas emissions need to be brought under control BEFORE global warming feedbacks start contributing significantly to the Earth's temperature, as an additional equivalent amount of CO2 wound then need be sequestered, driving the costs even higher.

The need for funds for CDR will be competing with the costs for sea level rise, ocean acidification, an aging population, poverty reduction, etc.

Bio-energy carbon capture and storage (BECCS) is the least expensive carbon dioxide removal (CDR) technique, but will likely play a minimal role in removing excess CO2 from the atmosphere. BECCS cannot be realistically deployed at sufficient scale to sequester really significant quantities of CO2 before 2100. Since costs for other techniques for sequestration are greater that costs for BECCS, $100/Ton CO2 seems to be a reasonable lower bound on average CDR costs even given technological advances

With almost no economic benefit from spending money on CDR, it would be nearly impossible to have an enforceable global treaty that would commit countries to spend the necessary $4 trillion per year for a 2°C degree world. So no country would have an incentive to fund CDR projects.

Incremental spending on CDR projects does not make economic sense – unless there is a reasonable expectation that sufficient funds could be committed to CDR so that CO2 levels could be reduced to below that needed to avoid disruptive climate change, it's hard to image that any meaningful investments will be made in CDR.

There a maximum amount that society could be realistically expected to be willing to pay for CDR. That maximum amount is almost certainly less than expected costs of the CDR expenditures that would be needed

No politician will ever recommend spending significant dollars "today" on CDR, so costs will always be passed on to future generations

C. Feedback Factors

"It [(permafrost melt)] was first proposed in 2005. And the first estimates came out in 2011." Indeed, the problem is so new that it has not yet made its way into major climate projections, Schaefer says." …"None of the climate projections in the last IPCC report account for permafrost," says Schaefer. "So all of them underestimate, or are biased low." … "It's certainly not much of a stretch of the imagination to think that over the coming decades, we could lose a couple of gigatons per year from thawing permafrost," says Holmes…. But by 2100, the "mean" estimate for total emissions from permafrost right now is 120 gigatons, say Schaefer. http://www.washingtonpost.com/news/energy-environment/wp/2015/04/01/the-arctic-climate-threat-that-nobodys-even-talking-about-yet

Feedback/Factor	Carbon Store Size	Range of Likely Emission Values/Temperature Changes
Albedo Changes		
Arctic Ocean	Already .27 W/M^{2,} with pollution reducing the amount[7]	
		.3-1.3 w/m[8,9]
Retreating snowline		1.3 w/m[8,9]
Tundra greening		
Land use changes		
Other?		
CO2 Emissions		
Permafrost	1,600	.4-.6°F by 2100[1] 190 GTC by 2200[2] 250 GTC[3] by 2100
Peat Bogs	270 to 370[4]	100-220[5]
Methane Hydrates	5,000 to 20,000[3,6]	
Other Soils		
Tropical Forests	86 GTC (Amazon)	
Temperate Forests		US forests will change from a sink to a source later this century
Other?		
Atmosphere	820 GTC	
Anthropogenic Emissions	515 GTC	(through 2011)
Fossil Fuel Reserves	760 GTC	1.6°C if all reserves burned
1. http://nca2014.globalchange.gov/report/our-changing-climate/melting-ice .4-.6°F		
2. http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt264.pdf		
3. http://whatweknow.aaas.org/wp-content/uploads/2014/07/whatweknow_website.pdf		
4. globalcarbonproject.org/global/pdf/pep/Limpens.2008.Peatlands& Carbon.BiogeosciencesDiscus.pdf		
5. http://thinkprogress.org/climate/2015/01/13/3610618/peat-wetlands-global-warming/		
6. http://www.killerinourmidst.com/methane and MHs2.html		
7. http://www.nasa.gov/press/goddard/2014/december/nasa-satellites-measure-increase-of-sun-s-energy-absorbed-in-the-arctic		
8. http://www.esrl.noaa.gov/gmd/co2conference/posters_pdf/jones1_poster.pdf		
9. http://arctic-news.blogspot.com/2012/07/albedo-change-in-arctic.html		

