Will Geoengineering Be Necessary?
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http://ccdatacenter.org/documents/WillGeoengineeringBeNecessary.pdf

Summary

Geoengineering will become necessary if it becomes obvious that catastrophic climate change cannot be prevented by mitigation and reasonably-priced carbon sequestration alone. One approach to determining if geoengineering will be necessary is estimating the contribution that all of the climate factors (both anthropogenic and natural) will make towards global warming by mid-century and then estimating the carbon sequestration costs needed to put the temperature trajectory on a path that will limit the temperature increase in 2100 to 2° C above pre-industrial levels. If the sequestration costs are too high (perhaps over hundreds of billions of dollars per year) then geoengineering will likely be the only viable option for limiting the temperature increase to a "safe" level.

Meeting the UNFCC's 1000 **giga**ton carbon budget has been the primary focus of analysts seeking emission pathways that limit the2100 temperature increase to less than 2° C above pre-industrial levels , even though it is generally accepted that the budget is too high. Since most climate believe that the Earth's climate sensitivity to a doubling of atmospheric carbon dioxide is at least 3.0° C, another approach is to look for pathways that result in a radiative forcing of 2.7 W m-2 in 2100, as the equilibrium temperature increase for a radiative forcing of about 2.7 W m-2 is about 2.0° C (note that the IPCC's RCP 2.6, which results in a radiative forcing of 2.6 W m-2 in 2100, was designed to limit the temperature increase to a bit less than 2.0° C). Since the oceans will continue to absorb CO2 after "net zero" CO2 emissions have been achieved, a reasonable mid-century target for radiative forcing is 2.9 W m-2. Geoengineering then needs to be considered only when the costs of meeting that goal through mitigation and carbon sequestration become prohibitive.

There are several important contributors to radiative forcing in addition to anthropogenic greenhouse gas emissions - peat and other soils, reservoirs, permafrost, aerosol reduction, and the change in the surface albedo in the Arctic region. Together, these could result in more than 1.2 W m-2 of additional radiative forcing by mid century. Adding this to the current radiative forcing (about 2.5 W m-2) and taking into account both anthropogenic CO2 emissions (0.44 W m-2) and sequestration from afforestation and soil building (-0.17 W m-2), a reasonable estimate for the radiative forcing in mid-century is about 4.0 W m-2, assuming no "mechanical" carbon sequestration (e.g., CCS, BECCS, DAC). Meeting the 2.9 W m-2 mid-century target would then require capturing and sequestering about 250 GTC of carbon at a minimum cost of about $40 Trillion. Since $1 Trillion per year is more than our society will be willing to spend on carbon sequestration and since 2°C of warming will almost certainly trigger significant natural greenhouse gas emissions in the Arctic region, some amount of geoengineering will be needed to limit the temperature increase in order to prevent catastrophic global warming.

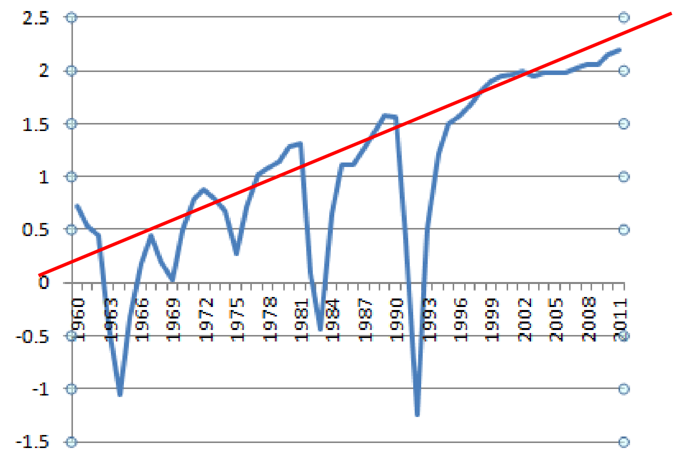
Global Warming and Radiative Forcing

Most climate scientists believe that the climate sensitivity for a doubling of atmospheric CO2 is about 3°C. Given the direct correlation between radiative forcing and atmospheric CO2, the following table shows the equilibrium temperature increase for various amounts of radiative forcing:

