A Simple Global Warming Model

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(http://ccdatacenter.org/documents/SimpleGWModel.pdf http://ccdatacenter.org/documents/SimpleGWModel.xlsx)

"How warm will it get?" is a frequent question that many of us ask. Unfortunately, this a very difficult question to answer for several reasons:

1. The climate system is very complex (there are lots of "climate factors" which affect the temperature increase, and the values for many of these are not know with much precision
2. The models that the IPCC uses cannot be use to estimate the future temperature based on the "climate factors" since the models are "outcome-based" (i.e., they are set up to "tweak" variables for population growth, energy consumption, energy sources, etc., until a specific radiative is reached in the year 2100 forcing (which results in a range of temperature increases that depend on climate sensitivity); for example, 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)
3. The models that the IPCC use for its latest report (AR5) are known to have either not included or underestimated the radiative forcings for several important climate factors (e.g., Arctic sea ice melt, greenhouse gas emissions from the thawing permafrost, etc.), and so their results are known to be overly conservative (i.e., their temperature estimates for 2100 are likely too low by a significant amount and their carbon budget is likely to be to high by a significant amount)

The IPPC has not attempted to provide a simple answer to the question "How warm will it get?". Instead, the IPCC has only provided us with a "carbon budget" (for various temperature increases) that is based on models that are known not to include much of the expected natural greenhouse gas emissions, and without providing many details on the assumptions behind their calculations. And yet this carbon budget is the primary "tool" that "climate analysts" use to explain to the public how to "solve" climate change, despite the assertion by many climate scientists that the budget might already be used up (e.g., Dr. Michael Mann thinks that we have to limit atmospheric CO2 to 405 PPM to meet the 2°C target, a level that we have already passed, thus implying that there is no budget left). In addition, other prominent climate scientists question the choice of either the 1.5°C or 2°C temperature target (e.g., Dr. 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).

We know that the Earth has warmed about 1°C since pre-industrial times (as of December 2016), that there is more warming "in the pipeline", and that significant climatic disruptions have already occurred or expected to occur (very significant coral bleaching, sea level rise of 6-10 feet this century, unprecedented extreme weather events, etc.) What is needed is both a serious public discussion about the appropriate temperature target (taking into account the natural feedbacks) and a simple model that can be used to estimate the future equilibrium temperature increase based on reasonable values for the various "climate factors" (both anthropogenic and natural greenhouse gas sources and sinks; changes in radiative forcings from the Arctic region, aerosols, black carbon, land use, etc.; and the costs associated with capturing and sequestering carbon). Only then can we have a reasoned public discourse about the severity of the climate crisis and develop an appropriate course of action.

The "Simple Global Warming Model" described in this document is an attempt to create a framework for the needed "simple model". I am hoping that other people will collaborate with me in coming up with a list of the most appropriate climate factors, suggesting reasonable values for 2015, and suggesting reasonable "pathways" as to how they will change this century. Working together we can develop a way to finally answer the question "How warm will it get?".

Note: A "first cut" at a global warming model, which incorporates emission-equivalents from natural feedbacks, shows an equilibrium temperature increase of about 3.5°C in 2100 for a reasonably aggressive GHG emissions reduction effort (3%/year after 10 years) with 90% of the CO2 emissions from the burning of fossil fuels being captured after 40 years.

The "Simple Model"

The "Simple Global Warming Model" spreadsheet **(**http://ccdatacenter.org/documents/SimpleGWModel.xlsx) implements a very simple model for estimating the equilibrium temperature for a set of values for various "climate factors". It was developed to answer a simple question: "What temperature increase can be expected from a specific set of greenhouse gas emissions"? The concept is very straightforward:

1. Start with a known atmospheric concentration of CO2 (along with known forcings - in Watts/square meter - from various climate factors)
2. Add up the annual the CO2 emissions from known CO2 sources and sinks and adjust the atmospheric concentration of CO2 accordingly
3. Calculate the annual radiative forcings of the various climate factors (for CO2, use the atmospheric concentration; adjust the other know forcings as specified by a set of parameters)
4. Add up the annual radiative forcings of all of the climate factors
5. Calculate the equilibrium temperature increase for 2050 and 2100 for a set of climate sensitivity values
6. For a set of climate sensitivity values, estimate the temperature increase for each year based on the previous year's temperature and the difference between the equilibrium temperature and the previous year's temperature

If the total radiative forcing is not changing significantly towards the end of the century, the expected temperature increase will be close to the calculated equilibrium temperature increase.

The model can then be used estimate how the temperature change will be affected by various changes to greenhouse gas emissions (e.g., by natural emissions from permafrost, soils, etc.; by various amounts of carbon capture and sequestration; etc.). The model can also be use to estimate the costs of carbon capture and sequestration. And by setting a target for atmospheric CO2, the quantity of CO2 removed by DAC can be adjusted to meet the target.

Note that some natural emissions (from soils, permafrost, peat, etc.) depend on the temperature. The current model does not take this into account, so the user will need to adjust the corresponding parameters to allow the emissions to first increase and then decrease.

Many of the current number used in the model are "educated guesses" . To be able to make more accurate estimates of future global warming, we need to reach agreement on reasonable values for the following climate factors:

Ref #	Climate factor	Educated Guess/Comments
6	Afforestation/reforestation/	Is 100 GTC a reasonable amount?
10	Soil carbon	55 GTC by 2050? Need estimates for various temperature trajectories
11	Permafrost emissions	120 GTC this century? Need estimates for various temperature trajectories
12	Peat	Have an estimate for current emissions (globally 2-3 Gt CO2-eq per year) but need to know how this will change this century
14	Methane hydrates	At what temperature are emissions from methane hydrates likely to start? Need estimates for various temperature trajectories
28-39	Radiative forcing estimates for some GHG's for 2100	CH4, contrails, etc.
42	Total Aerosols	-0.9 W m-2 per IPCC; -1.6 W m-2 per Hansen
46	Reduced Arctic albedo	The surface albedo in the Arctic is being reduced much faster than the models predicted - what is the best way to compensate for this?
52-54	Cost for BECCS,CCS, and DAC	

In addition to adding up the annual values for the various climate factors and using standard formulas that relate radiative forcing, the atmospheric concentration of greenhouse gases, and an equilibrium temperature, the model needs to make assumptions in two major areas:

1. The percentage of future CO2 emissions that will remain in the atmosphere in 2100, as this varies by both total emissions and climate sensitivity (e.g., if emissions were stopped immediately the oceans would continue to absorb CO2 until an equilibrium was reached - perhaps 180 GTC by 2100). See Appendix A for details.

2. How much the temperature will change in a year based on the current temperature and previous emissions (the "atmospheric response function") . By analyzing the results published in AR5 by the IPCC, is appears that by increasing the temperature annually by three percent of the difference between the projected temperature and the equilibrium temperature for the projected radiative forcing that the temperature increase projected by the IPCC can be matched for three different climate sensitivities. See Appendix B for details.

Current Model Results (to show how the model is used)

The user enters specifications for many of the climate factors on a "Parameters" worksheet. For example:

Calculations for Climate Sensitivity = 3																	
Ref#												Calculated Values					Climate Factors
		Change	2015	2100 Goal								Cum. Values		2015	2050	2100	
	Units	Unit	Value	Value	Cum.	%Change	#Years	%Change	#Years	%Change	Mode	2050	2100	Value	Value	Value	
																	I. Greenhouse Gas Emissions (and sinks)
																	Anthropogenic Greenhouse Gas Emissions
	GTC	Percent	9.86			0	5	-2	100		4	283.24	454.23	9.86	5.49	2.00	CO2 emissions (Fossil fuel and cement)
1	GTC	Percent	1.60			0	5	-2	100		4	45.96	73.71	1.60	0.89	0.32	CO2 emissions (Land use and forestry)
2																	CH4 emissions
3																	Nitrous Oxides
4																	Other GHG emissions
																	Anthropogenic Negative Emissions
6	GTC	Unit	0.00								3	0.00	0.00	0.00	0.00	0.00	Afforestation/reforestation/Ag improvements
7	Percent	Unit	0.00			0	5	2	30		3	-58.24	-160.83	0.00	-3.18	-1.20	BECCS
8	Percent	Unit	0.00			0	5	1	30		3	-4.73	-13.05	0.00	-0.26	-0.10	CCS
9	GTC	Unit	0.00								3	0.00	0.00	0.00	0.00	0.00	Direct Air Capture requirement
																	Natural Emission
10	GTC	Unit									3	0.00	0.00	0.00	0.00	0.00	Soil carbon
11	GTC	Unit									3	0.00	0.00	0.00	0.00	0.00	Permafrost emissions
12	GTC	Unit									3	0.00	0.00	0.00	0.00	0.00	Peat
13	GTC	Unit									3	0.00	0.00	0.00	0.00	0.00	Reservoirs
14	GTC	Unit									3	0.00	0.00	0.00	0.00	0.00	Methane hydrates
15	GTC	Unit									3	0.00	0.00	0.00	0.00	0.00	Other feedbacks
16	GTC	Unit									3	0.00	0.00	0.00	0.00	0.00	Additional Ocean uptake
17	GTC	Unit									3	0.00	0.00	0.00	0.00	0.00	Other sources/sinks
																	Total CO2 Emissions
18	GTC						Calculated					266.23	354.05	11.46	2.94	1.03	CO2 Emissions
																	Natural sinks
19																	Oceans
20																	Plant Growth
21												202.36	318.26	6.97	4.28	0.44	CO2 Removed from atmosphere
																	Summary
22												63.87	35.79	4.49	-1.34	0.59	Net CO2 Emissions
23												23.99	10.11	39.22	-45.60	57.55	Airborne Fraction
24	PPM	Unit					Not Implemented										Target Atmospheric CO2 PPM
25	PPM						Calculated							399.5	427.5	414.3	CO2 Atmospheric PPM