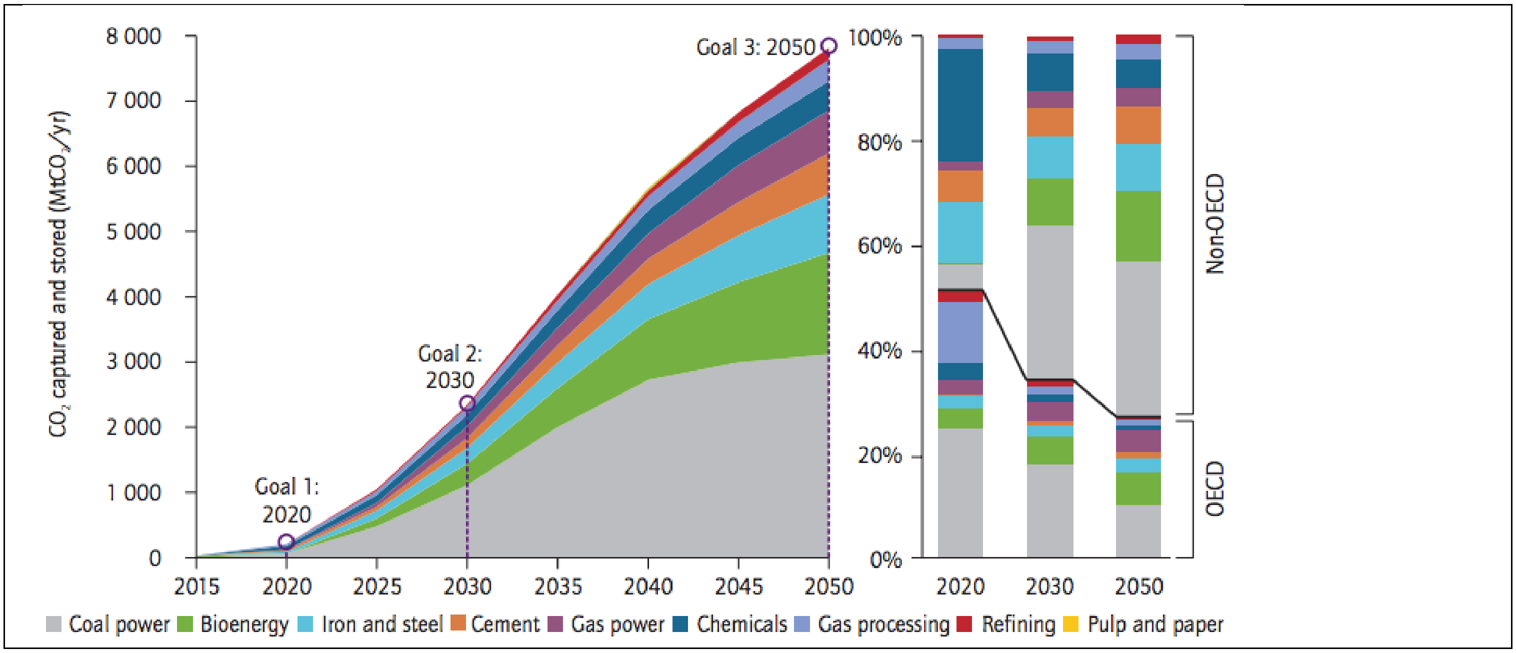
Table F1 – Feedback Factors

D. Sequestration

Carbon capture and storage (CCS) technologies can capture up to 90 percent of carbon dioxide (CO2) emissions from a power plant or industrial facility and store them in underground geologic formations. Since the incremental cost of capturing the other 10 percent of emissions is so high, if fossil fuel power plants are to stay in operation in a "net zero emissions" world, significant amounts of CO2 will have to be sequestered by other means. (Fossil fuel power plants with CCS cannot be used to sequester CO2 already in the atmosphere.) The technologies for both capture and storage are unproven at the scale that will be needed.

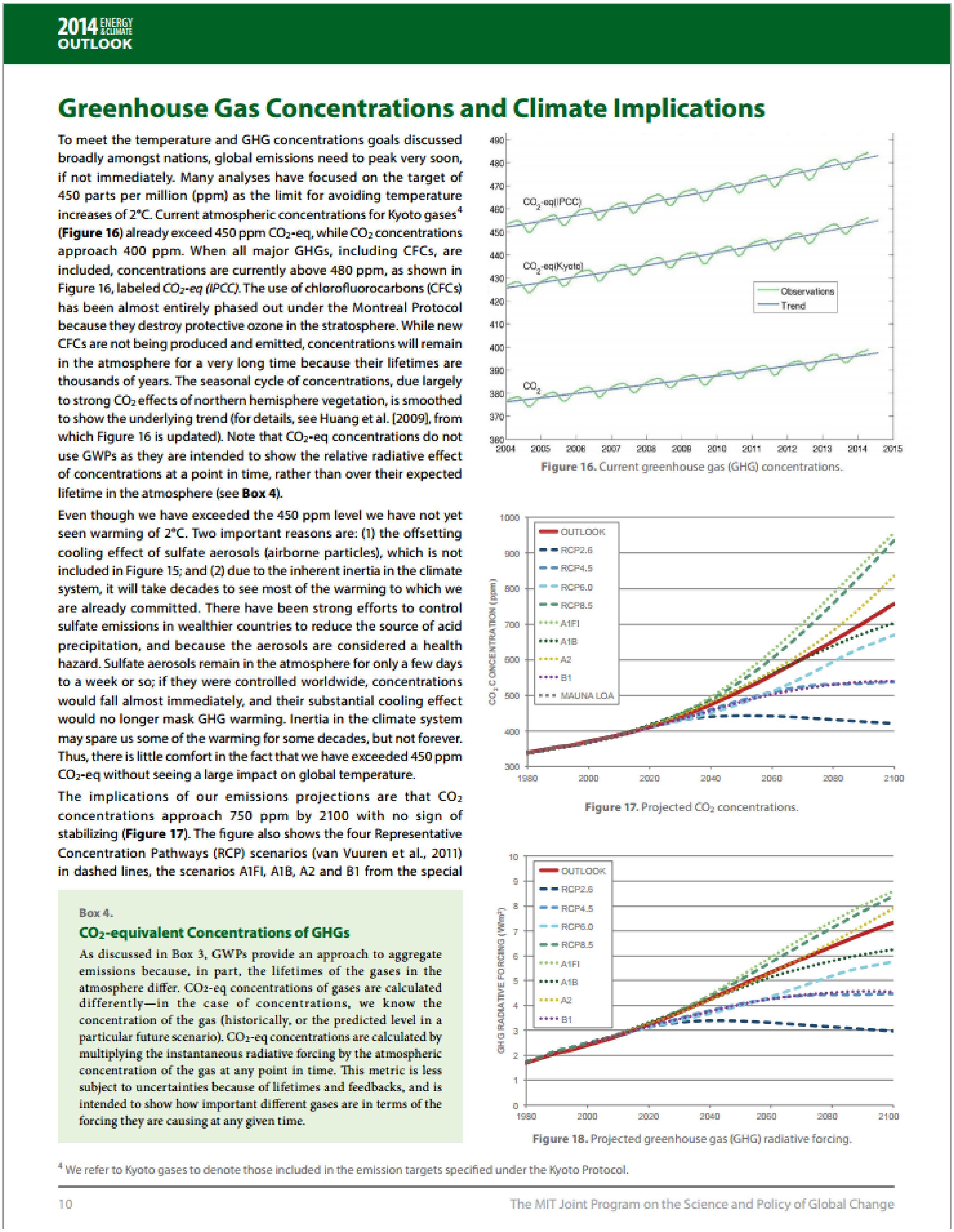
According to the IEA (https://www.iea.org/publications/freepublications/publication/technology-roadmap-carbon-capture-and-storage-2013.html - 2013), CCS is a critical component of meeting the 2°C target. They project that CCS will need to be used to sequester 50 MTCO2/year by 2020, 2,000 MTCO2/year by 2030, and almost 8,000 MTCO2/year by 2050.