Effective Radiative Forcing (W/m-2)	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7
Equiv. CO2e PPM	348	354	361	368	375	382	389	397	404	412	419	427	435	444	452	460
Temp Increase (°C)	0.8	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.8	1.9	2.0

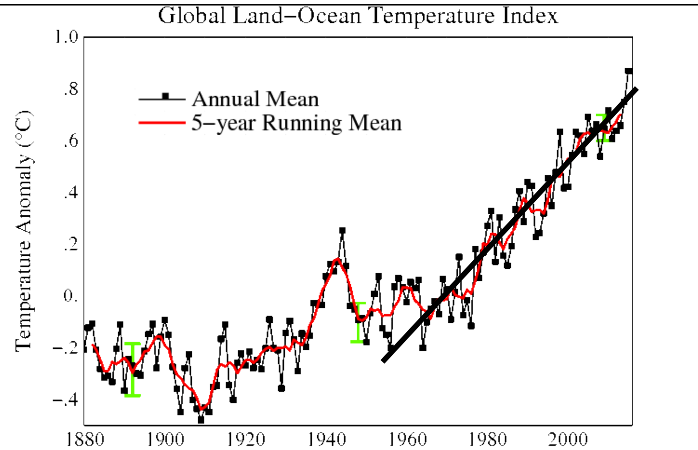
Rate of Global Warming

Based on data from NASA (Figure 1), the net radiative forcing has been increasing at a rate of about 0.37 W m-2 per decade since 1960. And at the same time the temperature as increased at about half that rate, about 0.19°C per decade (Figure 2). By looking at these trends over the last 50 years (and extrapolating this to 2020) and assuming a climate sensitivity of 3°C for a doubling of atmospheric CO2 (see Table 1) it appears that the increasing energy imbalance is not causing the global temperature to increase more rapidly, and, as a result, the equilibrium temperature is increasing at almost twice the rate as that of the global temperature (i.e., the global temperature increasing at about .19°C per decade but we are committing ourselves to a temperature increase of about .37°C per decade).



Based on the IPCCs' "Climate Change 2013 The Physical Science Basis" (AR5) - Pages 1408-1409

Figure 1 - Historical net forcing



http://data.giss.nasa.gov/gistemp/graphs_v3/
http://data.giss.nasa.gov/gistemp/graphs_v3/Fig.A2.gif

Figure 2 - Historical temperature increase

Current Radiative Forcing

According to the IPCC the total radiative forcing in 2011 was about 2.3 W m-2, and, with total radiative forcing increasing at about .4 W m-2 per decade, the total forcing is currently about 2.5 W m-2.

Radiative Forcing in 40-50 Years

Assuming that a relatively aggressive greenhouse gas emissions reduction effort is undertaken without any "mechanical" sequestration, the radiative forcing in 40-50 years will increase by about 1.5 W m-2, resulting in a total of about 4.0 W m-2:

	Global Warming Factor	Adjustments for 2060	RF Change	Description
Emissions		GTC	W m-2	(100 GTC =0.4 W/m-2)
1	CO2	110	0.44	2% increase in emissions through 2025 and then a two percent reduction per year (assumes a 45% airborne factor)
2	Peat/soils	45	0.18	"Drainage of peat soils results in carbon dioxide (CO2) and nitrous oxide (N2O) emissions of globally 2-3 Gt CO2-eq per year (Joosten & Couwenberg 2009)" http://www.wetlands.org/Portals/0/publications/Report/web_Methane_emissions_from_peat_soils.pdf

