Expected Global Temperature Increase

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http://ccdatacenter.org/documents/ExpectedTemperatureIncrease.pdf

Background

The recently signed COP 21 Paris Agreement calls for all nations to curb their CO2 emissions with the goal of keeping the global temperature rise this century to well below 2°C above pre-industrial levels (and striving to limit the increase to 1.5°C). The agreement assumes that the temperature will stabilize after the target is met. Unfortunately the planning does not appear to have taken into account the additional warming from natural causes (feedbacks) stemming from a warming planet. These include decreased albedo from the melting of summer-time ice in the Arctic Ocean, the reduced snow cover in the Northern Hemisphere, etc., and increased greenhouse gas emissions (primarily CO2 and methane) from peat bogs, thawing permafrost, etc.[1].

Radiative Forcing Computations

By estimating what the effective radiative forcings (ERF) of the major components of the climate system will be in 2100 it is possible to also estimate the resulting temperature increase based on an expected value for climate sensitivity. One can then determine if it is possible to meet the temperature goal of the Paris agreement through an aggressive emissions reduction effort with net-zero greenhouse gas emissions by 2060:

#	ERF (W/m-2)		Radiative Forcing Components
	2060	**2100**	
	Anthropogenic changes from 1870 - 2011		
1	2.29	2.29	ERF in 2011 (IPCC)[2]
	Anthropogenic changes from 2012 to 2100		
2	0.41	0.65	Due to the reduction of aerosols and precursors (IPCC AR5: total of -0.82 in 2011, mostly due to the burning of fossil fuels; for 2060, 50% of the value is used; for 2100, 80% of the value is used)[2]
3	0.80	0.80	Due to 1240 GTCO2 of CO2 emissions from an aggressive emission reduction scenario (emissions peak in 2025 and go to zero in 2055, resulting in increasing atmospheric CO2 by about 72 PPM)
4	-0.19	-0.37	Due to the reduction of atmospheric concentrations of CH4, N2O, and halocarbons (IPCC RCP 2.6: -0.37 in 2100; for 2060, ½ the estimated value is used)[3]
5	??	??	Other – land use changes, atmospheric changes, etc.
	Additions from natural feedbacks[4] (represents the equivalent of about 1,700 GTCO2 in 2100)		
6	0.14	0.25	Arctic Ocean - linear change in Arctic Ocean sea ice extent
7	0.12	0.18	Retreating snowline - linear change in Northern Hemisphere snow cover extent
8	0.06	0.32	Permafrost thawing (for 2060, 20% of the 120 GTC expected by 2100 (88 GTCO2, or 5 PPM CO2); for 2100, 440 GTCO2 or 25.5 PPM CO2)
9	0.14	0.27	Peatlands and Peat Bogs (4 GTCO2 per year: for 2060, for 50 years – 200 GTCO2, or 11 PPM; for 2100, 90 years – 360 GTCO2 or 21 PPM)
10	??	??	Other – methyl hydrates, forests, soils, etc.
	Total Changes in ERF		
	3.81	**4.43**	Total Change in ERF from preindustrial times
	Estimated temperature increase for an energy imbalance of 0.7 w/m-2 and a climate sensitivity = 3.0 °C[5]		
	2.4°C	**3.0°C**	Expected temperature increase[6]
	Estimated equilibrium temperature change for a climate sensitivity of 3.0 °C[5] **for a doubling of CO2 PPM**		
	3.1°C	**3.9°C**	Equilibrium temperature increase[6]

Table 1. Radiative forcing of the major components of the climate system for 2060 and 2100

If the climate sensitivity is 3[5], the ERF for 2100 needs to be about 2.7 W/m-2 in order to limit the temperature increase to 2°C. The above analysis shows that the goals of the COP 21 Paris Agreement can only be met by capturing and sequestering enough CO2 to reduce the projected ERF in 2100 by about 1.7 W/m-2. This would require reducing the atmospheric CO2 concentration by about 180 PPM, or 3,100 GTCO2.