- "Under the IEA Energy Technology Perspectives 2012 2°C Scenario (2DS), CCS contributes one-sixth of total CO2 emission reductions required in 2050, and 14% of the cumulative emissions reductions through 2050 against a business-as-usual scenario (6DS)."
- "Governments and industry must ensure that the incentive and regulatory frameworks are in place to deliver upwards of 30 operating CCS projects by 2020 across a range of processes and industrial sectors."
- "CCS is not only about electricity generation. Almost half of the CO2 captured between 2015 and 2050 in the 2DS, is from industrial applications (45%)."
- "Given their rapid growth in energy demand (70% by 2050), the largest deployment of CCS will need to occur in non-Organisation for Economic Co-operation and Development (OECD) countries."



It is likely that the 2020 goal will be met, but the majority of the current CCS plants use the captured CO2 for enhanced oil recovery and hence can capture the CO2 for a profit. But ramping up for the 2030 goal will be problematic as the average "energy penalty" is expected to be about 29 percent ("The energy penalty of post-combustion CO2 capture and storage" Jan 2009) and there will not be a way to recover the costs. For the US, the expected levelized cost of electricity in 2020 is $94/mwh for conventional coal and $144 for advanced coal with CCS. Since 1 MWH of coal produces about 1 metric ton of CO2, the CO2 capture costs are about $50/ton. Therefore the CCS capture costs are expected to be about $400 billion per year in 2050 *assuming that anthropogenic emissions can be mitigated at the rate necessary to meet the IPCC carbon budget and that there are not significant natural emissions from permafrost melt, peat bogs, etc.* (both very unlikely)

E. Greenhouse Gas Concentrations and Climate Implications



Greenhouse Gas Concentrations and Climate Implications

To meet the temperature and GHG concentrations goals discussed broadly amongst nations, global emissions need to peak very soon, if not immediately. Many analyses have focused on the target of 450 parts per million (ppm) as the limit for avoiding temperature increases of 2°C. Current atmospheric concentrations for Kyoto gases[4] (**Figure 16**) already exceed 450 ppm CO_2-eq, while CO_2 concentrations approach 400 ppm. When all major GHGs, including CFCs, are included, concentrations are currently above 480 ppm, as shown in Figure 16, labeled *CO_2-eq (IPCC)*. The use of chlorofluorocarbons (CFCs) has been almost entirely phased out under the Montreal Protocol because they destroy protective ozone in the stratosphere. While new CFCs are not being produced and emitted, concentrations will remain in the atmosphere for a very long time because their lifetimes are thousands of years. The seasonal cycle of concentrations, due largely to strong CO_2 effects of northern hemisphere vegetation, is smoothed to show the underlying trend (for details, see Huang et al. [2009], from which Figure 16 is updated). Note that CO_2-eq concentrations do not use GWPs as they are intended to show the relative radiative effect of concentrations at a point in time, rather than over their expected lifetime in the atmosphere (see **Box 4**).

Even though we have exceeded the 450 ppm level we have not yet seen warming of 2°C. Two important reasons are: (1) the offsetting cooling effect of sulfate aerosols (airborne particles), which is not included in Figure 15; and (2) due to the inherent inertia in the climate system, it will take decades to see most of the warming to which we are already committed. There have been strong efforts to control sulfate emissions in wealthier countries to reduce the source of acid precipitation, and because the aerosols are considered a health hazard. Sulfate aerosols remain in the atmosphere for only a few days to a week or so; if they were controlled worldwide, concentrations would fall almost immediately, and their substantial cooling effect would no longer mask GHG warming. Inertia in the climate system may spare us some of the warming for some decades, but not forever. Thus, there is little comfort in the fact that we have exceeded 450 ppm CO_2-eq without seeing a large impact on global temperature.

The implications of our emissions projections are that CO_2 concentrations approach 750 ppm by 2100 with no sign of stabilizing (**Figure 17**). The figure also shows the four Representative Concentration Pathways (RCP) scenarios (van Vuuren et al., 2011) in dashed lines, the scenarios A1FI, A1B, A2 and B1 from the special

Box 4.

CO_2-equivalent Concentrations of GHGs

As discussed in Box 3, GWPs provide an approach to aggregate emissions because, in part, the lifetimes of the gases in the atmosphere differ. CO_2-eq concentrations of gases are calculated differently—in the case of concentrations, we know the concentration of the gas (historically, or the predicted level in a particular future scenario). CO_2-eq concentrations are calculated by multiplying the instantaneous radiative forcing by the atmospheric concentration of the gas at any point in time. This metric is less subject to uncertainties because of lifetimes and feedbacks, and is intended to show how important different gases are in terms of the forcing they are causing at any given time.

Figure 16. Current greenhouse gas (GHG) concentrations.

Figure 17. Projected CO_2 concentrations.

Figure 18. Projected greenhouse gas (GHG) radiative forcing.

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[4] We refer to Kyoto gases to denote those included in the emission targets specified under the Kyoto Protocol.

