Climate Change Observations

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Summary

I don't think that climate scientists are as forthcoming as they should be with respect to the severity of the likely global warming expected this century. More and more articles are stating that that climate scientists no longer have confidence that the temperature increase by 2100 can be limited to 2°C without very significant negative emissions (i.e*., any optimism for preventing catastrophic climate change rests on the assumption that our world society will be willing to spend trillions of dollars per year to capture and sequester carbon dioxide*). In addition, 2°C is seen as too high a target (e.g., James Hansen calls for limiting the long-term temperature increase to less 1° C (and limiting the atmospheric CO2 to 320 PPM) in order to keep the "slow feedbacks" from becoming significant).

With (1) the current temperature increase of over 1° C; (2) projected anthropogenic emissions from fossil fuels; (3) the additional radiative forcing from an Arctic Ocean that is expected to become ice-free in September by mid century; (3) the projected natural emissions from global soils (including from permafrost); (4) the current atmospheric energy imbalance; (5) the temperature increase being masked by aerosols from the burning of fossil fuels; (6) and the expense of annually capturing (and sequestering) gigatons of CO2, it appears very likely that the global temperature increase will significantly exceed 2°C by 2100. As a result, the "slow feedbacks" cannot be prevented from "becoming significant" unless the Arctic region can be cooled substantially. This implies that, unless we implement some sort of solar radiation management to cool the Arctic, we are likely on a path for an eventual temperature increase of at least 4°C, which would be catastrophic for our civilization.

Observations

1. Sea level rise will be catastrophic well before 2100 no matter how much emissions are reduced[1]

An aggressive emissions reduction effort might slow SLR down just a bit, but not significantly, and certainly not enough to prevent catastrophic sea level rise of 6-9 meters in the next 100-200 years.

2. Climate models do not adequately take into account non-anthropogenic sources[2]

Climate models appear to assume that most of the warming will be the result of anthropogenic emissions. They do include some natural fast-feedbacks (e.g., Arctic ocean, snow cover, clouds, etc.) but underestimate how significant they will be[3,4,5]. In addition, it looks like most non-anthropogenic sources (e.g., peat, permafrost[2], reservoirs[6], soils[4], etc.) are not included. One reason for this is that it is very difficult to accurately model the expected greenhouse gas emissions (or radiative forcing) from the various climate feedbacks - "what cannot be modeled reasonably accurately is often ignored".

3. We don't need any more climate model runs or more sophisticated climate models

The climate models have served their purpose, as they have shown that increasing levels of greenhouse gases will increase the Earth's temperature. Most people don't realize it, but the climate models do not attempt to estimate the temperature increase based on the various "climate factors" (e.g., atmospheric greenhouse gas concentrations, clouds, aerosols, etc.). Instead, the models used by the IPCC are outcome-based, that is, they are set up to "tweak" variables for population growth, energy consumption, energy sources, etc., until a specific radiative forcing (resulting in a range of temperature increases) is reached in the year 2100 (e.g., the RPC 2.6 models are run over and over until they result in a radiative forcing of 2.6 W m-2 in 2100). But, because of the complexity of the climate system and the inability of the models to accurately take into account many of the climate factors (e.g., Arctic sea ice melt, greenhouse gas emissions from the thawing permafrost, etc.), their results are known to be overly conservative. But since they are accepted by the public as being reasonably accurate, the public has no idea as to how dire our current situation is.

4. Eliminating fossil fuels will cause a very significant temperature increase (at least 0.5°C is likely)[7]

In addition, "[M]easured Earth energy imbalance, +0.58 W/m^2 during 2005-2010, implies that the aerosol forcing is about -1.6 W/m^2, a greater negative forcing than employed in most IPCC models"[8] (which would imply a much greater warming than 0.5°C when the burning of fossil fuels is stopped) *If we greatly reduce the burning of coal, the masking of aerosols forcing would be reduced, perhaps adding the equivalent of 100 GTC to the atmosphere (my estimate).*

5. It is almost certain that the 2C target cannot be met

According to one recent study[9], a 5%/year mitigation rate is required to meet the 2°C - a rate that would be all but impossible to attain. And according to a recent article in *Nature Climate Change*, "[t]he likely range of global temperature increase is 2.0–4.9◦C, with median 3.2◦C and a 5% (1%) chance that it will be less than 2◦C (1.5◦C)."[10]

In addition, all of the IPCC models for a 2°C pathway where emissions peaked after 2011 assume "large-scale negative emissions technologies"[11], which is very unlikely to happen (see #8 below).

6. The carbon budget for 2°C is way to high - in fact, there is no budget left

Michael Mann thinks that we have to limit atmospheric CO2 to 405 PPM to meet the 2°C target[7], a level that we have already passed. This implies that there is no CO2 emissions budget remaining. Yet most analyses of what needs to be done are based a remaining budget of 400 GTC.