In this case

- CO2 emissions will remain flat for 5 years and then decrease by 2% per year for 100 years (a relatively aggressive emissions reduction scenario)
- BECCS will start after 5 years and increase the percent of CO2 emissions removed by 2% per year for 30 years
- CCS will start after 5 years and increase the percent of CO2 emissions removed by 1% per year for 30 years

(Note: The calculations are made after each parameter is entered)

An summary of the calculations is displayed on the "Summary" worksheet:

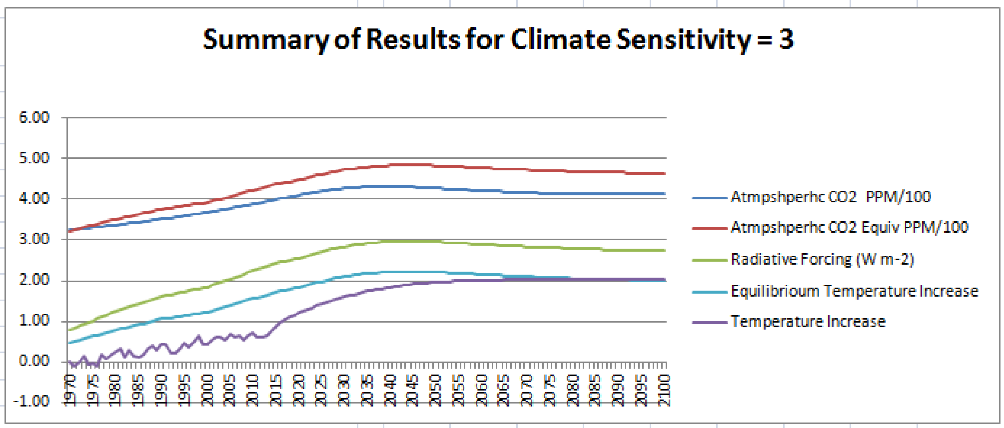
Calculated Values: Cum. Values 2050	Cum. Values 2100	2015 Value	2050 Value	2100 Value	Climate Factors	2015 Value	2100 Goal Value	Cum.	%Chang	#Years	%Chang	#Years	%Change
					I. Greenhouse Gas Emissions (and sinks)								
283.24	454.23	9.86	5.49	2.00	CO2 emissions (Fossil fuel and cement)	9.86	0.00	0.00	0.00	5.00	-2.00	100.00	0.00
45.96	73.71	1.60	0.89	0.32	CO2 emissions (Land use and forestry)	1.60	0.00	0.00	0.00	5.00	-2.00	100.00	0.00
0.00	0.00	0.00	0.00	0.00	Afforestation/reforestation/Ag improvements	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-62.97	-173.88	0.00	-3.44	-1.30	Total CDR (Carbon Dioxide Removal)								
0.00	0.00	0.00	0.00	0.00	Total Natural Emissoins								
266.23	354.05	11.46	2.94	1.03	Total CO2 Emissions								
202.36	318.26	6.97	4.28	0.44	CO2 Removed from atmosphere								
63.87	35.79	4.49	-1.34	0.59	Net CO2 Emissions								
		399.50	427.51	414.26	CO2 Atmospheric PPM								
					II. Radiative Forcing								
		1.94	2.30	2.13	CO2								
		-0.90	-0.50	-0.18	**Total Aerosols**	-0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	Reduced Arctic albedo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		2.44	2.95	2.75	Adjusted Radiative Forcing								
					III. Projections								
		438.45	482.76	464.89	Atmospheric CO2 Equivalent								
		1.73	2.21	2.02	Equilibrium Temperature								
		0.87	1.96	2.03	Projected Temperature Increase								
					IV. CDR Cost Estimates								
17.80	40.77	0.00	0.87	0.20	Total sequestration costs								

Projected Temperatures for Selected Years for Various Climate Sensitivities

Climate Sensitivity	2015	2050	2100
2.4	0.87	1.57	1.63
2.6	0.87	1.70	1.76
2.8	0.87	1.83	1.89
3	0.87	1.96	2.03
3.2	0.87	2.09	2.16
3.4	0.87	2.22	2.29
5	0.87	3.24	3.36

Projected Equilibrium Temperatures for

Climate Sensitivity	2015	2050	2100
2.4	1.39	1.77	1.63
2.6	1.50	1.92	1.76
2.8	1.62	2.06	1.88
3	1.73	2.21	2.00
3.2	1.85	2.35	2.12



Based on the parameters entered, the "Total CO2 emissions" (354 GTC) just about matches that of the carbon budget remaining after 2014 (356 GTC) and the temperature reached in 2100 is around 2°C

	GTC
GHG from 1870 -2014	555
Remaining Budget	445
Amount to allocate to CO2	356

Calculations for the remaining (post-2014) carbon budget

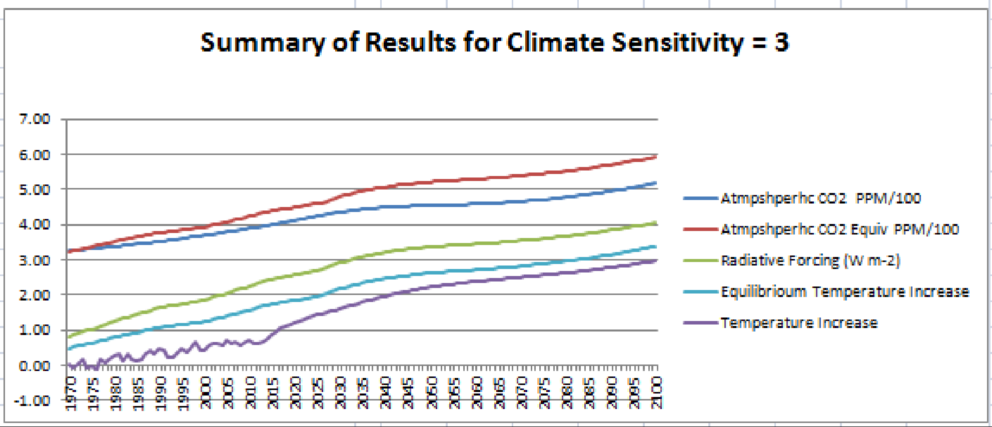
And the atmospheric CO2 PPM (414) is quite close to the value for IPCC RCP 2.6 (420). And note there is a temporary "overshoot" of the temperature before it reaches equilibrium, as also happened in RCP 2.6)

If likely natural emissions are added along with some afforestation and some accounting for the increased albedo in the Arctic region, the likely temperature increase gets close to 3°C (and this is with a very aggressive use of BECCS and CCS)

Calculated Values: Cum. Values 2050	Cum. Values 2100	2015 Value	2050 Value	2100 Value	Climate Factors	2015 Value	2100 Goal Value	Cum.	%Chang	#Years	%Chang	#Years	%Change
					I. Greenhouse Gas Emissions (and sinks)								
283.65	403.66	9.86	4.75	1.04	CO2 emissions (Fossil fuel and cement)	9.86	0.00	0.00	0.00	10.00	-3.00	100.00	0.00
46.03	65.50	1.60	0.77	0.17	CO2 emissions (Land use and forestry)	1.60	0.00	0.00	0.00	10.00	-3.00	100.00	0.00
-8.72	-50.59	0.00	-0.48	-1.18	Afforestation/reforestation/Ag improvements	0.00	-50.00	0.00	0.00	0.00	0.00	0.00	0.00
-39.51	-115.93	0.00	-2.46	-0.67	Total CDR (Carbon Dioxide Removal)								
93.42	371.67	1.65	3.78	7.28	Total Natural Emissoins								
374.86	674.31	13.11	6.35	6.64	Total CO2 Emissions								
254.74	419.39	8.62	5.54	1.14	CO2 Removed from atmosphere								
120.12	254.92	4.49	0.81	5.50	Net CO2 Emissions								
		399.50	454.04	517.63	CO2 Atmospheric PPM								
					II. Radiative Forcing								
		1.94	2.62	3.33	CO2								
		-0.90	-0.43	-0.09	Total Aerosols	-0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.01	0.01	0.01	Reduced Arctic albedo	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		2.45	3.35	4.04	Adjusted Radiative Forcing								
					III. Projections								
		439.05	520.23	591.83	Atmospheric CO2 Equivalent								
		1.74	2.61	3.39	Equilibrium Temperature								
		0.87	2.21	2.96	Projected Temperature Increase								
					IV. CDR Cost Estimates								
10.98	27.06	0.00	[illegible].63	0.10	Total sequestration costs								

Projected Temperatures for Selected Years for Various Climate Sensitivities

Climate Sensitivity	2015	2050	2100
2.4	0.87	1.77	2.44
2.6	0.87	1.92	2.61
2.8	0.87	2.07	2.78
3	0.87	2.21	2.95
3.2	0.87	2.35	3.12
3.4	0.87	2.50	3.28
5	0.87	3.61	4.50



How do we get this to be a collaborative model?

I'd appreciate any comments regarding:

1. Is the approach valid? (We can worry about getting the "correct" parameter values later)
2. Is improving the model worthwhile?
3. What other climate factors should be included?
4. Do you have any suggestions for 2015 values and/or "formulas" for calculating how the values should change between 2015 and 2100?
5. Do you know of anyone who could help with coming up with reasonable values for the model's parameters?
6. Would you be willing to "spread the word" on the model (perhaps after its "cleaned up" a bit) so that there could be a collaborative effort in its development?
7. How do we get the results of a model like this to become part of a national dialog on "solving" climate change?
8. Anything else?