http://globalchange.mit.edu/files/2014%20Energy%20%26%20Climate%20Outlook.pdf

F. Limit CO_2 to 405 PPM

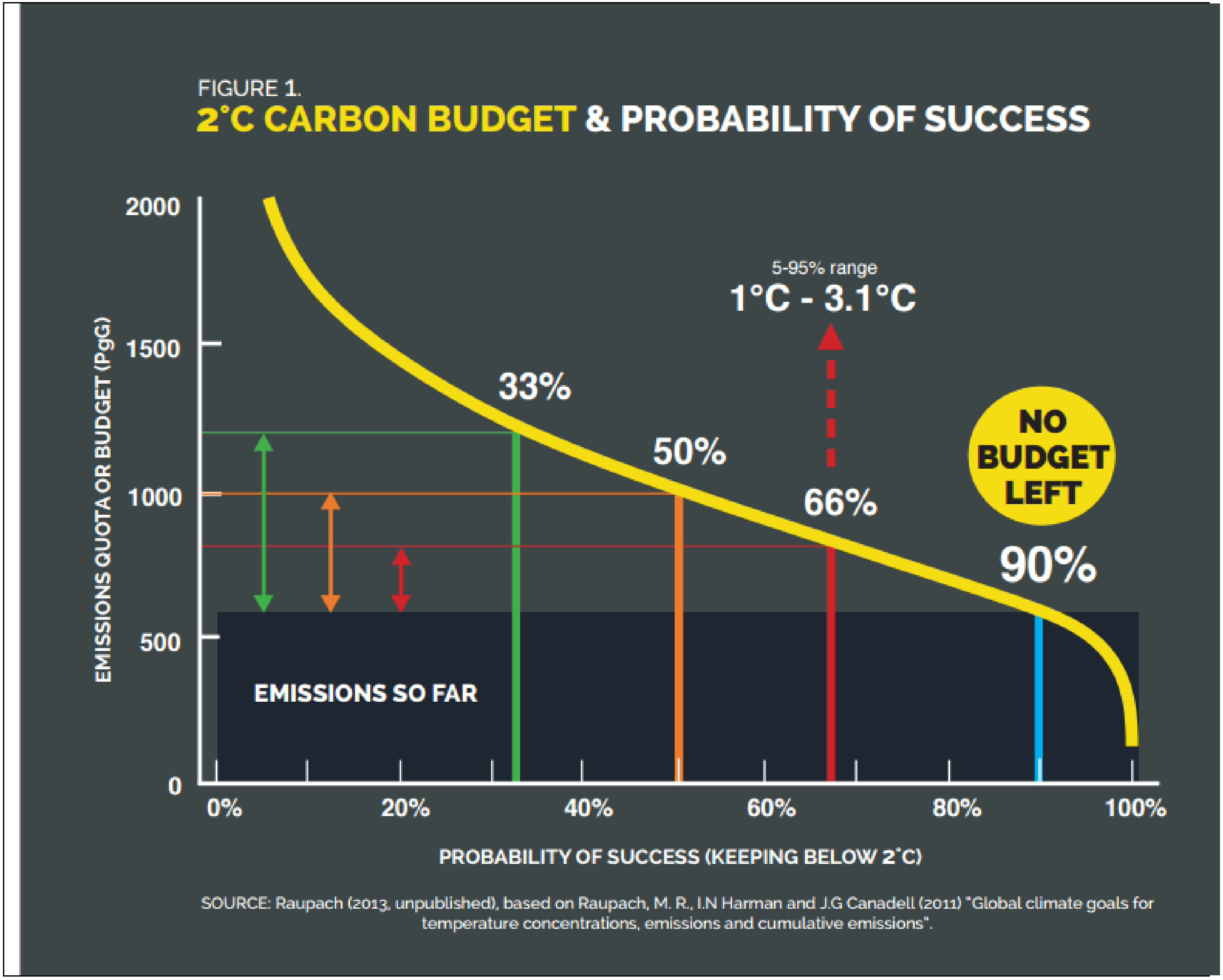
But let us return to the discussion of dangerous planetary warming. In the piece, I argued that the 3C value of ECS (i.e. where 3C warming of the globe ultimately results from increasing CO2 concentrations from their pre-industrial level of 280 ppm to a level of 560 ppm) is most likely given the various lines of scientific evidence. For this value of ECS I showed that limiting CO2 concentrations to 450 ppm (orange dashed curve in Fig. 3) would indeed limit warming to about 2C relative to pre-industrial. Problem solved? Not quite …

While greenhouse warming would abate, the cessation of coal burning (if we were truly to go cold-turkey on all fossil fuel burning) would mean a disappearance of the reflective sulphate pollutants (“aerosols“) produced from the dirty burning of coal. These pollutants have a regional cooling effect that has offset a substantial fraction of greenhouse warming, particularly in the Northern Hemisphere. That cooling would soon disappear, adding about 0.5C to the net warming. When we take this factor into account (orange dotted curve), the warming for 450 ppm stabilization is now is seen to approach 2.5C, well about the “dangerous” limit. Indeed, CO2 concentrations now have to be kept below 405 ppm (where we’ll be in under three years at current rates of emissions) to avoid 2C warming (blue dotted curve).
So evidently, we don’t have 1/3 of our total carbon budget left to expend, as implied by the IPCC analysis. We’ve already expended the vast majority of the budget for remaining under 2C. And what about 1.5C stabilization? We’re already *overdrawn*.

The more we delay rapid reductions in fossil fuel burning, the more we will need to offset additional carbon emissions by sequestration of atmospheric carbon, either through massive reforestation projects, or ‘geoengineering’ technology such as “direct air capture,” which involves literally sucking the CO2 back out of the atmosphere (It would be expensive, but the alternative—allowing dangerous planetary warming or implementing other potentially dangerous geoengineering schemes—could be far more costly).