7. Based on paleoclimatology proxy data and the amount of greenhouse gases currently in the atmosphere, we should expect a temperature increase over 3° C

If the future global warming were entirely dependent on the greenhouse gases currently in the atmosphere (about 490 PPMCO2e[12] then, based on paleoclimatic data, we would be committed to well over 2.0°C of warming and perhaps 40 meters of sea level rise (the current concentration of greenhouse gases in the atmosphere is much greater that it was 3 million years ago when temperatures were 2-3°C warmer than pre-industrial times).

8. The 2° C target is too high

The real target for a temperature increase should not be what humans can tolerate but should be below the temperature above which the annual contributions from natural feedbacks overwhelm societies ability to compensate for (e.g., by removing a corresponding amount of CO2 from the atmosphere). For example, if greenhouse gas emissions from the thawing permafrost and other natural causes were equivalent to 4 GTC[14] per year, we would need to remove (and sequester) 4 GTC of carbon from the atmosphere - at a cost of about $400/ton of CO2[15], this would amount to around $1.6 Trillion per year - just to keep the temperature from increasing further. One major problem is that it is not possible to develop models that can accurately predict either the future contributions from the natural feedbacks or the future costs to remove CO2 from the atmosphere ("Direct Air Capture" - DAC). But based upon the magnitude of the feedbacks that we are already seeing, the current (and projected) costs of DAC, and the above analysis, it is possible that we already on a trajectory to catastrophic climate change, even with an aggressive (but realistic) emissions mitigation effort. What is needed is a quantitative analysis of all of (1) all of the climate factors, (2) CDR costs for realistic removal amounts, (3) and an estimate of what our society would be willing to pay. Only then can a realistic temperature target (and budget) be set.[16]

James Hansen calls for limiting the long-term temperature increase to less 1° C (and limiting the atmospheric CO2 to 350 PPM) in order to keep the "slow feedbacks" from becoming significant[17].

"So what would be safe? The answer is that "limiting the period and magnitude of temperature excursion above the Holocene range is crucial to avoid strong stimulation of slow feedbacks".

In other words, aim to get temperatures back under the Holocene maximum of 0.5ºC, which implies a level of greenhouse gases below 320 parts per million (ppm) of atmospheric carbon dioxide (CO2), compared to the current level of 405 ppm."[18]

9. We need to remove lots of CO2 to prevent catastrophic climate change

Not only do we need to remove (and sequester) enough CO2 from the atmosphere to reduce its concentration from 410 PPM to 350 PPM (and even 320 PPM), we also need to sequester the equivalent of all future greenhouse gas emissions, both anthropogenic and natural. (And we might also need to compensate for the warming that is being masked by aerosols.) "Proposed methods of extraction such as bioenergy with carbon capture and storage (BECCS) or air capture of CO2 have minimal estimated costs of 89-535 trillion dollars this century and also have large risks and uncertain feasibility"[19] And a "back of the envelope" estimate of future emission-equivalents and carbon dioxide removal costs shows that we'd need to spend about $4 Trillion per year to make the reductions needed to limit the temperature increase to 1°C[20]. And even assuming that the remaining carbon budget is 400 GTC, we'd still need to sequester 25-50% of today's emissions by 2100[21].

10. But Carbon Capture and Storage (CCS) and Direct Air Capture (DAC) will never be implemented at sufficient scale

CCS and DAC will always used when make it makes economic sense on a timescale of years (for enhanced oil recovery, carbon-based products, etc.). But there is a maximum that society will be willing to pay for CCS and DAC(and it's certainly less than $2 trillion per year), and if that maximum amount is not adequate to "guarantee" that catastrophic climate change can be stopped, then CCS and DAC for just removing CO2 (without a direct economic benefit) won't happen. So I doubt any politicians will allow significant money to be spent on CCS/DAC until there is a reasonable accounting of expected costs AND the annual costs are "reasonable" AND the "reasonable" spending on CCS/DAC will be sufficient to prevent catastrophic climate change.

Even though costs for both CCS and DAC can be reduced over time, the problem is that by the time costs are reduced enough to make the CO2 extraction (and sequestration) economically feasible, the annual emission-equivalents from natural feedbacks will likely overwhelm our ability to compensate for them with DAC.