3	Reservoirs	30	0.12	http://www.climatecentral.org/news/greenhouse-gases-reservoirs-fuel-climate-change-20745 *Methane emissions from reservoirs contribute about .7GTC of CO2 equivalent per year, resulting in about 30 GTC through 2060 and 60 GTC through 2100.*
4	Permafrost	30	0.12	"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 http://ccdatacenter.org/documents/FeedbackFromPermafrost.pdf)
5	Afforestation/ Soils	-40	-0.17	Hansen estimates that up to 100 GTC could be sequestered with afforestation and soil management by 2100. Perhaps 40% of this amount could happen in the next 40-50 years ("Young People's Burden: Requirement of Negative CO2 Emissions" (October 4, 2016) (http://www.earth-syst-dynam-discuss.net/esd-2016-42/)
6	Other			
Radiative Forcing		W m-2	W m-2	
7	Greenhouse gases	0.0	0.0	Methane emissions have been increasing in recent years, but RCP 2.6 expects methane emissions to be 1/2 of 2010 emissions in 2100. So this analysis assumes that the RF from methane and other greenhouse gases will not be changed in 2060
8	Aerosols	0.5	0.5	Aerosols from the burning of fossil fuels, accounting for about 1 W m-2, mask about .5°C of warming. Since the aerosols "wash out" quickly, a rapid reduction of coal burning would likely result in rapid warming of .5°C. (http://www.pik-potsdam.de/~mmalte/simcap/publications/Hare_Meinshausen_2004_WarmingCommitment_PIK-Report.pdf) *Half of that value is used here as some fossil fuel emissions are apt to continue beyond the next 40-50 years*
9	Surface Albedo Change	0.3	0.3	According to Soden and Held (2006) surface albedo changes (primarily Arctic sea ice and Northern Hemisphere snow cover extent) contribute about 6% of the total radiative forcing at the global tropopause in models used by the IPCC. If the same percentage applies to surface warming, then the estimated radiative forcing for 2060 needs to be adjusted by at least 0.3 W m-2 http://ccdatacenter.org/documents/ImplicationsofExpectedRadiativeForcing.pdf (See also the following 2011 article, which concluded that "the albedo feedback [between 1979 and 2008] from the Northern Hemisphere cryosphere falls between 0.3 and 1.1 W m−2 K −1 , substantially larger than comparable estimates obtained from 18 climate models. " http://data.engin.umich.edu/faculty/flanner/content/ppr/FlS11.pdf)

10	Tundra Greening			
11	Other			
	Total		**1.5**	

See http://ccdatacenter.org/documents/TemperatureSensitivitytoChangesinRadiativeForcingsandCO2Emissions.pdf for the derivation of the formula the converts GTC to radiative forcing. Note that a rough estimate can be obtained as follows: Current CO2 emissions around 10 GTC per year, so emissions over 10 years would be about 100 GTC. With an "airborne fraction" of about 45%, about 45 GTC ends up in the atmosphere. Since 2.12 GTC will add 1 PPM of CO2, about 21 PPM of CO2 is added the atmosphere, which is close to the current rate of 2.1 PPM/year. Radiative forcing is increasing close to 0.4 W m-2/decade, so 100 GTC of CO2 emissions will increase the radiative forcing by about 0.4 W m-2.

Target Values for Radiative Forcing for 2100

Possible values for the long-range target value for radiative forcing include:

#	W/m-2	Description
1	1.3	James Hansen - there are "slow feedbacks" (glacier ice melt, sea level rise, etc.) which will likely "kick in" (and be out of our control) if the temperature stays much above that of the Holocene (a 0.25° C to 0.75° C increase over preindustrial times) for an extended period of time (decades to a century), so the total radiative forcing must be kept below this value ("Young People’s Burden: Requirement of Negative CO2 Emissions" (October 4, 2016) (http://www.earth-syst-dynam-discuss.net/esd-2016-42/)
2	1.6	The radiative forcing for the 1°C temperature increase through 2015. Radiative forcings from surface albedo in the Arctic are already contributing 0.25-.50 W m-2 to the total, and natural emissions from soils, permafrost, and reservoirs are contributing additional greenhouse gas emissions. The combination of all of these is probably sufficient to lead to "runaway global warming" (8-10°C, not like Venus) as the additional warming causes additional greenhouse gases to be released in the Arctic region in a feedback loop.
3	2.2	The "lower bound" of the Paris agreement
4	2.7	The "upper bound" of the Paris agreement