http://ecowatch.com/2015/12/24/dangerous-planetary-warming/2/

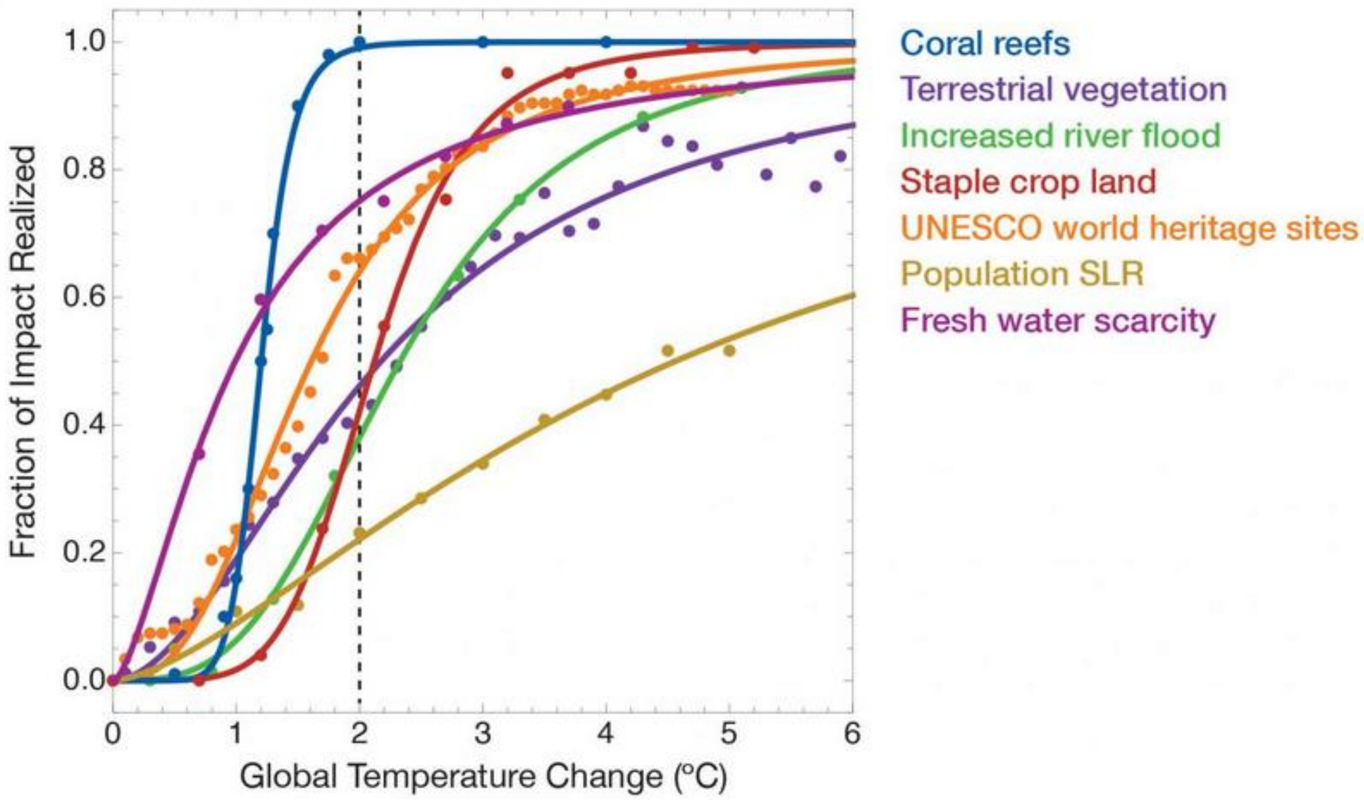
G. 2° C Carbon Budget



http://media.wix.com/ugd/148cb0_bb2e61584dbb403e8e33fd65b1c48e30.pdf

H. Climate Impacts vs. Temperature Increase

In the chart below, Caldeira and his colleagues graphed the extent of damage from climate change on various sectors of the environment. They found that the sensitivity of some of these categories to small increases in temperature will be highest within the first several degrees of warming, and then tapers off, having hit a physical limit, or what the researchers call a "saturation of impacts," as in the case of coral reefs at two degrees Celsius. Once the planet gets into the higher degrees of warming, the rate of impact begins to plateau—because there won't be anything left to be affected.



Some climate change impacts rise fast with little warming, and then taper off, write a team of researchers in a paper published during the 2015 Paris climate talks.

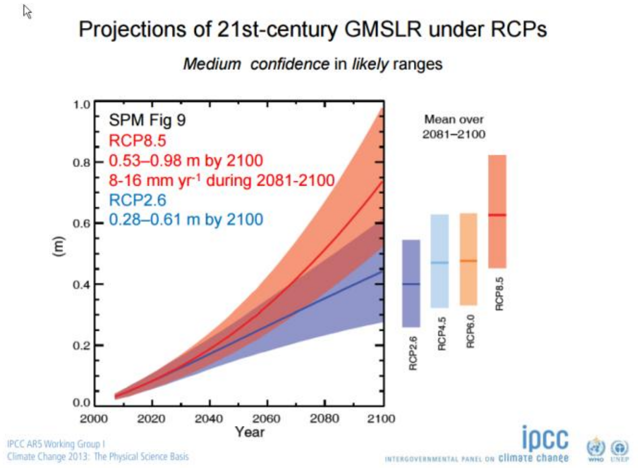
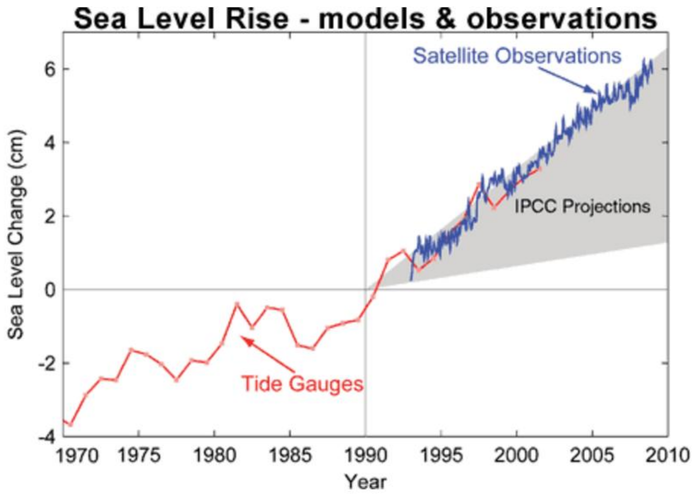
RICKE ET AL/NATURE GEOSCIENCE

http://www.newsweek.com/earth-resources-ruined-two-degrees-warming-threshold-404406

I. Sea Level Rise

The sea level is rising for two reasons: as the ocean warm the water expands; and as the Earth's average atmospheric temperature rises land ice melts. From 1870 to 1993 sea levels rose about 200 mm. Since 1993, global sea level has risen at an accelerating rate of around 3.38 mm/year for an additional 70mm.

In the most recent IPCC report (AR5), the IPCC projected that sea level would rise less than 1 meter by 2100 for even the "business as usual" (RCP8.5) scenario. This was based on the understanding of mechanisms for the melting of ice sheets around 2010, but recent advances in our understanding of the ice sheets indicates that these estimates are too low by a significant amount: if sea levels continue to rise at the current 3.38 mm/year rate, total sea level rise in 2100 would be about 550 mm (about 22 inches – the high end of the RCP 2.6 scenario and the low end of the RCP 8.5 scenario). If the rate increases to 8 mm/year for the rest of the century (a bit less than the 10mm/year increase coming out the last ice age, when the annual temperature increase was about 5% of the current rate) then the total sea level rise would be about 950 mm (37 inches).