Expected Costs

Since the additions from the natural feedbacks are so large (being responsible for almost one-fourth of the total temperature increase in 2100), the Earth's atmosphere will continue to warm long after anthropogenic greenhouse gas emissions are reduced to zero. Unless these natural feedbacks can either be reduced to zero or compensated for (by annually removing an equivalent amount or carbon dioxide from the atmosphere), eliminating all anthropogenic emissions will not be sufficient to meet the IPCC's goals. Our global warming goal should really be to keep the Earth's temperature low enough so that we can afford to offset (e.g., sequester) the equivalent emissions from the global warming feedbacks - otherwise the Earth will eventfully warm enough to cause catastrophic climate change.

To get a ballpark estimate of the economic challenge, cost estimates for three scenarios in which the net anthropogenic emissions match the IPCC budget can easily be made:

	(Emissions in GTCO2)	No sequestration of equivalent CO2 from feedbacks	Sequestration of equivalent CO2 from feedbacks	Remove enough CO2 (1,600 GTCO2) to eliminate feedbacks
1	Total Emissions over budget	2120	2120	2120
2	CO2 Sequestered	420 (to meet IPCC budget)	2120	2120+ 1600
3	CO2e not sequestered	1700 (from feedbacks)	0	0
4	Sequestration Costs (T$)	21	200	370
5	2100 ERF from feedbacks - extra CO2 removed	1.28	0	-1.08 (=2.6-1.52)
6	Total ERF (W/m-2)	3.88 (=2.6+1.28)	2.6	1.52 (ERF for 1°C)
7	Equilibrium Temperature (°C)	3.2	1.9	1.0

Table 2 – Equilibrium Temperature Increase for Various Amount of CO2 Sequestration

The above estimates are based on the following parameters and assumptions:

1	1240	The net amount of CO2 emissions (GTCO2) from an aggressive emissions reduction scenario (2010 emissions were about 34 GTCO2; if they increase annually by 2% until 2025 and then decline by 1.5 GTCO2 annually, there will be net zero emissions after 2055 and the total emissions will be about 1240 GTCO2)
2	180	Emissions (GTCO2)after 2055 that will need to be sequestered if annual emissions are about 4 GTCO2 [6]
3	1,000	The IPCC post-2011 CO2 budget(GTCO2) for a 66% chance of limiting the temperature increase to 2°C[7]
4	1,700	GTCO2 equivalent emissions from global warming feedbacks for a temperature increase of 2°C[4]
5	3	The climate sensitivity to CO2 from a doubling of atmospheric CO2 [8]
6	50	Per-ton cost ($) of capturing and sequestering CO2 for CCS (anthropogenic emissions only[9]
7	100	Per-ton cost ($) of capturing and sequestering CO2 for direct air capture (DAC)[9]
8	2.6	Effective radiative forcing (W/m-2) for a 1.9°C temperature increase and a climate sensitivity of 3[10]

Table 3 – Parameters for Ballpark Estimate of CO2 Sequestration Costs Based on Amount of CO2 Sequestered

If anthropogenic emissions are in line with the UNFCCC budget and if the UNFCCC budget would result in a 2°C temperature increase, we can expect a temperature increase over 3°C for a modest cost. If we also remove CO2 from the atmosphere that is equivalent to the global warming feedbacks we can limit the temperature to 2°C for a cost of about $200 Trillion, but the planet will continue to warm unless we spend another $1.5 Trillion per year to offset the feedbacks of roughly 15 GTCO2 . Since global warming feedbacks are already significant[10] with a temperature increase of only about 1.1°C, it would seem that we'd be lucky to eliminate the feedbacks with a temperature increase of only 1°C, which would cost over $370 Trillion.