Radiative Forcings in RCP 2.6

The RCP 2.6 pathway is supposed to demonstrate an emissions pathway that will result in a temperature increase of about 2°C by 2100. The following tables show some of the radiative forcing values from the IPCC's AR5 for both the . Table 6 shows the radiative forcing of some of the "climate factors" both 2011 and 2100, and Table 5 lists the radiative forcing at the end of each decade for RCP 2.6. Note that radiative forcing from all of the greenhouse gases does not change from 2011 to 2100, but just shifts significantly from methane and halocarbons to carbon dioxide. Note also that the IPCC data in "The Physical Science Basis" did not specifically list the aerosol radiative forcings after 2011. Since the majority of the aerosols come from the burning of fossil fuels, it's hard to see how the RCP 2.6 model "makes up" for the additional forcing that will come as fossil fuel use is reduced significantly (they could be assuming lots of CCS and BECCS and that these would both continue to emit aerosols). In addition, assuming the current growth rate in radiative forcing (0.43 W m-2) continues, the IPCC's 2030 value will be reached by 2023, and the 2040 value (which is just about the maximum value) will be reached in 2026. (Note: is surface albedo changes are taken into account then the IPCC's 2030 value will be reached by 2019, and the 2040 value will be reached in 2022.)

	2011	RCP2.6 (2100)
CO2	1.816	2.220
CH4	0.425	0.270
N20	0.195	0.230
Halocarbons	0.395	0.142
Greenhouse Gases	**2.831**	**2.862**
Statospheric	-0.050	-0.075
Tropospheric	0.400	0.170
Ozone	**0.350**	**0.140**
Strato. H20	0.073	
Land Use	-0.150	
Black Carbon	0.040	
Albedo	**-0.110**	
Contrails	0.050	
Radiation Inter.	-0.450	
Cloud Inter	-0.450	
Aerosols	-0.900	
Total Anthropogenic	**2.294**	
Solar Radiance	0.030	
Total IPCC	**2.324**	**2.600**

Table 5. Radiative Forcing Changes since 1750

RCP 2.6		
Year	Radiative Forcing	Change Per Decade
2010	2.17	
2020	2.53	0.36
2030	2.70	0.17
2040	2.84	0.14
2050	2.85	0.01
2060	2.77	-0.08
2070	2.71	-0.06
2080	2.60	-0.11
2090	2.64	0.04

From Page 1436 "Total anthropogenic plus natural ERF (W m–2) from CMIP5 and CMIP3, including historical" (Adjusted by .2 W m-2 to bring in line with values for 2011 and 2020)

Data based on the IPCCs' "Climate Change 2013: The Physical Science Basis" (AR5)

Table 6. Radiative Forcing by Decade for RCP 2.6

Target Radiative Forcing for 2060

Based on RCP 2.6, which shows a 0.2 W m-2 decline in radiative forcing after the peak value is reached and net CO2 emissions approach zero, the following table shows the amount of CO2 that would need to be sequestered in order to meet the various radiative forcing targets for 2100 assuming that we are on a trajectory for about 4.0 W m-2 by 2060

2100 Target Temperature (°C)	0.8	1.0	1.5	2.0
2100 Target RF	1.3	1.6	2.2	2.7
2060 Target RF (0.2 more than 2100)	1.5	1.8	2.4	2.9
RF of sequestered CO2 to meet the target	2.5	2.2	1.6	1.1
GTC to be sequestered to meet the target	563	495	360	248
Minimal Cost ($150/ton C)	84	74	54	37

Sequestering 90 GTC of CO2 will reduce the radiative forcing by .4 W m-2 at a cost of $13,500 to $31,500 Trillion (http://ccdatacenter.org/documents/TemperatureSensitivitytoChangesinRadiativeForcingsandCO2Emissions.pdf)