	 *Figure 2: Sea level change. Tide gauge data are indicated in red and satellite data in blue. The grey band shows the projections of the IPCC Third Assessment report (Allison et al 2009).*
https://www.ipcc.ch/pdf/unfccc/cop19/3_gregory13sbsta.pdf	https://www.skepticalscience.com/sea-level-rise-predictions.htm

Several recent studies (see below) have shown that catastrophic sea level rise cannot be prevented. Although we can expect that sea levels will eventually rise over 70 feet, what climate scientists are not sure about is how fast the sea level will rise in the next two centuries.

Recent sea level rise

Time Period	Description
20,000 -8,000 Years ago	From maximum ice extent in last ice age to about when the seas stopped rising
Last 7,000 years	Starting when the climate and sea level became relatively stable
Last 140 years	When CO2 concentrations began rising (also the first year on the chart for sea level rise)
Last 22 Years (1993-2015)	Reasonably accurate data is available from satellite observations (sea level rise: http://climate.nasa.gov/vital-signs/sea-level/) (temperature change: http://blog.chron.com/climateabyss/files/2012/04/1967withlines.pdf)

	20,000 -8,000 Years ago	Last 7,000 Years to 1850	Last 140 years	Last 22 Years (1993-2015)	If all ice melts
Sea Level Rise (SLR)	120 meters 400 feet	4 meters	230 mm 9 inches	70 mm 2.76 inches	70 meters 220 feet
Temperature Increase	8° C 14° F	0	1.0° C 1.8° F	0.25° C 0.45° F	6°C 11°F
SLR per degree	15 meters/°C 30 feet/° F	N/A	N/A	N/A	11 meters/°C 20 feet/° F
Average SLR/Year	10 mm .39 inches	0.57 mm 0.02 inches	1.8 mm 0.07 inches	3.38 mm 0.133 inches	
Temp increase/ 100 years	0.075 °C 0.135° F	-0.1 °C	0.71° C 1.28° F	1.5° C 2.7° F	
CO2 Concentration Change	100 PPM (180-280) (55% increase)	20 PPM (260-280)	125 PPM (275-400) (45% increase)	43 PPM (357-400)	
CO2 Average change/100 years	< 1 PPM < 1%	.29 PPM	90 PPM 32%	195 PPM 55%	

Scientists confirm their fears about West Antarctica — that it's inherently unstable
The Washington Post

"In 2014, several research groups suggested that the oceanfront glaciers in the Amundsen Sea region of West Antarctica may have reached a point of "unstoppable" retreat due to warm ocean waters melting them from below. There's a great deal at stake — West Antarctica is estimated to contain enough ice to raise global sea levels by 3.3 meters, or well over 10 feet, were it all to melt.
The urgency may now increase further in light of just published research suggesting that destabilization of the Amundsen sea's glaciers would indeed undermine the entirety of West Antarctica, as has long been feared."

https://www.washingtonpost.com/news/energy-environment/wp/2015/11/02/scientists-confirm-their-fears-about-west-antarctica-that-its-inherently-unstable/

Global Sea Level Likely to Rise as Much as 70 Feet in Future Generations (March 19, 2012)
"Even if humankind manages to limit global warming to 2 degrees Celsius (3.6 degrees Fahrenheit)--as the Intergovernmental Panel on Climate Change recommends--future generations will likely have to deal with a completely different world.

One with sea levels 40 to 70 feet higher than at present, according to research results published this week in the journal Geology."

http://www.nsf.gov/news/news_summ.jsp?cntn_id=123545

Greenland meltwater storage in firn limited by near-surface ice formation
Nature Climate Change (2016) doi:10.1038/nclimate2899
"Approximately half of Greenland's current annual mass loss is attributed to runoff from surface melt[1]. At higher elevations, however, melt does not necessarily equal runoff, because meltwater can refreeze in the porous near-surface snow and firn[2]. Two recent studies suggest that all[3] or most[3, 4] of Greenland's firn pore space is available for meltwater storage, making the firn an important buffer against contribution to sea level rise for decades to come[3]. Here, we employ *in situ* observations and historical legacy data to demonstrate that surface runoff begins to dominate over meltwater storage well before firn pore space has been completely filled. Our observations frame the recent exceptional melt summers in 2010 and 2012 (refs 5,6), revealing significant changes in firn structure at different elevations caused by successive intensive melt events. In the upper regions (more than ~1,900 m above sea level), firn has undergone substantial densification, while at lower elevations, where melt is most abundant, porous firn has lost most of its

capability to retain meltwater. Here, the formation of near-surface ice layers renders deep pore space difficult to access, forcing meltwater to enter an efficient[7] surface discharge system and intensifying ice sheet mass loss earlier than previously suggested[3]”

A “cap of ice” is forming under large parts of the Greenland glacier and preventing meltwater from being stored in the glacier, thus resulting in more meltwater reaching the ocean and this is raising sea levels more than expected.