For example, assuming that we need to get atmospheric CO2 to 350PPM and that it takes emissions of about 4.4 GTC to increase atmospheric CO2 by 1PPM (4.4*.5/2.12), about 260 GTC would need to be removed from the atmosphere to reduce its concentration to that level. If emission (currently about 10 GTC/year) peak in 2020 and were reduced by 3% per year (an unrealistically high rate), total anthropogenic emissions would be about 270 GTC by 2060. If another 100 GTC are emitted by the permafrost while the temperatures are high enough to thaw it, the total emission-equivalent that would need to be sequestered is about 630 GTC. If that can be averaged over the rest of this century, then the amount that needs to be "air captured" and sequestered is about 8GTC per year (or about 80% of current emissions). At $500/ton C (current estimates range from around $220/ton carbon to capture CO2 to over $3,500/ton of carbon for both capture and sequestration[22], that's $4 trillion per year (which is obviously more than we'd be willing to pay) (See Footnote 23 for additional arguments as to why CDR will never be implemented as scale.)

11. The dollar "cost of action" is higher than "cost of inaction" (without geoengineering)

Natural disasters caused $175 billion in damage in 2016, and with over $30 billion for earthquakes, the total for weather-related natural disasters is under $150 billion. if the average for the rest of the century is triple that ($500 billion) then the total cost by 2100 would be about $40 trillion. That's much less than the cost of mitigation and CCS to reduce atmospheric CO2 to 350 PPM ($89-535 trillion).

"Insurance losses from natural catastrophes have increased from almost $10 billion to nearly $50 billion per year since the 1980s."[16]

12. How much we emit the next few decades really doesn't matter, so we should continue to let the "free market" reduce emissions as much as possible

Mitigation of greenhouse gases has primarily been driven by the "free market" and will likely continue to be in the future. Environmental regulations (e.g., renewable portfolio standards, CAFE standards, carbon pricing, etc.) have helped some, but probably not very much. Since mitigation and natural sequestration alone will not be sufficient to prevent catastrophic climate change and since CCS and DAC will be too expensive for the foreseeable future, the only real hope is that DAC will eventually be cheap enough to remove the necessary CO2 from the atmosphere. If that is the case, it doesn't make too much difference how much we emit (e.g., if we can pay to sequester X tons of CO2 we can probably pay to sequester 1.5X tons). And if DAC never happens, then reducing emissions now will only provide a few extra years before catastrophic climate change occurs (or we start some sort of solar radiation management). Not that mitigation is a bad idea, but the extra costs of reducing emissions now must be weighed against the costs of preparing for catastrophic climate change (I.e., there is no need to "act now" where "acting now" incurs substantial costs that cannot be recouped over a relatively short period of time - just pay for mitigation that makes economic sense and don't pay for CCS or DAC that does not make short-term economic sense.)

13. We need to cool the Arctic (and geoengineering is the only way to do it)

One major impediment to "solving" global warming is the increased radiative forcing caused by feedback loops in Arctic region as the decrease in the surface albedo and the greenhouse gas emissions from permafrost thawing have the potential to raise the Earth's temperature over an additional 0.5°C by 2100 (and by several degrees C in the following centuries). Since the Arctic Ocean is expected to be ice-free for several weeks as early as 2040 and the tundra may already be changing from a carbon sink to a carbon source, we appear to be at a point where we can only avert catastrophic climate change if we can cool the Arctic region enough to allow the sea ice to recover and to stop additional permafrost from thawing. And the longer we wait to do this the harder it becomes as we'd need to sequester the equivalent of all future emissions from the permafrost. (But if we expect DAC to become cheap enough, the amount of emissions from the permafrost doesn't make much difference.)

14. Other than geoengineering, there is no socially acceptable way to prevent global warming of less than 4°C

Since atmospheric CO2 must be reduced below 350PPM (to prevent significant contributions from natural feedbacks) and doing so will likely cost more than $200 trillion, the CO2 emission-equivalents from both natural feedbacks and anthropogenic sources will be enough to drive the temperature to 2 °C and then onto 4 °C no matter what action (other than solar radiation management) we take - it's just a matter of "when", not "if".

15. For such a significant problem, we are talking past each other. We need a core set of data/ideas on which most of us can agree

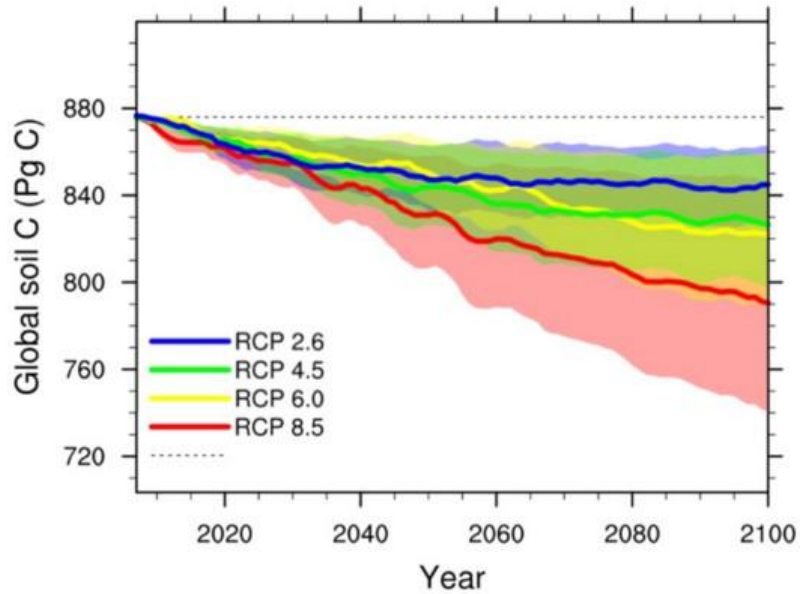
"The evidence that climate change is a serious problem that we must contend with now, is overwhelming on its own." according to Michael Mann. But we are NOT contending with it - there has been no serious discussion as to how bad it actually is and what can realistically be done. What is really needed is an analysis of all of the various "climate factors", a discussion of the limitations of climate models, and a realistic estimate of future emissions. Unfortunately, this will almost certainly show that the current atmospheric levels of greenhouse gases are already too high and that reducing them enough to prevent catastrophic climate change is too expensive even given the technological advances that are expected in the next 50 years. But at least we will be able to have a reasonable discussion of the steps that we should take to prevent catastrophic climate change. Footnote 24 contains a partial set of "climate factors" that should be considered when discussing future emissions and the likely temperature increase. Since our current climate models work to constrain the radiative forcing of the future climate to a specific value (rather than taking using specific values for the various climate factors and estimating the resulting temperature increase), if the results from the climate models could be presented as shown in footnote 24 it would be much easier to discus realistic solutions. (See footnote 25 for a pessimistic accounting of some of the climate factors).

Conclusion

Climate scientists (and the media) have a responsibility to discuss the above realities of global warming as "[i]t 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 well before 2100. We then have two main choices – we can either (1) use albedo modification to reduce the Earth's average temperature (in order to prevent the natural emissions and albedo changes from global warming feedbacks), or (2) start planning for catastrophic climate change. If we really want human civilization to survive for at least another thousand years then the sooner we can start having realistic conversations about our likely future the greater the chances of survival will be"[26].

Footnotes

1	**Estimates of Sea Level Rise by 2100 Have Tripled in the Past Few Years** June 26, 2017 Let's talk about those impacts on the assumption that we remain below two degrees Celsius. We're somewhere in the range of 1.5 to two degrees Celsius, and we see sea level rise within 100 to 200 years of six to nine meters as Dr. Rignot predicts. http://therealnews.com/t2/index.php?option=com_content&task=view&id=31&Itemid=74&jumival=19241
2	"It [(permafrost thawing)] 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
	Also, see http://ccdatacenter.org/documents/GlobalWarmingFeedbacks.pdf
3A	Brian J. Soden and Isaac M. Held ("An Assessment of Climate Feedbacks in Coupled Ocean–Atmosphere Models", 2006; http://journals.ametsoc.org/doi/full/10.1175/JCLI3799.1) estimated that the radiative forcing of the models they reviewed (roughly doubling in equivalent CO_2 between 2000 and 2100) was 4.3 W m^{-2} and, "[o]n average, the strongest positive feedback is due to water vapor (1.8 W m^{-2} K^{-1}), followed by clouds (0.68 W m^{-2} K^{-1}), and surface albedo (0.26 W m^{-2} K^{-1}), thus 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.
3B	In "Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008", Flanner, et. al., concluded that "cyrospheric cooling declined by 0.45 W m−2 from 1979 to 2008, with nearly equal contributions from changes in land snow cover and sea ice. On the basis of these observations, we conclude that the albedo feedback 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)

4	 We found that about 55 trillion kg of carbon could be lost by 2050. This value is equivalent to an extra 17% on top of current expected emissions over that time. These losses are like having another huge carbon emitting country on the planet, accelerating the rate of climate change. https://medium.com/@Alex_Verbeek/another-reason-to-be-worried-about-climate-change-1bf1e21e78e#.bzhqdsrsz
5	Climate models have underestimated Earth's sensitivity to CO2 changes, study finds (4/7/2016) A Yale University study says global climate models have significantly underestimated how much the Earth's surface temperature will rise if greenhouse gas emissions continue to increase as expected. Yale scientists looked at a number of global climate projections and found that they misjudged the ratio of ice crystals and super-cooled water droplets in "mixed-phase" clouds — resulting in a significant under-reporting of climate sensitivity. The findings appear April 7 in the journal Science. Equilibrium climate sensitivity is a measure used to estimate how Earth's surface temperature ultimately responds to changes in atmospheric carbon dioxide (CO2). Specifically, it reflects how much the Earth's average surface temperature would rise if CO2 doubled its preindustrial level. In 2013, the Intergovernmental Panel on Climate Change (IPCC) estimated climate sensitivity to be within a range of 2 to 4.7 degrees Celsius. The Yale team's estimate is much higher: between 5 and 5.3 degrees Celsius. Such an increase could have dramatic implications for climate change worldwide, note the scientists. http://news.yale.edu/2016/04/07/climate-models-have-underestimated-earth-s-sensitivity-co2-changes-study-finds
6	" Globally, reservoirs are responsible for about 1.3 percent of the world's man-made greenhouse gas emissions each year" http://www.climatecentral.org/news/greenhouse-gases-reservoirs-fuel-climate-change-20745 Methane emissions from reservoirs contribute about .7GTC of CO2 equivalent (.25 GTC) per year, resulting in about 30 GTC through 2060 and 60 GTC through 2100. Assuming coal emissions are almost eliminated, the that will add the equivalent of
7	**How Close Are We to 'Dangerous' Planetary Warming?**

	Michael Mann **Updated** Dec 23, 2016 [T]he 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). http://www.huffingtonpost.com/michael-e-mann/how-close-are-we-to-dangerous-planetary-warming_b_8841534.html
8	http://www.giss.nasa.gov/research/briefs/hansen_16/
	Hansen et al. 2011 Hansen, J., M. Sato, P. Kharecha, and K. von Schuckmann, 2011: Earth's energy imbalance and implications. *Atmos. Chem. Phys.*, **11**, 13421-13449, doi:10.5194/acp-11-13421-2011. Aerosol climate forcing today is inferred to be -1.6±0.3 W/m^2, implying substantial aerosol indirect climate forcing via cloud changes https://pubs.giss.nasa.gov/abs/ha06510a.html
	Ramanathan and Feng calculates a 0.9 °C temperature masking from aerosols http://www.theenergycollective.com/jim-baird/2378159/climate-change-the-choices-couldnt-be-starker
9	"For a carbon quota consistent with a 2 °C warming limit (relative to pre-industrial levels), the necessary long-term mitigation rates are very challenging (typically over 5% per year), both because of strong limits on future emissions from the global carbon quota and also the likely short-term persistence in emissions growth in many regions." http://www.nature.com/nclimate/journal/v4/n10/full/nclimate2384.html
10	https://www.nature.com/articles/nclimate3352.epdf
11	Kevin Anderson (2015) (open-access text) reports that of the 400 scenarios that have a 50% chance or greater of no more than 2 °C of warming, 344 assume large-scale negative emissions technologies. The remaining 56 scenarios have emissions peaking in 2010, which, as we know, did not happen. https://skepticalscience.com/print.php?n=3183

12

Greenhouse Gas Concentrations and Climate Implications

While there is good news of more progress in gradually slowing emissions growth, those numbers confront the reality of the cumulative nature of GHGs and the climate problem. Many analyses have focused on the target of 450 parts per million (ppm) as the limit for avoiding a temperature increase of more than 2°C above the pre-industrial average. Current GHG concentrations for Kyoto gases (**Figure 16**) are nearing 460 ppm CO_2-eq, and CO_2 concentrations are essentially at 400 ppm. We refer to Kyoto gases to denote those included in the emissions targets specified under the Kyoto Protocol. When all major GHGs, including chlorofluorocarbons (CFCs), are included, concentrations are currently nearing 490 ppm, as shown in **Figure 16** labeled CO_2-eq (IPCC). The use of 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 thousands of years due to their very long time lifetimes. In **Figure 16**, the seasonal cycle of CO_2 concentrations, due largely to the strong effect of northern hemisphere vegetation respiration, is smoothed to show the underlying trend (for details, see Huang *et al.* (2009), from which **Figure 16** is updated). The increase for all three time series has been nearly linear over the period, with CO_2 concentrations increasing by about 1.8 ppm/yr and all GHGs (CO_2-eq-IPCC) increasing at 3 ppm/yr. Note that here we use instantaneous radiative forcing to create CO_2-eq concentrations rather than GWPs because this calculation shows the contribution to warming at a point in time (see **Box 5**).

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 16**; and (2) 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, their concentrations would decrease almost immediately and their cooling effect would no longer mask a substantial amount of GHG-induced warming. Also, 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 while still seeing relatively small impacts on the global temperature.

The implication of our emissions projections are that CO_2 concentrations approach 710 ppm by 2100, which is 40 ppm less than our 2014 Outlook, but still with no sign of stabilizing (**Figure 17**). Also shown are CO_2 concentration pathways from the IPCC. These include the four Representative Concentration Pathways (RCP) scenarios (van Vuuren *et al.*, 2011) in dashed lines and the A1FI, A1B, A2 and B1 scenarios from the special report on emissions scenarios (SRES) (Nakicenovic *et al.*, 2000) in dotted lines. The smoothed Mauna Loa record through 2015 (as shown in **Figure 16**) is also plotted, although it is indistinguishable from the other scenarios, which lie atop it. The 2015 Outlook scenario lies between the SRES A1B and the RCP6.0 scenarios.

Carbon dioxide and long-lived greenhouse gases are not the only contributors to radiative forcing. Also important are ozone (O_3) and aerosols. Aerosols include black carbon (BC), which absorbs radiation and contributes to warming, as well as sulfate aerosols, which are reflective and hence have a cooling effect that partially offsets the warming influence of other aerosols and GHGs (**Figure 18**). Combining all of these, our 2015 Outlook scenario reaches nearly 7 W/m^2 by 2100 from 2.5 W/m^2 in 2010.

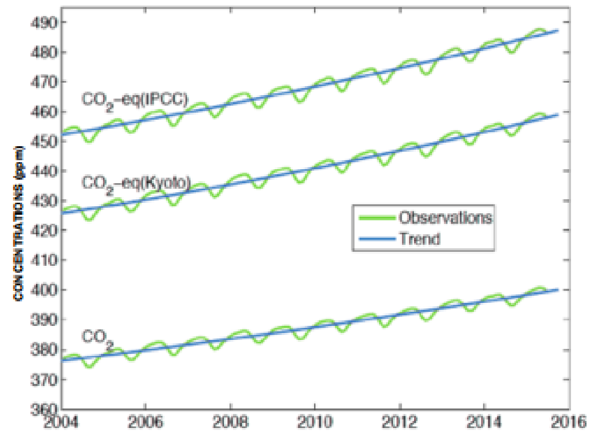


Figure 16. Current greenhouse gas (GHG) concentrations (ppm).

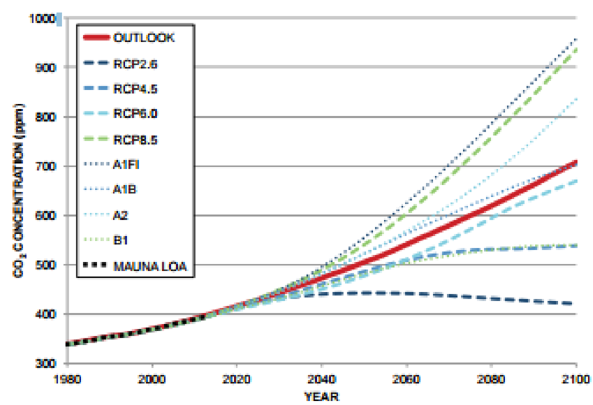


Figure 17. Projected CO_2 concentrations (ppm).

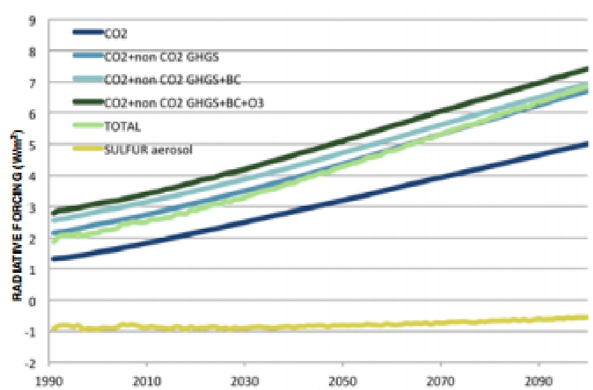
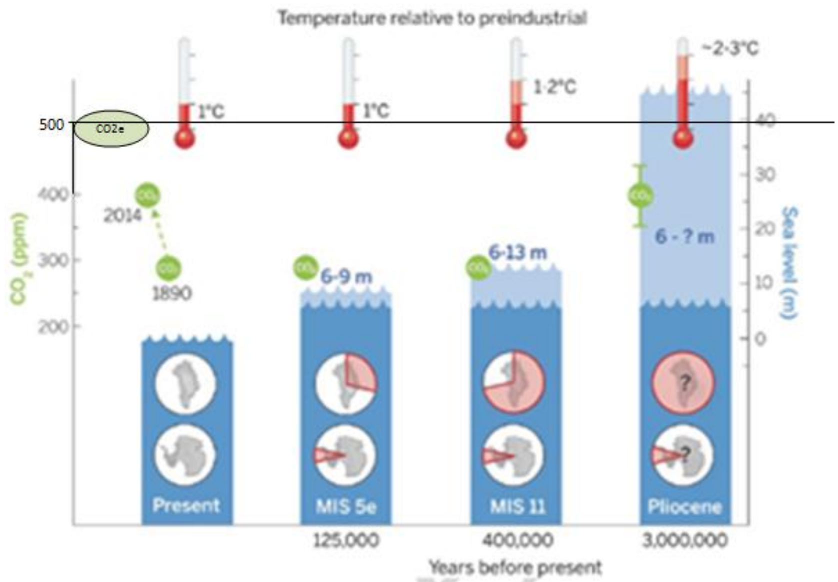


Figure 18. Projected greenhouse gas (GHG) radiative forcing (W/m^2).

https://globalchange.mit.edu/sites/default/files/newsletters/files/2015%20Energy%20%26%20Climate%20Outlook.pdf

13	CSSR TOD: DO NOT CITE, QUOTE, OR DISTRIBUTE Chapter 4  **Figure 4.3:** Putting present-day global mean temperature, CO_2 concentrations, and sea level into context, this figure summarizes what is known about the range in peak global mean temperature, atmospheric CO_2, maximum global mean sea level (GMSL), and source(s) of meltwater over three periods in the past with CO_2 levels similar to pre-industrial levels (around 270 ppm) or today (around 400 ppm). Light blue shading indicates uncertainty of GMSL maximum. Red pie charts over Greenland and Antarctica denote fraction, not location, of ice retreat. (Figure source: Dutton et al. 2015) Source: Draft of the U.S. GLOBAL CHANGE RESEARCH PROGRAM CLIMATE SCIENCE SPECIAL REPORT (CSSR) (from the National Academy of Sciences, August 2017, Figure 4.3 Page 172) Note the addition of an indication of CO2e atmospheric concentration of all greenhouse gases as of 2016 -about 490 PPM (added because there are anthropogenic greenhouse gases in the atmosphere now but which were not present in pre-industrial times).
14	3GTC from soils in 2050 (55/20, since annual loss will increase over time)[4], .25GTC from reservoirs[6], 0.5GTC equivalent from albedo changes in the Arctic, .25GTC from other sources
15	**The Feasibility of Air Capture** (2010) The cost of direct air capture reported in literature is in the range of $100/tC and $500/tC ($27/tCO2 - $136/tCO2). A thermodynamic minimum work calculation performed in this thesis shows that just the energy cost of direct air capture would be in the range of $1540-$2310/tC ($420-$630/tCO2) or greater. To this, one must add the capital costs, which will be significant. http://sequestration.mit.edu/research/aircapture.html Costs of DAC are likely to be of the order of $1000/t of CO2 avoided http://ieaghg.org/docs/General_Docs/Publications/Information_Papers/2015-IP23.pdf
16	http://ccdatacenter.org/documents/What is the correct carbon budget.pdf
	In "Young People's Burden: Requirement of Negative CO2 Emissions ", James Hansen calls for limiting the long-term temperature increase to less 1° C (and limiting the atmospheric CO2 to 320 PPM) in order to keep the "slow feedbacks" from becoming significant). https://arxiv.org/ftp/arxiv/papers/1609/1609.05878.pdf
18	https://reneweconomy.com.au/paris-1-5-2c-target-far-from-safe-say-world-leading-scientists-81532/
19	https://arxiv.org/ftp/arxiv/papers/1609/1609.05878.pdf
20	For example, assuming that we need to get atmospheric CO2 to 350PPM and that it takes emissions of

	about 4.4 GTC to increase atmospheric CO2 by 1PPM (4.4*.5/2.12), about 260 GTC would need to be removed from the atmosphere to reduce its concentration to that level. If emission (currently about 10 GTC/year) peak in 2020 and were reduced by 3% per year (an unrealistically high rate), total anthropogenic emissions would be about 270 GTC by 2060. If another 100 GTC are emitted by the permafrost while the temperatures are high enough to thaw it, the total emission-equivalent that would need to be sequestered is about 630 GTC. If that can be averaged over the rest of this century, then the amount that needs to be "air captured" and sequestered is about 8GTC per year (or about 80% of current emissions). At $500/ton C (current estimates range from around $220/ton carbon to capture CO2 to over $3,500/ton of carbon for both capture and sequestration[19], that's $4 trillion per year (which is obviously more than we'd be willing to pay)
21	"That means we must start burying and sequestering carbon (in some models as early as 2020) and rapidly scale up until we are burying more than we're emitting. That is a truly daunting undertaking — some models show us burying 10 to 20 gigatons a year by 2100, which is 25 to 50 percent of today's total emissions." https://www.vox.com/energy-and-environment/2017/8/18/16166014/negative-emissions
22	http://nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration National Research Council study - page 72
23	Why CDR will never be implemented at anywhere near the scale required Other than activities like enhanced oil recovery, 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 1°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
24	Partial list of climate factors - the radiative forcing for these should be specified for climate model results

	Anthropogenic Emissions	
1	CO2 emissions from fossil fuels and cement	
2	CH4 emission`s	
3	Other GHG emissions	
	Natural Emissions	
4	Permafrost emissions	perhaps 120 GTC by 2100 (http://www.washingtonpost.com/news/energy-environment/wp/2015/04/01/the-arctic-climate-threat-that-nobodys-even-talking-about-yet)
5	Soil carbon (including peat)	- perhaps 55 GTC by 2050 (some permafrost emissions might be included in this) (https://medium.com/@Alex_Verbeek/another-reason-to-be-worried-about-climate-change-1bf1e21e78e#.bzhqdsrsz)
6	Aerosol reduction	eliminating fossil fuel emissions will add 0.9°C to the temperature increase (http://www.pnas.org/content/105/38/14245.full, as reported in http://www.theenergycollective.com/jim-baird/2378159/climate-change-the-choices-couldnt-be-starker; and Hansen estimated that the aerosol climate forcing was -1.6±0.3 W/m^2 in 2011 https://pubs.giss.nasa.gov/abs/ha06510a.html
7	Reservoirs	Methane emissions from reservoirs contribute about .7GTC of CO2 equivalent per year, resulting in about 30 GTC through 2060 and 60 GTC through 2100. (http://www.climatecentral.org/news/greenhouse-gases-reservoirs-fuel-climate-change-20745)
8	Reduced Arctic albedo	"cyrospheric cooling declined by 0.45 W m−2 from 1979 to 2008, with nearly equal contributions from changes in land

		snow cover and sea ice" (http://data.engin.umich.edu/faculty/flanner/content/ppr/FIS 11.pdf)
9	Methane hydrates	
10	Other feedbacks	
	Other Natural Climate Factors	
11	Ocean uptake	(this will be negative)
12	Land use change	
13	Other sources/sinks	
	Anthropogenic Negative Emissions	
14	Afforestation/reforestation	
15	BECCS	
16	CCS	
17	Direct Air Capture	

25

Committed Global Temperature Increases

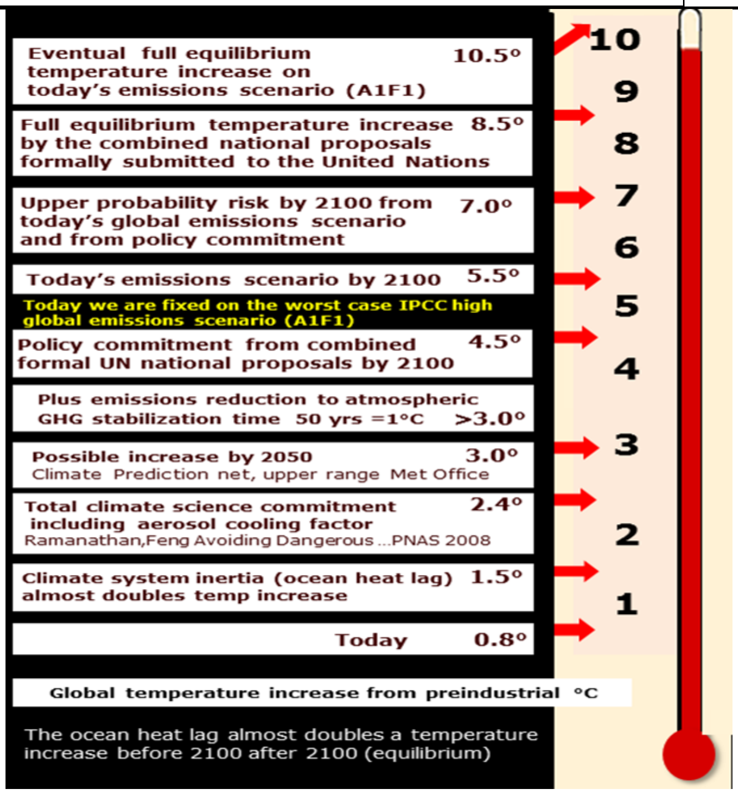
Today's full committed global warming due to climate science is **2.4°C** (Ramanathan, Feng Avoiding Dangerous Climate interference ... PNAS 2008) and warming will continue for over **1000 years**

•0.8°C today's surface temperature increase

•0.7°C 'hidden' deferred warming from the ocean heat lag. The ocean heat lag commits any temperature increase before 2100 to almost double after 2100 at temperature equilibrium.

•0.9°C 'hidden' deferred warming due to aerosol cooling that will be 'unmasked' when fossil air pollution or fossil energy production stops

• Plus another 1.0°C which is the fastest time from emergency emissions reduction to atmospheric GHG stabilization.



https://www.climateemergencyinstitute.com/committed_global_warming_basic_science.html

26 http://ccdatacenter.org/documents/ExpectedTemperatureIncrease.pdf (by the same author as this document)