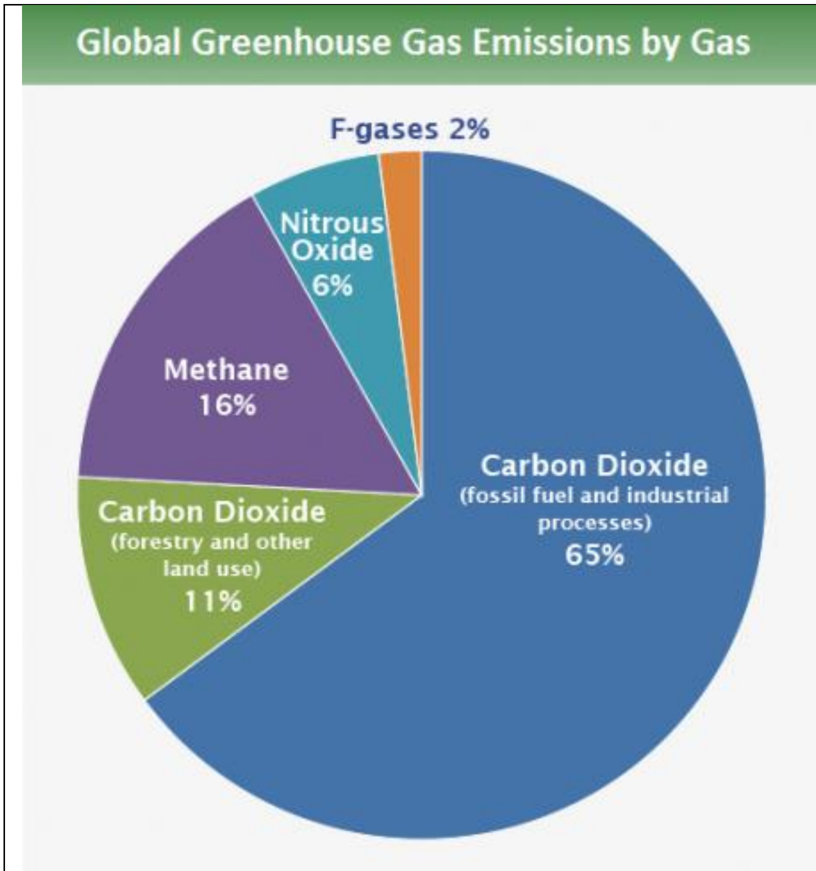
The current climate factors are

Ref#	I. Greenhouse Gas Emissions (sources and sinks)
	Anthropogenic Greenhouse Gas Emissions
1	CO2 emissions (Fossil fuel and cement)
2	CO2 emissions (Land use and forestry)
3	CH4 emissions
4	Nitrous Oxides
5	Other GHG emissions
	Anthropogenic Negative Emissions
6	Afforestation/reforestation
7	BECCS
8	CCS
9	Direct Air Capture requirement
	Natural Emissions and sinks
10	Soil carbon
11	Permafrost emissions
12	Peat
13	Reservoirs
14	Methane hydrates
15	Other feedbacks
16	Additional Ocean uptake
17	Other sources/sinks
	Total CO2 Emissions
18	CO2 Emissions
	Natural sinks
19	Oceans
20	Plant Growth
21	CO2 Removed from atmosphere
	Summary
22	Net CO2 Emissions
23	Airborne Fraction
24	Target Atmospheric CO2 PPM
25	Atmospheric PPM
26	CO2 to remove next year to hit PPM target
	II. Radiative Forcing
	Radiative Forcings for Climate Factors
27	CO2
28	CH4
29	Nitrous Oxides
30	Other GHG emissions
31	**Total Greenhouse Gases**
32	Stratospheric
33	Tropospheric
34	Total Ozone
35	Strato. H20
36	Land Use Albedo Change
37	Black Carbon
38	Total Albedo
39	Contrails
40	Radiation Inter.
41	Cloud Inter
42	**Total Aerosols**
43	Total Anthropogenic
44	Solar Radiance
45	Total IPCC
	Additional Radiative Forcing
46	Reduced Arctic albedo
	Radiative Forcing and CO2 PPM Calcs
47	Adjusted Radiative Forcing
48	Atmospheric CO2 Equivalent
49	Equilibrium Temperature
50	Change in temperature for next year
51	Temperature increase
	III. CDR Cost Estimates
	Cost Estimates = $/Ton C
52	BECCS
53	CCS
54	DAC
	Cost Estimates ($Trillions)
55	BECCS
56	CCS
57	DAC
58	Total sequestration costs
59	Maximum annual CDR costs
60	Average annual CDR costs

The following section describes the various climate factors

I. Greenhouse Gas Emissions (and sinks)

Anthropogenic Greenhouse Gas Emissions



https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

Box 2 - Global greenhouse gas emissions in 2014

https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf				
	2010 PCT	**2010 GTC**	**2015 GTC**	
CO2 from fossil fuel comb and industrial processes	62	8.57	9.86	Assumed
CO2 from Forestry and Other Land Use (FOLU)	10	1.38	1.59	Calculated
Methane (CH4)	20	2.77	3.18	Calculated
Nitrous oxide (N2O)	5	0.69	0.79	Calculated
Fluorinated gases	**2.2**	**0.30**	**0.35**	Calculated
Total	**99.2**	**13.83**	**15.90**	

Box 3 - Calculating 2015 GHG emissions based on 2010 IPCC data and 2015 estimated CO2 emissions from fossil fuels

1. CO_2 emissions (Fossil fuel and cement)

   This model does not deal directly with global energy requirements, renewable energy, energy efficiency, or the costs associated with an emission reduction scenario. Instead the user simply specifies how CO_2 emissions from fossil fuels (#2) and land use (#3) change over time and what percentage of the fossil fuel emissions in a specific year are captured either with BECCS (#8) or CCS (#9).

   According to the Carbon Dioxide Information Analysis Center, global CO_2 emissions from fossil-fuel burning, cement manufacture, and gas flaring were about 9.855 GTC in 2014. Since global emissions did not change much in 2015, the 2014 number can be used for 2015. (Hansen uses 9.857 for 2015 CO_2 emissions for fossil fuel, cement, and gas flaring- see http://www.columbia.edu/~mhs119/Burden/Fig.A1.ann.txt)

   The user can specify how the emissions change before 2100 by specifying to sets of percentage change for two time periods and then one final percentage change (e.g., the values in Box 4 specify a scenario which calls for emissions to start out at 9.86 GTC/year, then not change for 10 years, then decline by 3 percent per year).

Ref#										
		Change	2015	2100 Goal						
	Units	Unit	Value	Value	Cum.	%Change	#Years	%Change	#Years	%Change
2	GTC	Percent	9.86			0	10	-3	100	

   Box 4 - Sample Fossil Fuel emissions scenario

2. CO_2 emissions (Land use and forestry)
   If CO_2 emissions from forestry and other land use changes are about 17 percent of CO_2 emissions from the burning of fossil fuels (see Box 2), the 2015 emissions would be about 1.67 GTC. This is relatively close to the value from Box 3, so 1.6 GTC seems like a reasonable value for 2015

3. CH_4 emissions - values for estimated radiative forcing on 2100 are used instead of emissions

4. Nitrous Oxides - values for estimated radiative forcing on 2100 are used instead of emissions

5. Other GHG emissions - values for estimated radiative forcing on 2100 are used instead of emissions

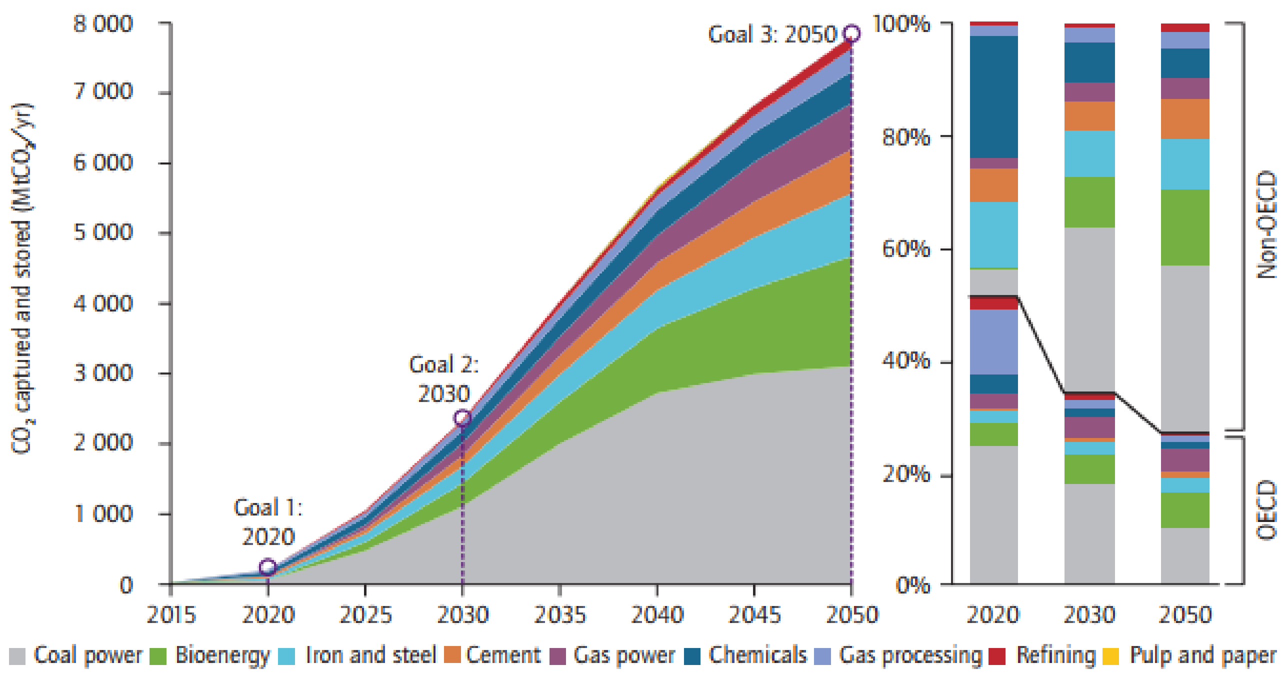
Anthropogenic Negative Emissions

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

Box 5A -All relevant RCP2.6 scenarios required significant negative emissions

Figure 4. CCS in the power and industrial sectors in the 2DS



KEY POINT: the 2DS suggests a steep deployment path for CCS technologies applied to power generation and a number of industries. Over 70% of all CCS projects take place in non-OECD countries by 2050.

https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf

Box 5B -Estimate of carbon capture requirements for IEA's "2 Degrees" scenario

6. Afforestation/reforestation/Agricultural improvements

Hansen estimates that about 100 GTC of CO2 could be sequestered by an "ambitious" effort (see Box 6). But given the recent trends in desertification and forest loss, what is a reasonable value for sequestration by 2100? (The model assumes a linear increase in sequestration such that that the total amount sequestered equals the parameter entered)

We conclude that 100 PgC is an appropriate ambitious estimate for potential carbon extraction via a concerted global-scale effort to improve agricultural and forestry practices with carbon drawdown as a prime objective

"Young People's Burden: Requirement of Negative CO2 Emissions" (October 4, 2016) (http://www.earth-syst-dynam-discuss.net/esd-2016-42/) - page 15

Box 6 - Hansen's estimate of "natural sequestration"

7. Bio-energy Carbon Capture and Storage (BECCS)

   The user can specify how fast BECCS is adopted (annual percentage increase - for a specified number of years - of CO_2 fossil fuel emission captured by BECCS). Box 7 shows the parameters for BECCS starting from 0 after 5 years, and increasing by 2% of CO_2 fossil fuel emissions for 30 years, then remaining at 60% of CO_2 fossil fuel emissions for the rest of century.

Ref#										
		Change	2015	2100 Goal						
	Units	Unit	Value	Value	Cum.	%Change	#Years	%Change	#Years	%Change
8	Percent	Unit	0.00			0	5	-2	30	0

Box 7- Sample BECCS scenario

8. Carbon Capture and Storage (CCS)

   The user can specify how fast CCS is adopted (annual percentage increase - for a specified number of years - of CO_2 fossil fuel emission captured by CCS)

9. Direct Air Capture requirement

   The user can specify the annual increase in GTC- for a specified number of years of DAC of CO_2. The user should also specify a target for atmospheric CO_2, and the quantity removed by DAC will be reduced to meet this target. Box 8 shows the parameters for DAC starting from 0 after 5 years, and increasing by 1 GTC per year for 20 years, then remaining at 20 GTC until atmospheric CO_2 reaches that target PPM

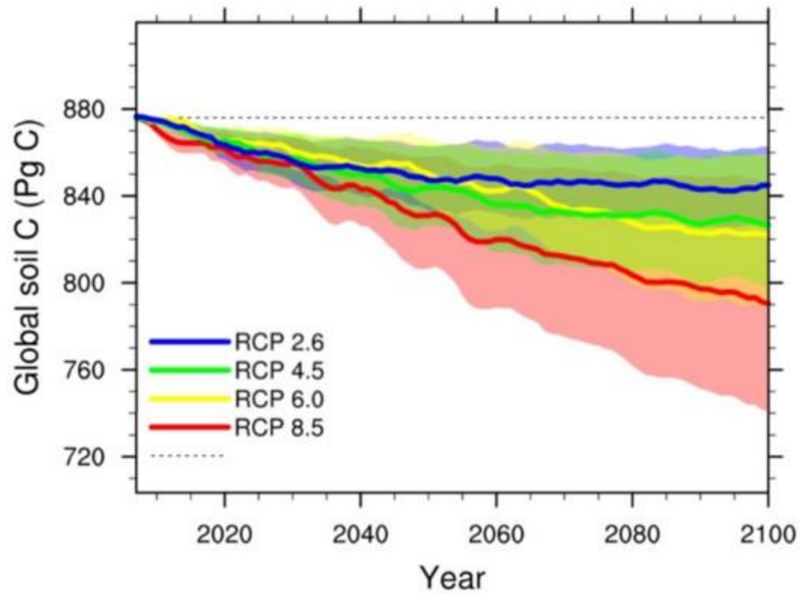
Ref#										
		Change	2015	2100 Goal						
	Units	Unit	Value	Value	Cum.	%Change	#Years	%Change	#Years	%Change
10	GTC	Unit	0.00			0	5	-1	20	0

Box 8- Sample BECCS scenario

Natural Emissions and Sinks

10. Soil carbon

As the world warms, additional CO2 will be released from the soils (see Box 9). The amount is likely related to the temperature, but this model simply allows the user to specify annual change in GTC per year.



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

Box 9 - Natural CO2 emissions from soils

11. Permafrost emissions

"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

Box 10 - Emissions from the thawing of permafrost

12. Peat

Since I could not find any estimates for future emissions from peatlands and peat bogs, I assumed that the current annual emissions of about 4GTCO2e would continue until 2100. To see if this is in the right "ballpark", if carbon from 40% of shallow peat and 86% of deep bogs will be emitted over several centuries, perhaps 70% of the carbon will be emitted over four centuries, which would be about 3.6 GTCO2e/year.

"Our modeling suggests that higher temperatures could cause water tables to drop substantially, causing more peat to dry and decompose," says Paul R. Moorcroft, professor of organismic and evolutionary biology in Harvard's Faculty of Arts and Sciences. "Over several centuries, some 40 percent of carbon could be lost from shallow peat bogs, while the losses could total as much as 86 percent in deep bogs."

Typically found at northerly latitudes, peat bogs are swampy areas whose cold, wet environment preserves organic matter, preventing it from decaying. This new work shows how peat bogs' stability could be upset by the warming of the Earth, which has disproportionately affected the higher latitudes where the bogs are generally found.

Each square meter of a peat bog contains anywhere from a few to many hundreds of kilograms of undecomposed organic matter, for a total of 200 billion to 450 billion metric tons of carbon sequestered in peat bogs worldwide. This figure is equivalent to up to 65 years' worth of the world's current carbon emissions from fossil-fuel burning.

http://news.harvard.edu/gazette/story/2008/11/global-warming-predicted-to-hasten-carbon-release-from-peat-bogs/

Peatlands are a major storage of carbon in the world. They account for 550 Gt carbon worldwide.

Peat fires, such as those take place in Southeast Asia every year and also in Russia, release huge amounts of CO_2 as well. Altogether global CO_2 emissions amount to at least 2,000 million tonnes annually, equivalent to 5% of the global fossil fuel emissions.

http://www.wetlands.org/Whatarewetlands/Peatlands/Carbonemissionsfrompeatlands/tabid/2738/Default.aspx

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

Box 11 - Emissions from Peat

13. Reservoirs

" 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

Box 12

14. Methane hydrates

15. Other feedbacks

16. Additional Ocean uptake

A place to specify that addition CO2 will be taken up by the oceans. Not needed in the "basic" model as it is accounted for by the calculations that compute "21. CO2 removed from atmosphere"

17. Other sources/sinks

Total CO_2 Emissions

18. CO_2 Emissions - adds up all CO_2 emissions (sources and sinks)

Natural sinks

19. Oceans - are accounted for by "#21 CO_2 Removed from Atmosphere "

20. Plant Growth - are accounted for by "#21 CO_2 Removed from Atmosphere "

21. CO_2 Removed from the atmosphere

    As net CO_2 emissions approach zero the ocean will begin to absorb more CO_2 than is being emitted. If the atmospheric CO_2 is reduced below a certain amount the oceans will begin to emit CO_2. .

    Hansen calculated that, with emissions of 340 GTC that atmospheric CO_2 would rise to about 417 PPM (on emissions of 340 GTC and natural sequestration of 100 GTC) if emissions went to zero and there was no CO_2 extraction. Since 240 GTC would raise the atmospheric CO_2 by about 100 PPM, the oceans would have absorbed about 185 GTC of CO_2 (equivalent to 85 PPM) ("Young People's Burden: Requirement of Negative CO_2 Emissions" (October 4, 2016) (http://www.earth-syst-dynam-discuss.net/esd-2016-42/))

Summary

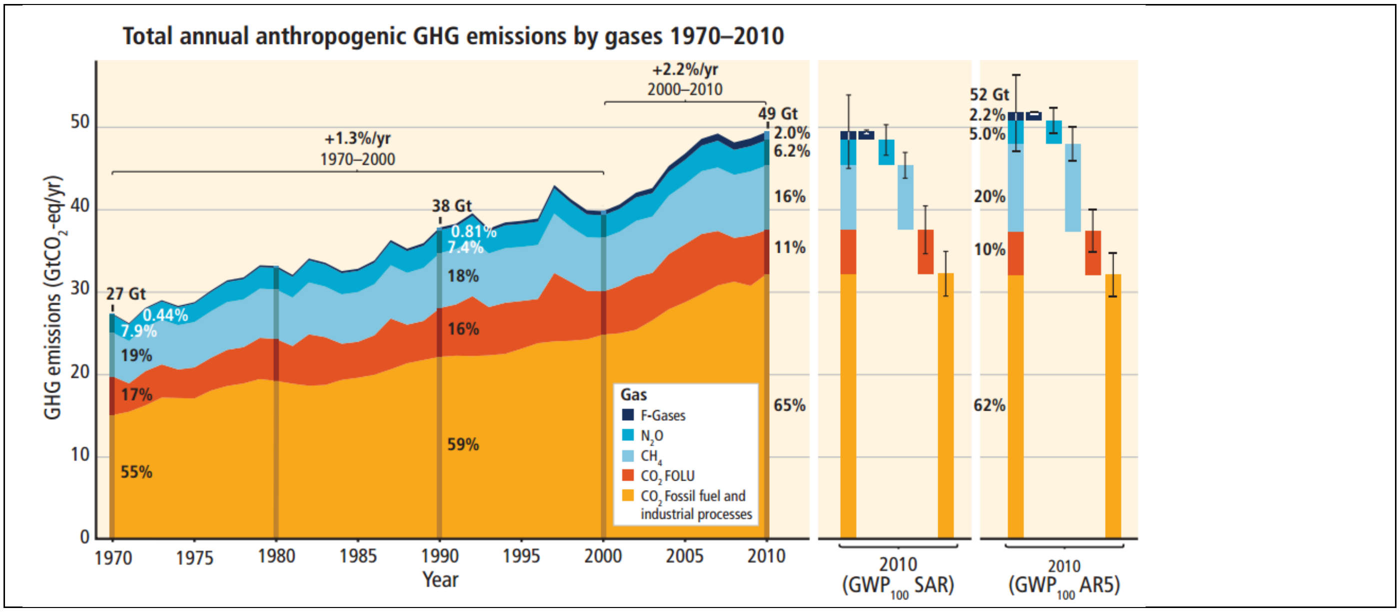
22. Net CO_2 Emissions

23. Airborne Fraction

    The *airborne fraction* is the percentage of CO_2 emissions that remain in the atmosphere after natural processes absorb some of the emissions. The number currently in general use is 45%. As the oceans warm they will be able to absorb less CO_2. And as the land surfaces warm forests will likely be able to absorb less CO_2.

Jones & Cox (2005) calculated the AF as a constant 42%. In a recent paper, Canadell et al (2007) calculate that it has risen from 40% in 1960 to 45% at present, with a statistically significant trend of 0.25±0.21 % per year. https://www.esrl.noaa.gov/gmd/co2conference/posters_pdf/jones1_poster.pdf

Box 1 - Reference to airborne fraction value



Box1 A - Recent Annual Greenhouse Gas Emissions (IPCC - AR5)

CO2 emissions were about 19.5 GTCO2 in 1970 (=27 * (55+17)/100) and about 37.25 GTCO2 in 2010 (=49 * (65+11)/100). This amounts to a total of about 302 GTC over 40 years (=(40*(19.5+37.25)/2)/3.76). In those same 40 years the atmospheric CO2 concentration rose from 328.7 PPM to 392.9 PPM, an increase of about 136 GTC (=(392.9-328.7) * 2.12). So the airborne fraction over 40 years as averaged about 45%.

However, the airborne fraction in future years will depend primarily on the net CO2 emissions - if net annual emissions are negative (or perhaps less than 1-2 GTC), the airborne fraction will be 0 and CO2 will actually be removed from the atmosphere, while if CO2 emissions are very high the airborne fraction will likely increase as warmer water can hold less oxygen and the vegetation will likely absorb less CO2. To simplify the calculation for the airborne fraction for each year between 2015 and 2100, an average value can be estimated by examining the data for the various RCP's and developing a quadratic function based on netCO2 emissions. When the average value is over about 45%, the projected equilibrium temperature will likely be a bit high for the 40 years or so and likely a bit low for the final 40 years. And when the average value is below about 45%, the projected equilibrium temperature will likely be a bit low for the 40 years or so and likely a bit high for the final 40 years. But since none of the other calculations are based on temperature this will not be a problem for calculating the expected 2100 equilibrium temperature. (And note that with this approach there will not be any additional uptake by the oceans as the net CO2 emissions approach zero.)

If the net CO2 emissions become less than zero (most likely because of direct air capture) the model needs to be revised slightly - the airborne fraction needs to be set zero and some additional ocean uptake will be required.

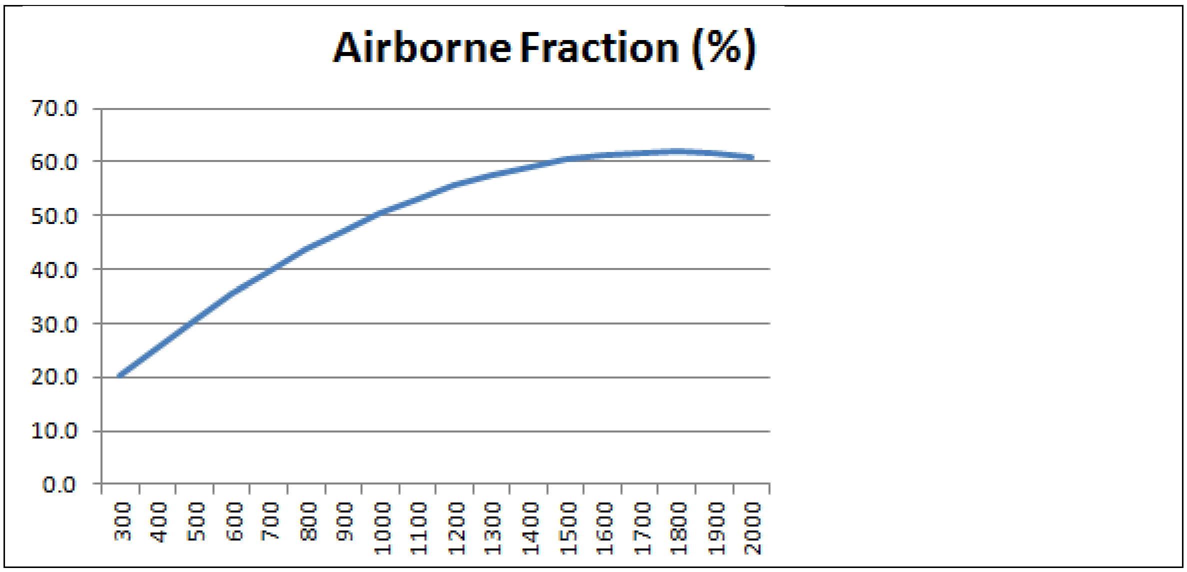
For net emissions over 200 GTC the following coefficients for a quadratic formula ($y= Ax^2 + Bx + C$, where 'x' is the net CO2 emissions through 2100) for the average airborne fraction between 2015 and2100 were derived using the results of the RCP models:

A: -1.91282E-05   B: 0.067988   C: -1.25098388

A linear fit was used by selecting the net CO2 emission values from pages 1410 (Table AII.2.1c | Anthropogenic total CO2 emissions (PgC yr–1)) and the CO2PPM values from page 1422 (Table AII.4.1 | CO2 abundance (ppm)) of the IPCC's "CLIMATE CHANGE 2013 The Physical Science Basis" report.

RCP	Net Anthropogenic CO2 emissions 2015-2100 (GTC)	Atmospheric CO2 PPM in 2100	Increase in Atmospheric CO2 from 2015-2100 (PPM)	Increase in Atmospheric CO2 from 2015-2100 (GTC)	Airborne Fraction (Percent)
2.6	303.2	420.0	20.5	43.5	14.3
4.5	724.8	538.4	138.9	294.5	40.6
6	1128.5	669.7	270.2	572.8	50.8
8.5	1857.1	935.9	536.4	1137.2	61.2

Box 1B - Values for computing the airborne fraction for the RCP pathways



Box 1C - Plot of Airborne Fraction vs. Net CO2 Emissions

300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
20	26	31	35	40	44	47	50	53	56	58	59	60	61	62	62	62	61

Box 1D - Airborne Fraction for various quantities of net CO2 emissions 2015-2100

24. Target Atmospheric CO2 PPM (not currently implemented)

    Allows the user to specify a value for the case where DAC is toto be reduced after a specific target is met

25. CO2 Atmospheric PPM
    Calculated as previous year PPM + CO2 Emissions/AIrborne Fraction/GTC per PPM

26. CO_2 to remove next year to hit PPM target (not currently implemented)

Calculates GTC of CO_2 to be removed to meet the target specified in #21 above. When the amount is less than what was removed by DAC in the previous year the amount to be removed by DAC is reduced

Radiative Forcing

Radiative Forcings for Climate Factors

Global Radiative Forcing (W m^{-2})								CO_2-eq (ppm)	AGGI	
Year	CO_2	CH_4	N_2O	CFC12	CFC11	15-minor	Total	Total	1990 = 1	% change
2015	1.938	0.504	0.19	0.165	0.058	0.118	2.973	485	1.374	1.8
2016	1.985	0.507	0.193	0.164	0.057	0.121	3.027	489	1.399	2.5

https://www.esrl.noaa.gov/gmd/aggi/aggi.html

Box 13

Radiative Forcing Calculations

To determine the total radiative forcing of the greenhouse gases, we have used IPCC *[Ramaswamy et al., 2001]* recommended expressions to convert greenhouse gas changes, relative to 1750, to instantaneous radiative forcing (see Table 1). These empirical expressions are derived from atmospheric radiative transfer models and generally have an uncertainty of about 10%. The uncertainties in the global average abundances of the long-lived greenhouse gases are much smaller (<1%).

Table 1. Expressions for Calculating Radiative Forcing*

Trace Gas	Simplified Expression Radiative Forcing, ΔF (Wm^{-2})	Constant
CO_2	$\Delta F = \alpha \ln(C/C_o)$	$\alpha = 5.35$
CH_4	$\Delta F = \beta(M^{½} - M_o^{½}) - [f(M,N_o) - f(M_o,N_o)]$	$\beta = 0.036$
N_2O	$\Delta F = \varepsilon(N^{½} - N_o^{½}) - [f(M_o,N) - f(M_o,N_o)]$	$\varepsilon = 0.12$
CFC-11	$\Delta F = \lambda(X - X_o)$	$\lambda = 0.25$
CFC-12	$\Delta F = \omega(X - X_o)$	$\omega = 0.32$

*IPCC (2001)

The subscript "o" denotes the unperturbed (1750) abundance

$f(M,N) = 0.47\ln[1 + 2.01\times10^{-5} (MN)^{0.75} + 5.31\times10^{-15}M(MN)^{1.52}]$

C is CO_2 in ppm, M is CH_4 in ppb
N is N_2O in ppb, X is CFC in ppb

$C_o = 278$ ppm, $M_o = 722$ ppb, $N_o = 270$ ppb, $X_o = 0$

https://www.esrl.noaa.gov/gmd/aggi/aggi.html

Box 14

	ERF Change Since 1750		
	2011	RCP2.6	
CO2	1.816	2.220	From "CLIMATE CHANGE 2013 The Physical Science Basis"
CH4	0.425	0.270	
N20	0.195	0.230	
Halocarbons & Other	0.395	0.142	
Greenhouse Gases	**2.831**	**2.862**	
Stratospheric	-0.050	-0.075	
Tropospheric	0.400	0.170	
Ozone	0.350	0.140	
Stratospheric H20	0.073	0.099	Estimated so that the "Total IPCC" ERF change is 2.6
Land Use	-0.150	-0.203	
Black Carbon	0.040	0.054	
Albedo	-0.110	-0.149	
Contrails	0.050	0.068	
Radiation Inter.	-0.450	-0.225	assumes 1/2 2015 emissions in 2100, so 1/2 of 2015 aerosol forcing
Cloud Inter	-0.450	-0.225	
Aerosols	-0.900	-0.450	
Total Anthropogenic	2.294	2.570	
Solar Radiance	0.030	0.030	
Total IPCC	2.324	2.600	

Box 15A

```
-------------------------------------------------------------------------------
Table A1. Effective Forcings (W/m2) Relative to 1850: 1850-2015
-------------------------------------------------------------------------------
year    CO2    (a)CH4  (b)CFCs   N2O    (c)O3   (d)TA+SA (e)Volc  Solar     Net
----------------------------------------------------------------------------
2015   1.927   0.730   0.373   0.195   0.129  -1.199  -0.100   0.137    2.192
-------------------------------------------------------------------------------
(a)CH4:   CH4-induced changes of tropospheric O3 and stratospheric H2O are included.
(b)CFCs:  All GHGs except CO2, CH4, N2O and O3.
(c)O3:    half of tropospheric O3 forcing + stratospheric O3 forcng from IPCC (2013).
(d)TA+SA: tropospheric aerosols and surface albedo forcings combined.
(e)Volc:  volcanic forcing is 0 when there is no stratospheric aerosols.
```

Box 15B - Hansen - http://www.columbia.edu/~mhs119/Burden/Table.A1.ann.txt

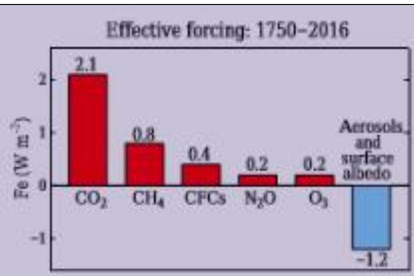


Figure 4. Estimated effective climate forcings (update through 2016 of Fig. 28b of Hansen et al., 2005, which are consistent with estimates of Myhre et al., 2013, in the most recent IPCC report, IPCC, 2013). Forcings are based on observations of each gas, except simulated CH_4-induced changes of O_3 and stratospheric H_2O included in the CH_4 forcing. Aerosols and surface albedo change are estimated from historical scenarios of emissions and land use. Oscillatory and intermittent natural forcings (solar irradiance and volcanoes) are excluded. CFCs include not only chlorofluorocarbons, but all Montreal Protocol trace gases (MPTGs) and other trace gases (OTGs). Uncertainties (for 5–95 % confidence) are 0.6 W m^{-2} for total GHG forcing and 0.9 W m^{-2} for aerosol forcing (Myhre et al., 2013).

Box 15C - Hansen - Young Peoples Burden

27. CO2
    Calculated per formula in above "box" based on atmospheric CO2

28. CH4
    2015 value from the above "box". 2100 value from RCP2.6

29. Nitrous Oxides
    2015 value from the above "box". 2100 value from RCP2.6

30. Other GHG emissions
    2015 value from the above "box". 2100 value from RCP2.6

31. Total Greenhouse Gases
    Sum of the radiative forcings from greenhouse gases

32. Stratospheric ozone - included in total ozone

33. Tropospheric - included in total ozone

34. Total Ozone
    Estimated base on RCP 2.6 values (see box #15 above)

35. Stratospheric. H20
    Estimated based on RCP 2.6 values (see box #15 above)

36. Land Use Albedo Change
    Estimated based on RCP 2.6 values (see box #15 above)

37. Black Carbon
Estimated based on RCP 2.6 values (see box #15 above)

38. Total Albedo - total of the above two numbers

39. Contrails
Estimated based on RCP 2.6 values (see box #15 above)

40. Radiation Inter. - included in "Total Aerosols"

41. Cloud Inter - included in "Total Aerosols"

42. Total Aerosols

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

Box 16

43. Total Anthropogenic - total of changes due to anthropogenic emissions and radiative forcing changes

44. Solar Radiance - kept constant

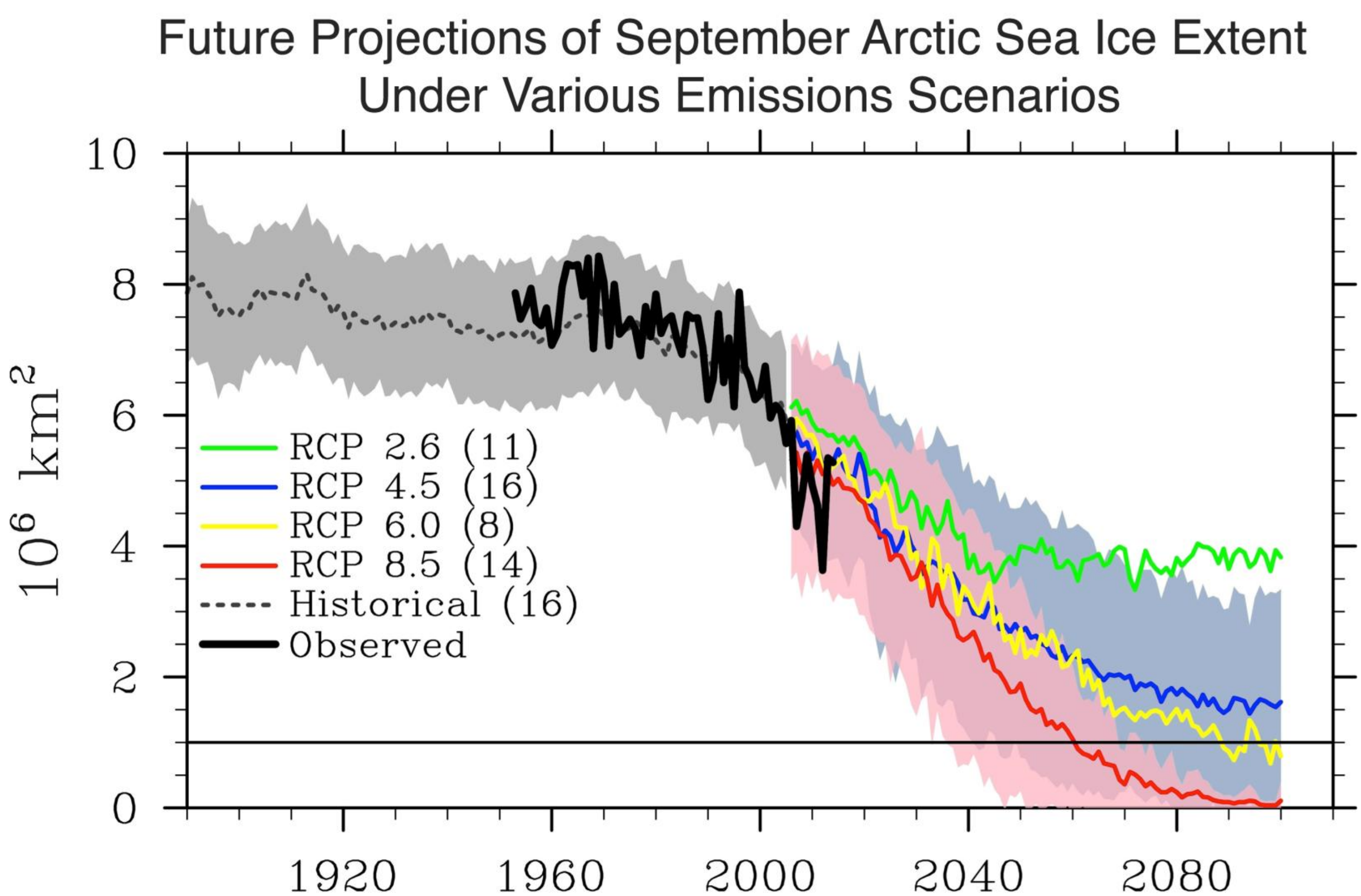
45. Total IPCC

Additional Radiative Forcing

46. Reduced Arctic albedo

There is an apparent lag in the albedo-feedback effect in the Arctic region projected by the global climate models when compared to actual observations (i.e., the warming in the Arctic is further along that most of models currently simulate - see Box 17). Since climate sensitivity includes fast feedbacks such as surface albedo changes in the Arctic, what is the best way to compensate for this lag when estimating the future warming based on the total radiative forcing?

If the models expect that 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 (see Box 18) (or about 0.14 W m-2 (-2.3 * .06) and the actual forcing was closer to 0.45 W m-2 (see Box 18), then there is an "extra" radiative forcing of about about .30 W m-2. So perhaps adjusting the radiative forcing up by about 10% (a bit less the 2 * 6%) would compensate for the additional radiative forcing in the Arctic.



Note: The IPCC has really underestimated when the summer-time Arctic ocean will likely become ice free, so it's temperature estimates are likely low

Box 17 - September Arctic Sea Ice Extent 1953-2012 - with data added for 2013-2015

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.
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)

Box 18

Radiative Forcing and CO2 PPM Calcs

47. Adjusted Radiative Forcing

Calculated - includes "Total IPCC" forcing and forcing from the reduced Arctic albedo

48. Atmospheric CO2 Equivalent
Computed from " Adjusted Radiative Forcing " so that the equilibrium temperature can be calculated

49. Equilibrium Temperature

The equilibrium temperature is calculated by a formula which contains the effective radiative forcing and the climate sensitivity. For the current model the main calculations are for a climate sensitivity of 3.0 °C for doubling of atmospheric CO2 (or CO2 equivalent)

Note that a climate sensitivity likely includes many of the natural emissions, so the corresponding temperature increase likely makes sense when the model uses only anthropogenic emissions.

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

Box 19

50. Change in Temperature for Next Year

51. Temperature Increase

III. CDR Cost Estimates

Cost Estimates = $/Ton C
Includes estimates of current costs reduced by a specific percent per year

52. BECCS

53. CCS
54. DAC

Howard Herzog (senior research engineer at MIT) estimated that total system costs for air capture could be as much as $1,000 per ton of CO2, or about 10 times the cost of carbon removal at a fossil fuel plant.
http://www.sciencemag.org/news/2017/06/switzerland-giant-new-machine-sucking-carbon-directly-air

4. **What are the pros and cons of DAC as a carbon management technology? ...** Because DAC systems do not need to be sited directly at power plants, they can be sited close to sequestration/manufacturing sites, eliminating the sometimes costly CO2 transportation step associated.

6. **How is DAC related to other carbon capture and storage (CCS) systems?** ...[P]ower plants generate exhaust gas with around 15% concentration of CO2, natural gas power plants around 5%, and ambient air has around 0.04%.

7. **How much energy is required for DAC?**...[F]or every million tons of compressed CO2 generated from a maximally efficient DAC system, a power plant running at 100% capacity factor of 10 MW is required. To get to the billion ton scale of CO2 capture viewed by many experts as climatically significant, DAC systems would thus require about 10 GW of power, equal to about 3 times the capacity of the largest nuclear plant in the US.

8. **How much does DAC cost? ...** It is likely that the first commercial-scale DAC projects will cost several hundreds of dollars per ton of concentrated CO2, but as manufacturing improves over time, these costs are likely to come down significantly, especially if DAC is manufactured modularly like many startups are attempting to do. It is also likely that operating costs will come down overtime as novel chemical structures are developed that cost less and/or require less material than existing capture chemicals.

(http://www.centerforcarbonremoval.org/blog-posts/2015/9/20/direct-air-capture-explained-in-10-questions)

When valid physics is evaluated, the costs of new technology DAC is very similar to what the physics shows (see also Holmes and Kieth 2012) regardless of atmospheric concentration.

" Direct Air Capture Cost Controversy (DAC)" Bruce Melton, Climate Change Now, August 2016

1. Climeworks (http://www.climeworks.com/)

- 900 Tons annually/plant
- Uses energy recovered from waste heat to remove CO2 from a filter
- Captured CO2 is used for commercial purposes (greenhouse gases, carbonated beverages, etc.)
- Current CO2 removal costs are $75/ton CO2 ($25/ton CO2 if use waste heat)
- Possible cost efficiency gains might reduce this to $8/ton CO2 for capture
- It would take 25 million plants to capture 20 GTC/year

2. Carbon Engineering (British Columbia) (http://carbonengineering.com/)

- Goal: Use CO2 in the synthesis of clean transportation fuels that displace crude oil
- The system uses a wet scrubbing air contactor with a chemical regeneration cycle
- Current CO2 removal costs are $100-150 per ton of CO2 captured, purified, and compressed to 150 bar.

Based on the need to ramp up DAC (with sequestration) rapidly (perhaps by 1 GTC/year starting in2020), a reasonable starting cost might be$1000/ton C for capture and storage ("It is likely that the first commercial-scale DAC projects will cost several hundreds of dollars per ton of concentrated CO2", or about $250/ton CO2 for capture and concentration + $15/ton CO2 for storage, for a total of about $265/ton CO2). If the costs of DAC can be reduced by 2.5%/year, then the cost in 2100 would be about 1/10 of the current costs ($116/ton).

Cost Estimates ($Trillions)

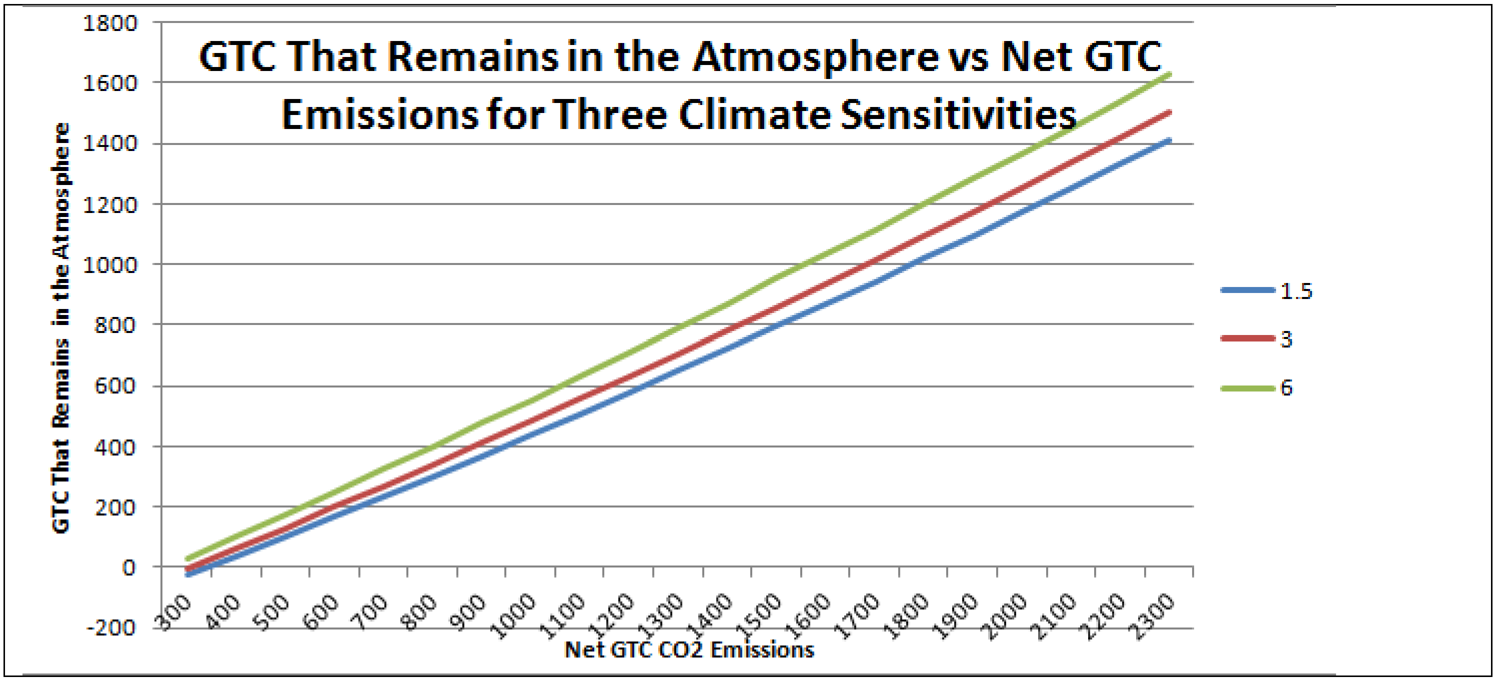
Calculated based on amount sequestered per year and estimated costs that year

55. BECCS
56. CCS
57. DAC
58. Total sequestration costs
59. Maximum annual CDR costs
60. Average annual CDR costs

Appendices (See "Data Sources" below for the sources for the data)

Appendix A - The percentage of future CO2 emissions that will remain in the atmosphere in 2100

The amount of future emissions that will remain in the atmosphere in 2100 varies by both total emissions and climate sensitivity (e.g., if emissions were stopped immediately the oceans would continue to absorb CO2 until an equilibrium was reached - perhaps 180 GTC by 2100). One way to estimate this amount is "reverse engineer" the results from climate models on the assumption that if the relationship between the total emissions and net emissions is relatively linear, a simple quadratic formula can be developed. One such set of data is available from the "Model for the Assessment of Greenhouse-gas Induced Climate Change" (MAGICC), which provides 44 scenarios for climate sensitivities of 1.5, 3, and 6. Based on the MAGICC scenarios, quadratic scenarios were developed for the three climate sensitivities, and the following graph was created:



Because the "simple model" is based on the climate sensitivity of 3, a "table" (of rows and columns) was created to simplify the process of estimating the future emissions for any climate sensitivity between 1.5 and 6 and any emissions amount between 300 and 2300 GTC by interpolating between to emission values to get a "Percent Change to CO2 Added to Atmosphere", where the value being changed is the amount added for a climate sensitivity of 3.

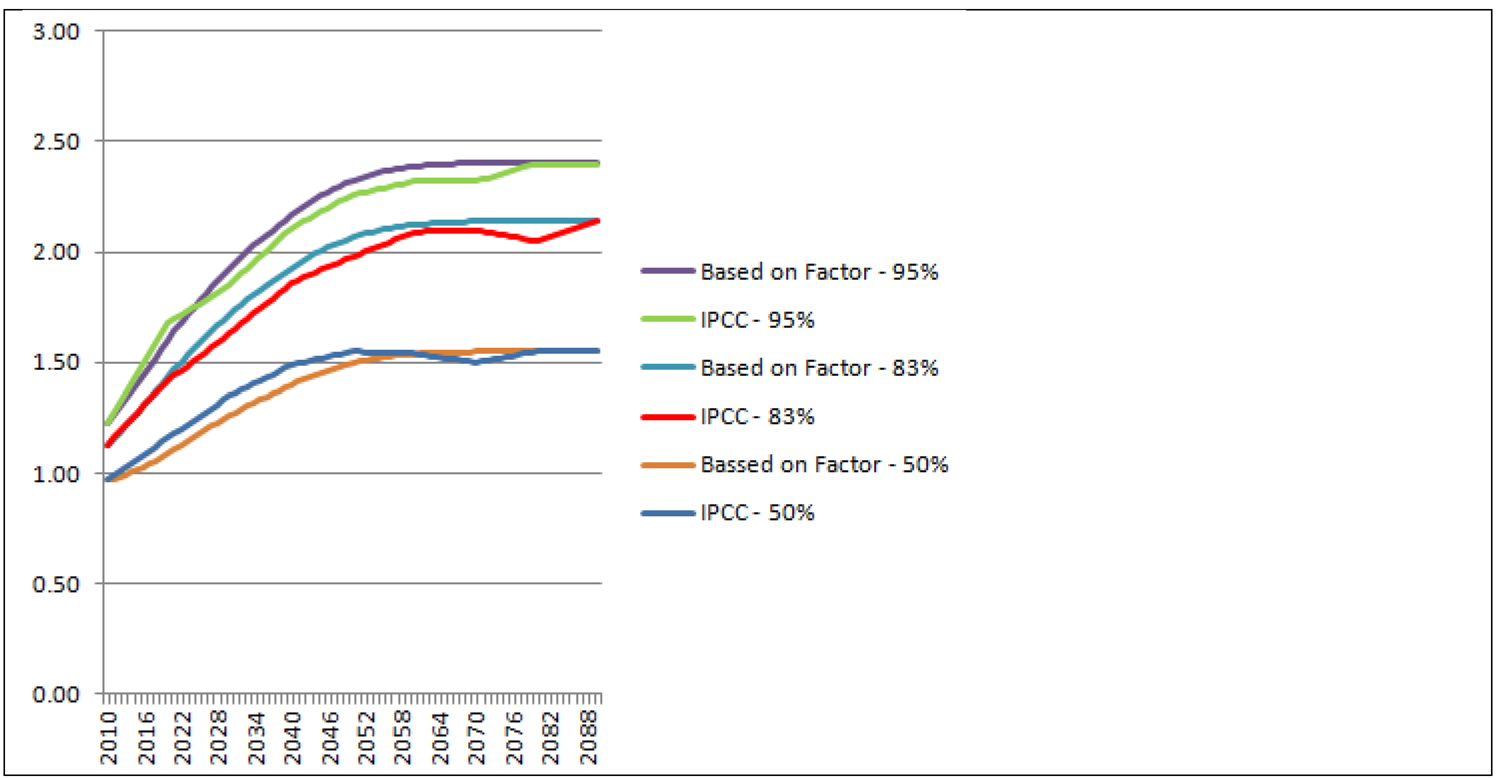
	Emissions 100	300	400	500	600	700	800
Climate Sensitivity	1.5	6.782813	-0.39559	-0.22119048	-0.16438	-0.13593	-0.11866
	1.6	6.330625	-0.36921	-0.20644445	-0.15342	-0.12687	-0.11074
	1.7	5.878438	-0.34284	-0.19169842	-0.14247	-0.1178	-0.10283
	1.8	5.42625	-0.31647	-0.17695239	-0.13151	-0.10874	-0.09492
	1.9	4.974063	-0.2901	-0.16220635	-0.12055	-0.09968	-0.08701
	2	4.521875	-0.26372	-0.14746032	-0.10959	-0.09062	-0.0791
	2.1	4.069688	-0.23735	-0.13271429	-0.09863	-0.08156	-0.07119
	2.2	3.6175	-0.21098	-0.11796826	-0.08767	-0.07249	-0.06328
	2.3	3.165313	-0.18461	-0.10322223	-0.07671	-0.06343	-0.05537
	2.4	2.713125	-0.15823	-0.08847619	-0.06575	-0.05437	-0.04746

	2.5	2.260938	-0.13186	-0.07373016	-0.05479	-0.04531	-0.03955
	2.6	1.80875	-0.10549	-0.05898413	-0.04384	-0.03625	-0.03164
	2.7	1.356563	-0.07912	-0.0442381	-0.03288	-0.02719	-0.02373
	2.8	0.904375	-0.05274	-0.02949206	-0.02192	-0.01812	-0.01582
	2.9	0.452188	-0.02637	-0.01474603	-0.01096	-0.00906	-0.00791
	3	0	0	0	0	0	0
	3.1	-0.34527	0.019968	0.011088246	0.008191	0.006737	0.005852
	3.2	-0.69053	0.039936	0.022176492	0.016383	0.013474	0.011704

For example, for a climate sensitivity of 3, if total CO2 emissions are 600 GTC, net emissions (remaining in the atmosphere) will be 203GTC (per the preceding graph). For a climate sensitivity of 2.4, net emissions will need to be reduced by 6.575 percent, for a total of 190 GTC added to the atmosphere.

Appendix B - How much the temperature will change in a year based on the current temperature and previous emissions

One possible method of estimating the change in temperature for any given year is to assume that the temperature change will be proportional to the difference between the current temperature and the equilibrium temperature. By analyzing the results published in AR5 by the IPCC, it appears that by increasing the temperature annually a factor multiplied by the square of the difference between the previous year's projected temperature and the previous year's equilibrium temperature, the temperature increase projected by the IPCC can be matched pretty well for three different climate sensitivities. The factors for climate sensitivities of 2.7, 3.7, and 4.17 are 13.4, 9.9, 8.7 respectively. See Appendix B for details. See worksheet "Temp Calcs" for the calculations



Temperature increase projected by the IPCC and by a factor * the square of the (Equilibrium Temperature - Projected Temperature)

Data Sources

Data Sources For Appendix A

Sample Data

Magicc - Emissions Scenario WRE550

Data for CO2 Emissions

YEAR	ETOTAL	EFOSS	CH4OXN	NETD	GROSSD	OFLUX	ABFRAC	PLANT C	HLITT	SOIL	CONC	DEL-M	YEAR
2015	9.98	9	0.04	0.93	2.54	3.07	0.48	721	90.2	1422	401	4.74	2015
2020	10.5	9.54	0.04	0.87	2.49	3.28	0.47	725	91.1	1423	412	4.95	2020
2025	10.8	9.96	0.04	0.8	2.42	3.49	0.47	730	92.1	1425	424	5.02	2025
2030	11	10.2	0.04	0.72	2.34	3.7	0.45	735	93	1426	436	4.97	2030
2035	11	10.3	0.04	0.63	2.26	3.87	0.44	741	93.9	1428	447	4.8	2035
2040	10.9	10.3	0.04	0.55	2.17	4.01	0.42	747	94.8	1429	458	4.56	2040
2045	10.6	10.1	0.04	0.47	2.07	4.11	0.4	754	95.6	1431	468	4.23	2045
2050	10.2	9.79	0.04	0.38	1.97	4.16	0.38	760	96.3	1433	478	3.84	2050
2055	9.74	9.4	0.04	0.3	1.87	4.17	0.35	767	97	1435	486	3.43	2055
2060	9.24	8.98	0.04	0.23	1.77	4.15	0.33	774	97.7	1436	494	3.02	2060
2065	8.72	8.51	0.04	0.17	1.68	4.11	0.3	781	98.2	1438	500	2.61	2065
2070	8.18	8.04	0.04	0.1	1.59	4.05	0.27	788	98.7	1440	506	2.22	2070
2075	7.66	7.56	0.04	0.07	1.52	3.98	0.24	794	99.2	1442	510	1.86	2075
2080	7.16	7.1	0.04	0.03	1.45	3.89	0.21	801	99.5	1444	514	1.52	2080
2085	6.7	6.65	0.03	0.01	1.4	3.8	0.18	807	99.9	1445	518	1.23	2085
2090	6.28	6.25	0.03	0	1.35	3.7	0.16	813	100	1447	520	0.97	2090
2095	5.88	5.85	0.03	0	1.32	3.6	0.13	819	100	1449	522	0.74	2095
2100	5.52	5.49	0.03	0	1.28	3.5	0.1	824	101	1451	523	0.55	2100
YEAR	ETOTAL	EFOSS	CH4OXN	NETD	GROSSD	OFLUX	ABFRAC	PLANT C	HLITT	SOIL	CONC	DEL-M	YEAR

Data for Atmospheric CO2 PPM

YEAR	CO2	CH4	N2O	CH4LO	CH4MID	CH4HI	CO2LO	CO2MID	CO2HI	YEAR	TAUCH4	
2015	399.736	1813	328	1804	1813	1822	395	400	405	2015	9.68	
2100	540.378	1444	364	1460	1444	1431	509	540	576	2100	9.53	
YEAR	CO2	CH4	N2O	CH4LO	CH4MID	CH4HI	CO2LO	CO2MID	CO2HI	YEAR	TAUCH4	

Summing the average of the total CO_2 emissions for each 5 year period results in the following total emissions thru 2100:

Ending	GTC
2020	51.1
2025	53.2
2030	54.5
2035	55.0
2040	54.7
2045	53.7
2050	52.1
2055	49.9
2060	47.5
2065	44.9
2070	42.3
2075	39.6
2080	37.1
2085	34.7
2090	32.5
2095	30.4
2100	28.5
Total	761.3

Calculation of CO_2 remaining in the atmosphere
Results for Climate Sensitivity = 3

	CO2 PPM
2015	399.736
2100	540.378
Change	140.642
GTC	298.161

Sample Results for Climate Sensitivity = 3

Profile	CO2 Added To Atmosphere	Emissions 2015 to 2100
B1HIME	292.825	710
B1HIMI	500.73128	993.6
B1IMA	294.22844	769.85
B1MES	237.90428	635.925
B1MIN	299.9588	720.075
B1TME	190.21064	563.975
B2AIM	611.0158	1175.275
B2ASF	758.02932	1379.05
B2HIMI	846.1662	1474.125
B2IMA	467.3964	980.275
B2MES	472.29784	958.45
B2MIN	588.04348	1127.5
WRE350	-58.06044	163.3
WRE450	111.08164	450.825
WRE550	298.16104	761.3
WRE650	433.40432	958.5
WRE750	527.41572	1078.85

Data Sources For Appendix B

From the IPCC AR5 - RPC 2.6

Year	ERF
2010	1.97
2020	2.33
2030	2.50
2040	2.64
2050	2.65
2060	2.57
2070	2.51
2080	2.40
2090	2.44

Average Temp by Decade by Percentile		
50%	83%	95%
2.684	3.705	4.170
0.97	1.13	1.23
1.16	1.42	1.68
1.35	1.63	1.85
1.49	1.86	2.11
1.55	1.98	2.26
1.54	2.09	2.32
1.50	2.10	2.32
1.55	2.05	2.40
1.55	2.14	2.40

Note:

2.684	3.705	4.170

are the climate sensitivities that correspond to the IPCC's projected average temperature for 2085-2095 (which are included in their tables as the year 2090)

Yearly values were calculated by interpolating between the decadal values provided.