http://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate2899.html

J. Carbon Dioxide Removal Costs

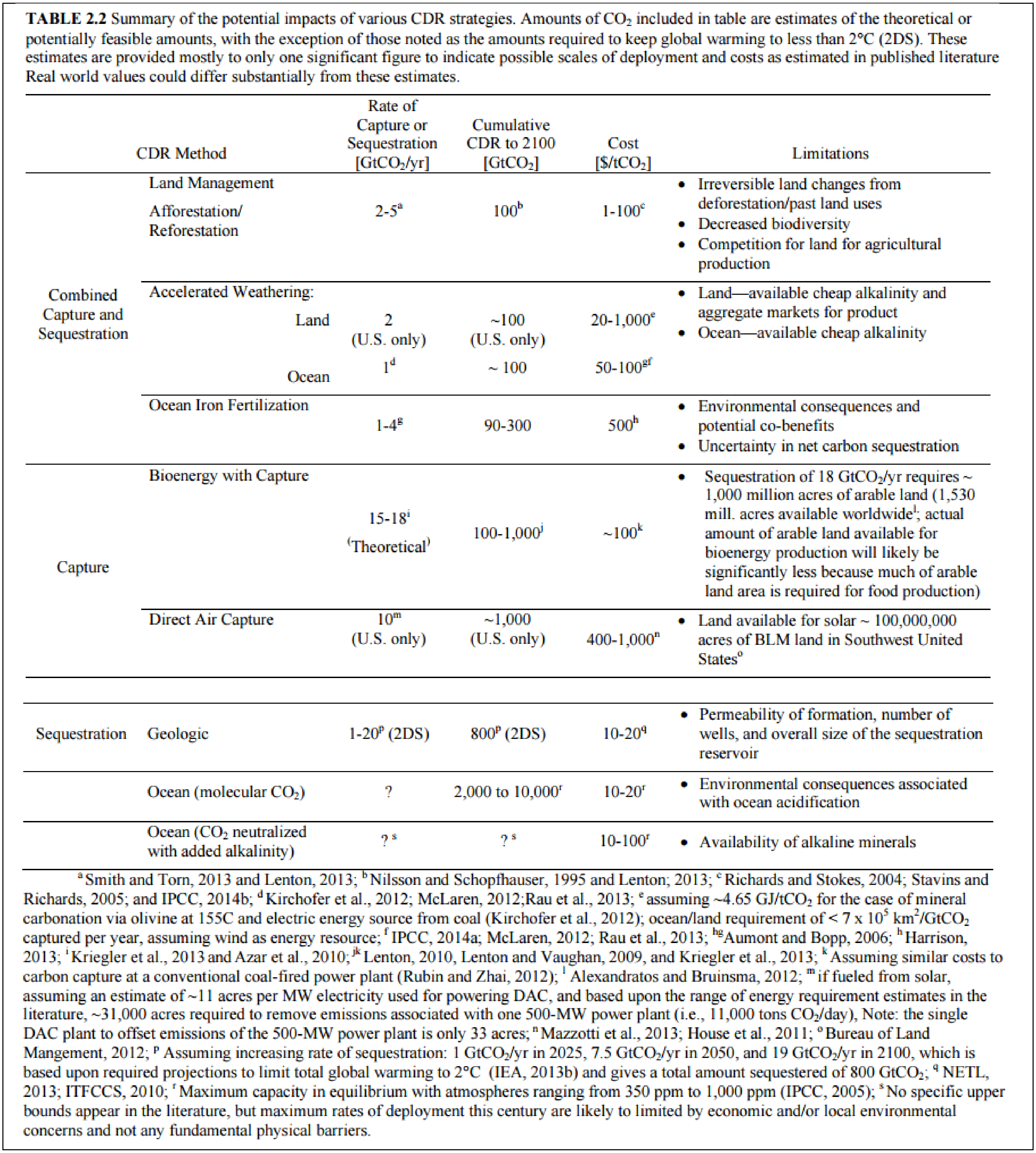


TABLE 2.2 Summary of the potential impacts of various CDR strategies. Amounts of CO_2 included in table are estimates of the theoretical or potentially feasible amounts, with the exception of those noted as the amounts required to keep global warming to less than 2°C (2DS). These estimates are provided mostly to only one significant figure to indicate possible scales of deployment and costs as estimated in published literature Real world values could differ substantially from these estimates.

CDR Method		Rate of Capture or Sequestration [$GtCO_2/yr$]	Cumulative CDR to 2100 [$GtCO_2$]	Cost [$\$/tCO_2$]	Limitations
Combined Capture and Sequestration	Land Management Afforestation/ Reforestation	2-5[a]	100[b]	1-100[c]	• Irreversible land changes from deforestation/past land uses • Decreased biodiversity • Competition for land for agricultural production
	Accelerated Weathering: Land	2 (U.S. only)	~100 (U.S. only)	20-1,000[e]	• Land—available cheap alkalinity and aggregate markets for product • Ocean—available cheap alkalinity
	Ocean	1[d]	~ 100	50-100[gf]	
	Ocean Iron Fertilization	1-4[g]	90-300	500[h]	• Environmental consequences and potential co-benefits • Uncertainty in net carbon sequestration
Capture	Bioenergy with Capture	15-18[i] (Theoretical)	100-1,000[j]	~100[k]	• Sequestration of 18 $GtCO_2/yr$ requires ~ 1,000 million acres of arable land (1,530 mill. acres available worldwide[l]; actual amount of arable land available for bioenergy production will likely be significantly less because much of arable land area is required for food production)
	Direct Air Capture	10[m] (U.S. only)	~1,000 (U.S. only)	400-1,000[n]	• Land available for solar ~ 100,000,000 acres of BLM land in Southwest United States[o]
Sequestration	Geologic	1-20[p] (2DS)	800[p] (2DS)	10-20[q]	• Permeability of formation, number of wells, and overall size of the sequestration reservoir
	Ocean (molecular CO_2)	?	2,000 to 10,000[r]	10-20[r]	• Environmental consequences associated with ocean acidification
	Ocean (CO_2 neutralized with added alkalinity)	? [s]	? [s]	10-100[r]	• Availability of alkaline minerals