The prevailing assumption is that we will be willing (and able) to spend whatever it costs to keep meet the temperature target 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 around $370 Trillion this century if we can significantly reduce the expected cost of carbon dioxide removal to $100/ton of CO2 for direct air capture) shows that we have a very daunting (and almost certainly insurmountable) problem.

Conclusions

- We can already expect about a 2°C temperature increase based on the greenhouse gases currently in the atmosphere (assuming emissions from burning coal are eliminated)[11,12]
- There will be significant future anthropogenic greenhouse gas emissions for any realistic mitigation scenario
- Global warming feedbacks are already significant[10]
- There will be both significant future natural greenhouse gas emissions and significant albedo changes from the feedbacks from a warming world[4]
- Widespread thawing of the permafrost could start when the global temperature increases by 1.5°C[13]
- If only a small fraction of Arctic carbon is released into the atmosphere the result could be catastrophic[14]
- 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 (see above analysis)
- Most climate change damage will happen before the two-degree warming threshold[15]
- Once the temperature increase is over 3°C (and possibly over 1.5°C), the feedbacks from the global warming will likely drive the temperature increase to well over 4°C, resulting in a planet that is not hospitable to civilization as we know it
- Long-term sea level rise will exceed 40 feet[16]
- Ocean acidification will be catastrophic[17]

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 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.

Footnotes *(links to articles cites are provided at the end of each footnote)*

1

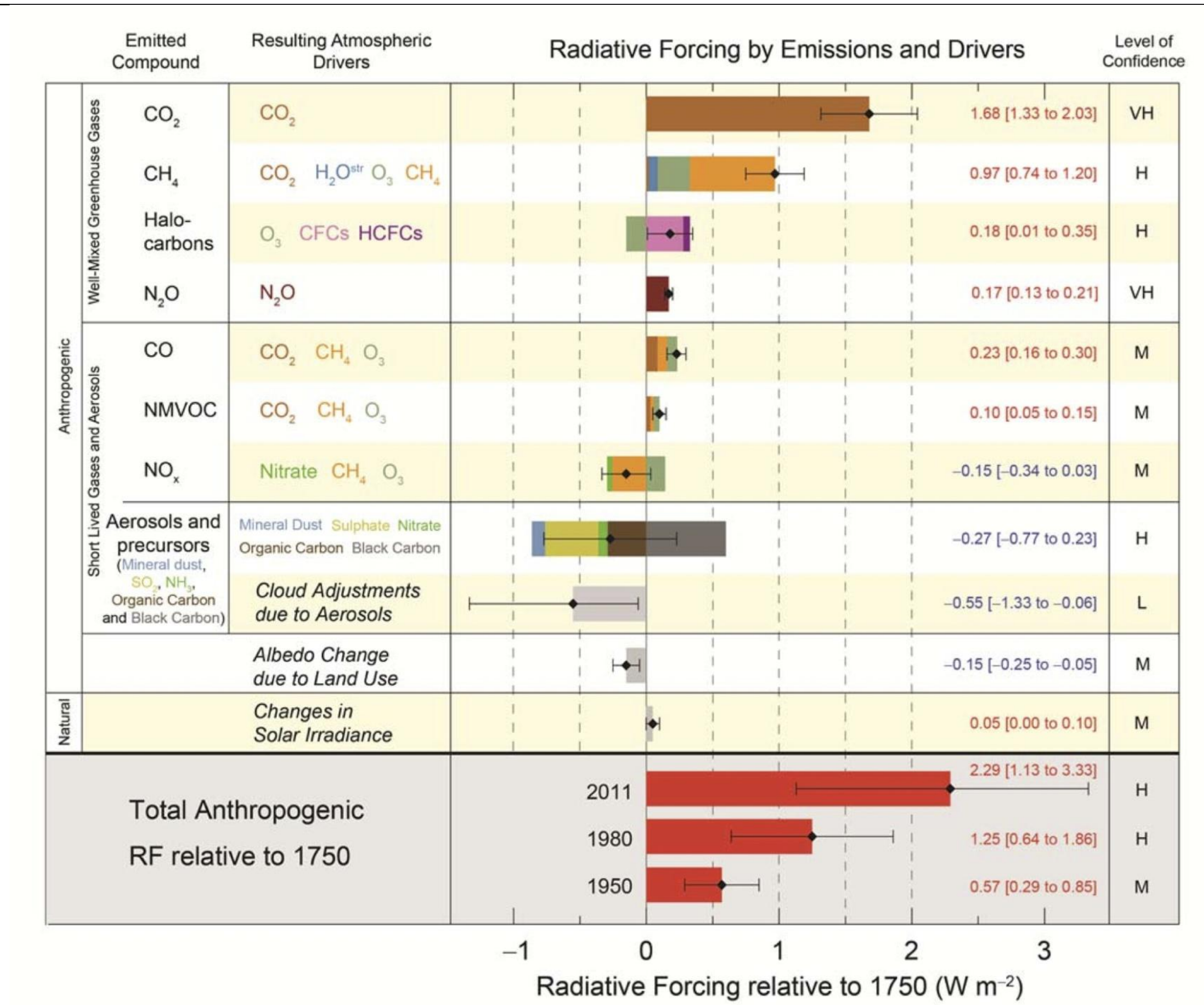
Models do not account sufficiently for climate feedbacks

From an April 2015 article in the Washington Post:

> "It 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, [Dr. Kevin] 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 [Dr. Robert Max] Holmes.
>
> But by 2100, the "mean" estimate for total emissions from permafrost right now is 120 gigatons [440 GTCO2], says Schaefer.

http://www.washingtonpost.com/news/energy-environment/wp/2015/04/01/the-arctic-climate-threat-that-nobodys-even-talking-about-yet

2A



IPCC AR5 – Radiative Forcing Components

http://www.realclimate.org/index.php/archives/2013/10/the-evolution-of-radiative-forcing-bar-charts/

2B

Aerosol reduction from burning coal would add about 0.5°C to the net warming – Huffington Post

> While greenhouse warming [from CO2] 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 0.5°C to the net warming.

http://www.huffingtonpost.com/michael-e-mann/how-close-are-we-to-dangerous-planetary-warming_b_8841534.html

Note: The above was reported on several blogs without identifying the original source. However, the IPCC reported that the total radiative forcings due to aerosols and precursors was about -0.82 W/m-2 (see Figure above), so if two thirds of that is due coal, then the aerosols from coal reduce the radiative forcing by about 0.55 W/m-2; so the aerosols from coal could easily be masking 0.5°C. And since the burning of other fossil fuels and biomass also contribute to the aerosols, an 80% reduction in the aerosol "masking" is probably reasonable.

3

	ERF Change Since 1750		
	2011	RCP2.6	Difference
CO2	1.816	2.220	0.404
CH4	0.425	0.270	-0.155
N20	0.195	0.230	0.035
Halocarbons	0.395	0.142	-0.253
CH4, N20, Halocarbons	1.015	0.642	-0.373
Greenhouse Gases	**2.831**	**2.862**	0.031

IPCCPhysicalBasisAR5.pdf

4

Feedbacks

The significance of the magnitudes of the positive feedbacks from global warming is not widely appreciated. This is most likely because (1) modeling the expected magnitudes through the end of the century is very difficult; (2) most analyses of the feedbacks look only at what has happened so far; and (3) the feedbacks are usually looked at individually. By doing some simple analyses of four of the primary feedbacks (albedo changes from melting Arctic sea ice and Northern Hemisphere snow cover; and greenhouse gas emissions from permafrost and peat) and estimating their magnitudes through 2100, a startling picture emerges:

1. The warming potential in 2100 from the four feedbacks are roughly equivalent to about ½ of current fossil fuel emissions
2. By 2100 this will result in a warming potential (110 PPM CO2e), about equivalent to that of all fossil fuel emissions since pre-industrial times, and capable of adding about 0.9° C to the Earth's average temperature.
3. The "CO2 emissions equivalent" of these feedbacks through 2100 is about twice the UNFCCC's carbon budget.

The results of the simple analysis are shown in the table below. The analysis for the albedo changes are based on data from the National Snow and Ice Data Center (Arctic sea Ice extent) and from the "Snow Lab" at Rutgers University (Northern Hemisphere snow cover extent). The estimate for the permafrost is based on the "mean" estimate for total emissions from permafrost (120 GTC) reported by Kevin Schaefer of the National Snow and Ice Data Center. The estimate for peatlands and peat bogs assumes that the emissions will remain at the current rate (4 GTCO2/year) through 2100.

Feedback	Likely Change 2011- 2100			
Albedo Changes	Rad. Forcing (W/m-2)	Atmos. CO2e Change (PPM)	Total Equiv. Emissions	Temp Increase
Arctic Ocean	.34	26.1	452	0.20
Retreating snowline	.31	24	409	0.18
GHG Emissions				
Permafrost	.33	25.5	440	0.19
Peatlands and Peat Bogs	.30	23.0	400	0.17
Total	1.28	98.6	1701	0.81#
# Temperature increases are not "additive", so the total temperature increase is based on the total radiative forcing				

http://ccdatacenter.org/documents/GlobalWarmingFeedbacks.pdf

5 **Climate sensitivity**

http://www.realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/
http://www.skepticalscience.com/climate-sensitivity-advanced.htm
http://www.bitsofscience.org/real-global-temperature-trend-climate-sensitivity-leading-climate-experts-7106

6 **Effective radiative forcing**

Calculations of the expected temperature increase for changes in both the Earth's albedo and annual emissions of CO2 require a value for climate sensitivity. The following representative values were obtained from http://ccdatacenter.org/documents/AlbedoCO2TempCalcs.pdf, which used a climate sensitivity of 3.0:

Yearly Albedo Decrease	Effective Radiative Forcing (W/m-2)	Equiv. CO2e PPM	Equiv CO2 Em. (GTCO2)	Temp Increase (°C)
0.00300	0.306	23.70	411	0.18
0.00320	0.326	25.33	439	0.19
0.00340	0.347	26.97	468	0.20
0.00360	0.367	28.61	496	0.21
0.00380	0.388	30.26	525	0.23

Effective Radiative Forcing (W/m-2)	Annual Emissions (GTCO2)	Total Emissions 2015-2100	CO2 PPM (2015-2100) (GTCO2)	Temp Increase (2015-2100) (°C)
0.254	4	340	19.60	0.15
0.316	5	425	24.51	0.18
0.377	6	510	29.41	0.22
0.437	7	595	34.31	0.26
0.497	8	680	39.21	0.29

Expected Temperature Increase for changes in radiative forcing and for annual emissions of CO2

Change Since Preindustrial		
Effective Radiative Forcing (W/m-2)	Equiv. CO2e PPM	Temp Increase (°C)
2.0	404	1.4
2.1	412	1.4
2.2	419	1.5
2.3	427	1.6
2.4	435	1.7
2.5	444	1.8
2.6	452	1.9
2.7	460	2.0

Change Since Preindustrial		
Effective Radiative Forcing (W/m-2)	Equiv. CO2e PPM	Temp Increase (°C)
3.0	487	2.3
3.1	496	2.4
3.2	506	2.5
3.3	515	2.6
3.4	525	2.7
3.5	535	2.8
3.6	545	2.9
3.7	555	3.0

Change Since Preindustrial		
Effective Radiative Forcing (W/m-2)	Equiv. CO2e PPM	Temp Increase (°C)
4.0	587	3.3
4.1	598	3.5
4.2	609	3.6
4.3	621	3.7
4.4	633	3.8
4.5	645	4.0
4.6	657	4.1
4.7	669	4.2

2.8	469	2.1	3.8	566	3.1	4.8	682	4.4
2.9	478	2.2	3.9	576	3.2	4.9	695	4.5

Expected Temperature Increase for a change in radiative forcing

7 **Emissions after 2055**

It is very unlikely that total greenhouse gas emissions can ever get to zero. For example, see the IEA "Energy Technology Perspectives 2012 2°C Scenario" , which estimates the over 7 GTCO2 will need to be stored annually in 2050 – http://www.iea.org/publications/freepublications/publication/technology-roadmap-carbon-capture-and-storage-2013.html

8 **The IPCC post-2011 CO2 budget**

Table 2.2 | Cumulative carbon dioxide (CO_2) emission consistent with limiting warming to less than stated temperature limits at different levels of probability, based on different lines of evidence. *{WGI 12.5.4, WGIII 6}*

Cumulative CO_2 emissions from 1870 in $GtCO_2$									
Net anthropogenic warming [a]	<1.5°C			<2°C			<3°C		
Fraction of simulations meeting goal [b]	66%	50%	33%	66%	50%	33%	66%	50%	33%
Complex models, RCP scenarios only [c]	2250	2250	2550	2900	3000	3300	4200	4500	4850
Simple model, WGIII scenarios [d]	No data	2300 to 2350	2400 to 2950	2550 to 3150	2900 to 3200	2950 to 3800	n.a. [e]	4150 to 5750	5250 to 6000
Cumulative CO_2 emissions from 2011 in $GtCO_2$									
Complex models, RCP scenarios only [c]	400	550	850	1000	1300	1500	2400	2800	3250
Simple model, WGIII scenarios [d]	No data	550 to 600	600 to 1150	750 to 1400	1150 to 1400	1150 to 2050	n.a. [e]	2350 to 4000	3500 to 4250
Total fossil carbon available in 2011 [f]: 3670 to 7100 $GtCO_2$ (reserves) and 31300 to 50050 $GtCO_2$ (resources)									

https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf, page 61, Table 2.2

9 **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). 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.

Assuming some progress in the coming years, a reasonable CCS cost between now and 2055 might be $50/ton CO2 (which can be used for future fossil fuel emissions).

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 four, costs later this century might be $100/ton CO2.

(What would be really important to determine is the energy requirement to compress the captured CO2 and compress it. It should then be possible to estimate the number of "power plant equivalents" to compress and sequester annually 1 PPM of the atmospheric CO2.)

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 < 7×10^5 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

10 **Global warming feedbacks are already significant**

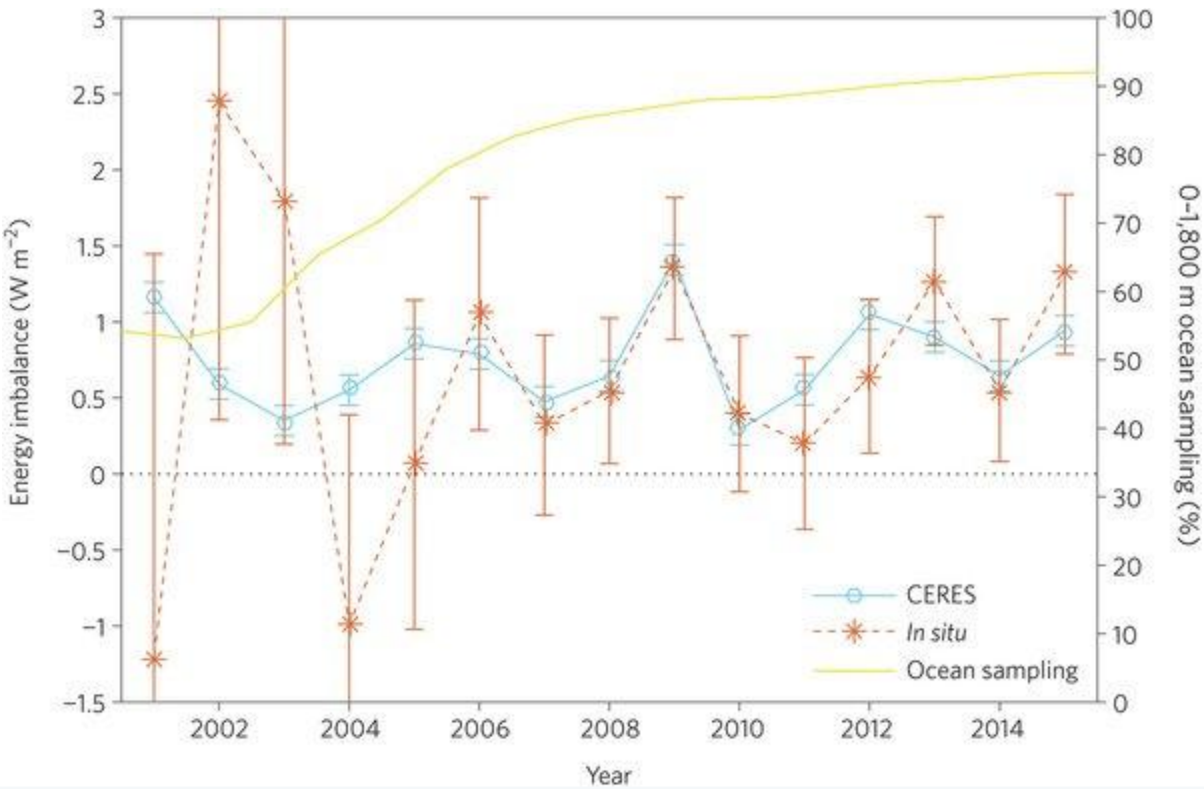
Observational determination of albedo decrease caused by vanishing Arctic sea ice
Sept 2013
http://www.pnas.org/content/111/9/3322.full

The Arctic sea ice retreat has been one of the most dramatic climate changes in recent decades. Nearly 50 y ago it was predicted that a darkening of the Arctic associated with disappearing ice would be a consequence of global warming. Using satellite measurements, this analysis directly quantifies how much the Arctic as viewed from space has darkened in response to the recent sea ice retreat. We find that this decline has caused 6.4 ± 0.9 W/m-2 of radiative heating since 1979, considerably larger than expectations from models and recent less direct estimates. Averaged globally, this albedo change is equivalent to 25% of the direct forcing from CO_2 during the past 30 y.

*Note: The albedo from Arctic ice extent change 1979-2011 is the equivalent of about 14 PPM CO2e. (=278*POWER(2.718,((6.4*14/510)+1.99)/5.35)-403), which is equivalent to emissions of about 240 GTCO2*

11 **Current energy imbalance**

The current enargy imbalance is about 0.7 W/m-2, equivalent to about 0.42° C of warming.



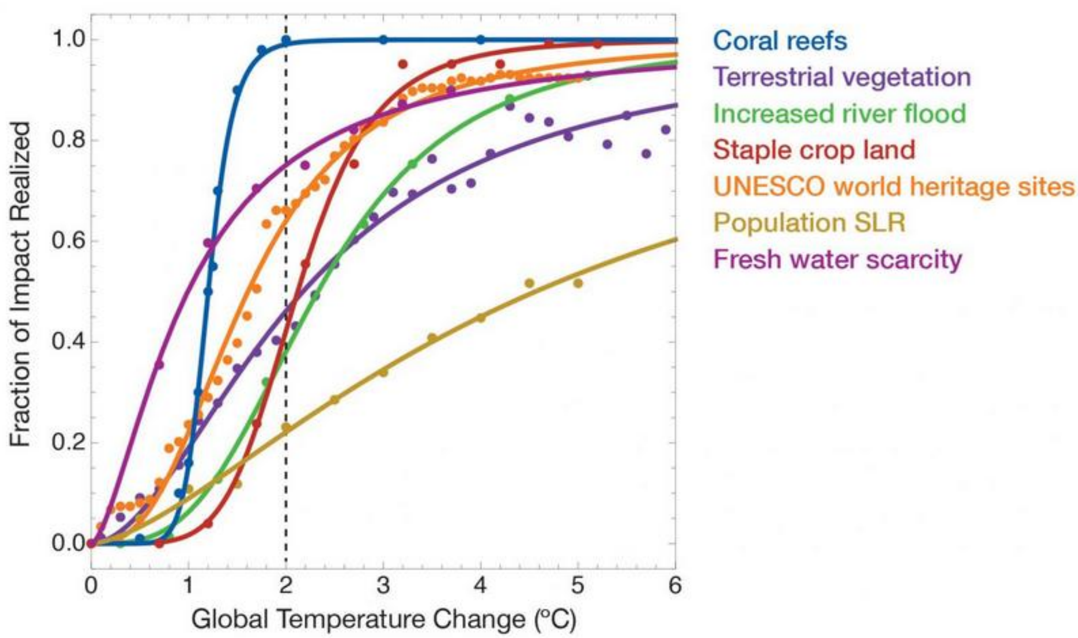
Gavin Schmidt @ClimateOfGavin Jun 23
New estimate of Earth's energy imbalance ~0.7 W/m-2 (2005-15) nature.com/nclimate/journ… NB predicted before observed
https://twitter.com/ClimateOfGavin/status/765237770839269378 8/15/16

http://www.nature.com/nclimate/journal/v6/n7/full/nclimate3043.html

12 **Temperature increase from eliminating emissions from burning coal**
"While greenhouse warming [from CO2] 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 0.5°C to the net warming."

http://www.huffingtonpost.com/michael-e-mann/how-close-are-we-to-dangerous-planetary-warming_b_8841534.html

See also: http://ccdatacenter.org/documents/BurningCoalCoolsPlanet.pdf

13	**Widespread thawing of the permafrost** **"**The new research suggests that based on what's happened in the Earth's past, global temperatures 1.5 degrees Celsius above pre-industrial levels could cause vast areas of carbon-rich permafrost to thaw." https://www.carbonbrief.org/new-research-projects-widespread-permafrost-thaw-with-1-5-degrees-of-warming "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 [of carbon] per year from thawing permafrost," says Holmes. https://www.washingtonpost.com/news/energy-environment/wp/2015/04/01/the-arctic-climate-threat-that-nobodys-even-talking-about-yet/
14	**If only a small fraction of Arctic carbon is released into the atmosphere the result could be catastrophic** "Even if a small fraction of the Arctic carbon were released to the atmosphere, we're fucked," Dr Jason Box http://motherboard.vice.com/read/if-we-release-a-small-fraction-of-arctic-carbon-were-fucked-climatologist
15	**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

16	**Sea Level Rise** Looking the geologic record, sea level rise has typically been about 10– 20 m/°C. Given that we are currently committed to at least a 2°C temperature increase, the long-term sea level rise will likely be at least 20 meters (over 60 feet) http://ccdatacenter.org/documents/Sea%20Level%20Rise.pdf
17	**Ocean Acidification** **"**We are now carrying out an extraordinary chemical experiment on a global scale. Our fossil-fuel emissions raise the dissolved CO_2 levels in the ocean, which reduces carbonate ion concentrations and lowers pH. The ocean's sunlit surface layer (the top 100 yards or so) could easily lose 50 percent of its carbonate ion by the end of this century unless we reduce emissions dramatically. Marine animals will find it harder to build skeletons, construct reefs, or simply to grow and breathe. Compared with past geologic events, the speed and scale of this conversion is astonishing." http://www.scientificamerican.com/article/rising-acidity-in-the-ocean/