[a] Smith and Torn, 2013 and Lenton, 2013; [b] Nilsson and Schopfhauser, 1995 and Lenton; 2013; [c] Richards and Stokes, 2004; Stavins and Richards, 2005; and IPCC, 2014b; [d] Kirchofer et al., 2012; McLaren, 2012;Rau et al., 2013; [e] assuming ~4.65 GJ/tCO_2 for the case of mineral carbonation via olivine at 155C and electric energy source from coal (Kirchofer et al., 2012); ocean/land requirement of $< 7 \times 10^5$ $km^2/GtCO_2$ captured per year, assuming wind as energy resource; [f] IPCC, 2014a; McLaren, 2012; Rau et al., 2013; [hg]Aumont and Bopp, 2006; [h] Harrison, 2013; [i] Kriegler et al., 2013 and Azar et al., 2010; [jk] Lenton, 2010, Lenton and Vaughan, 2009, and Kriegler et al., 2013; [k] Assuming similar costs to carbon capture at a conventional coal-fired power plant (Rubin and Zhai, 2012); [l] Alexandratos and Bruinsma, 2012; [m] if fueled from solar, assuming an estimate of ~11 acres per MW electricity used for powering DAC, and based upon the range of energy requirement estimates in the literature, ~31,000 acres required to remove emissions associated with one 500-MW power plant (i.e., 11,000 tons CO_2/day), Note: the single DAC plant to offset emissions of the 500-MW power plant is only 33 acres; [n] Mazzotti et al., 2013; House et al., 2011; [o] Bureau of Land Mangement, 2012; [p] Assuming increasing rate of sequestration: 1 $GtCO_2/yr$ in 2025, 7.5 $GtCO_2/yr$ in 2050, and 19 $GtCO_2/yr$ in 2100, which is based upon required projections to limit total global warming to 2°C (IEA, 2013b) and gives a total amount sequestered of 800 $GtCO_2$; [q] NETL, 2013; ITFCCS, 2010; [r] Maximum capacity in equilibrium with atmospheres ranging from 350 ppm to 1,000 ppm (IPCC, 2005); [s] No specific upper bounds appear in the literature, but maximum rates of deployment this century are likely to limited by economic and/or local environmental concerns and not any fundamental physical barriers.

http://www.nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration

Given both the amount of CO2 that needs to be removed (over 2000 GTCO2) and the rate of capture for the various alternatives, BECCS and DAC are the only viable alternatives for CDR. And given the limitations of land for BECCS, DAC is the only method that captures CO2 in the needed quantities. Assuming technological advances, if DAC costs can be reduced by a factor of five, costs later this century might be $100/ton CO2.

K. Global Greenhouse Gas Emissions (1970-2010)

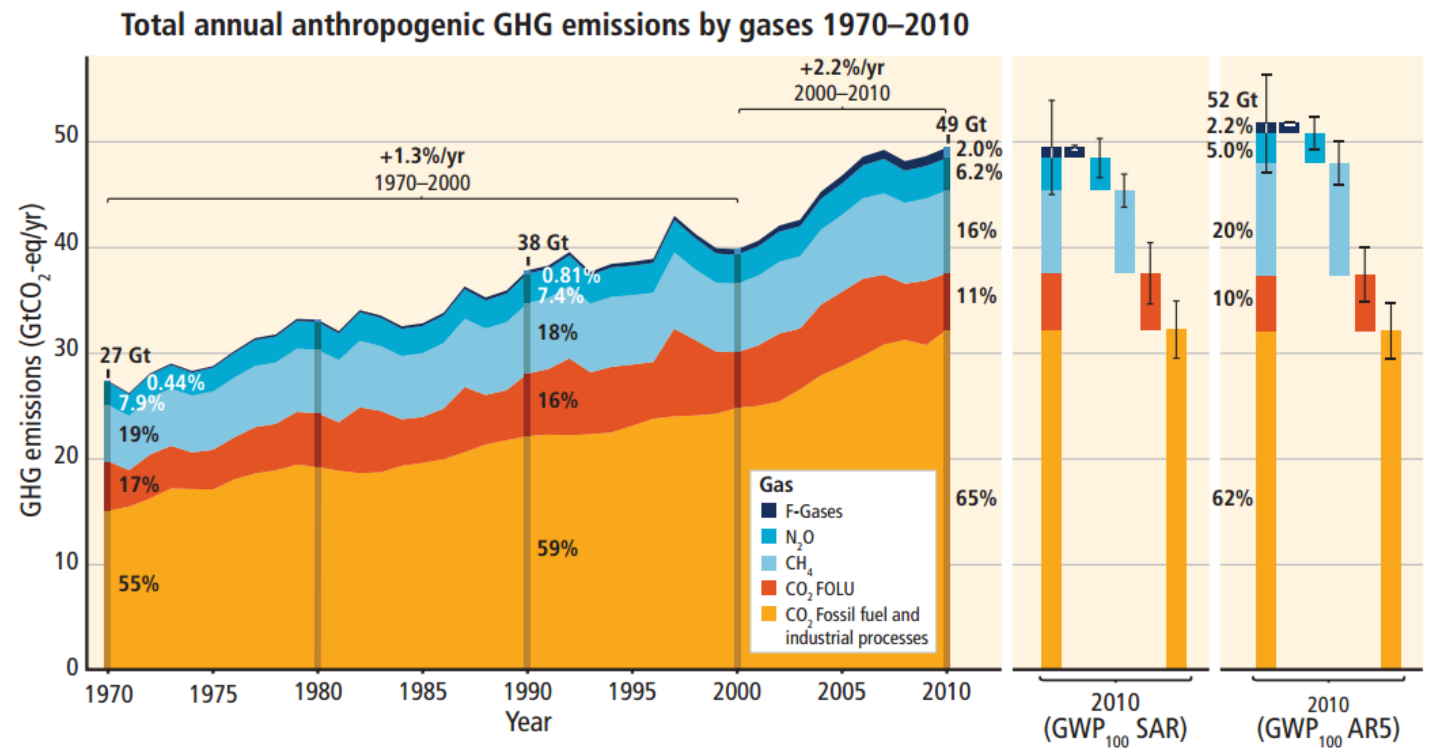


Figure SPM.2 | Total annual anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO2-equivalent per year, GtCO2-eq/yr) for the period 1970 to 2010 by gases: CO2 from fossil fuel combustion and industrial processes; CO2 from Forestry and Other Land Use (FOLU); methane (CH4); nitrous oxide (N2O); fluorinated gases covered under the Kyoto Protocol (F-gases). Right hand side shows 2010 emissions, using alternatively CO2-equivalent emission weightings based on IPCC Second Assessment Report (SAR) and AR5 values. Unless otherwise stated, CO2-equivalent emissions in this report include the basket of Kyoto gases (CO2, CH4, N2O as well as F-gases) calculated based on 100-year Global Warming Potential (GWP100) values from the SAR (see Glossary). Using the most recent GWP100 values from the AR5 (right-hand bars) would result in higher total annual GHG emissions (52 GtCO2-eq/yr) from an increased contribution of methane, but does not change the long-term trend significantly. {Figure 1.6, Box 3.2}

https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf