"A Simple Formula for Calculating Carbon Budgets"

AGU Poster GC33F-1437
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Synopsis

Data from 410 scenarios from the recent IPCC 1.5°C Report was analyzed and two simple formulas for calculating CO2 emission budgets were derived by examining three correlations: the atmospheric concentration of CO2 in 2100 based on cumulative CO2 emissions (2010-2100), the radiative forcing of methane in 2100 based on methane emissions in 2100, and the radiative forcing of N2O in 2100 based on cumulative N2O emissions (2010-2100)

Based on the formulas, I

1. Created CO2 emission budget "lookup tables" (allowing CO2 emission budgets to be estimated without needing to use either the simple formulas or sophisticated climate models)
2. Created a "sensitivity table" (which specifies how existing CO2 emission budgets can be adjusted as more scientific information becomes available)

By looking at recent scientific information, the adjusted IPPC carbon budgets appear to be quite small compared to expected CO2 emissions.

In this case, the future temperature increase will depend primarily on climate sensitivity and the difference between how much CO2 is emitted and how much CO2 we are able to remove from the atmosphere.

By selecting a desired temperature increase and by estimating (1) climate sensitivity, (2) future anthropogenic CO2 emissions, (3) CO2 emission equivalents from natural feedbacks, and (4) costs to remove CO2 from the atmosphere, one can estimate

1. The quantity of CO2 to that needs to be remove from the atmosphere to meet the desired temperature increase
2. The cost to remove the CO2

And one can also think about

1. The responsibility of individual countries for atmospheric CO2 removal
2. The implications of not removing CO2 from the atmosphere

Objective

Use the output of sophisticated climate models to develop simple formulas for estimating CO2 emission budgets

Use the formulas to

- Create “lookup tables” for carbon emission budgets
- Create equivalence table for climate factors
- Create worksheets for adjusting existing CO2 emission budgets

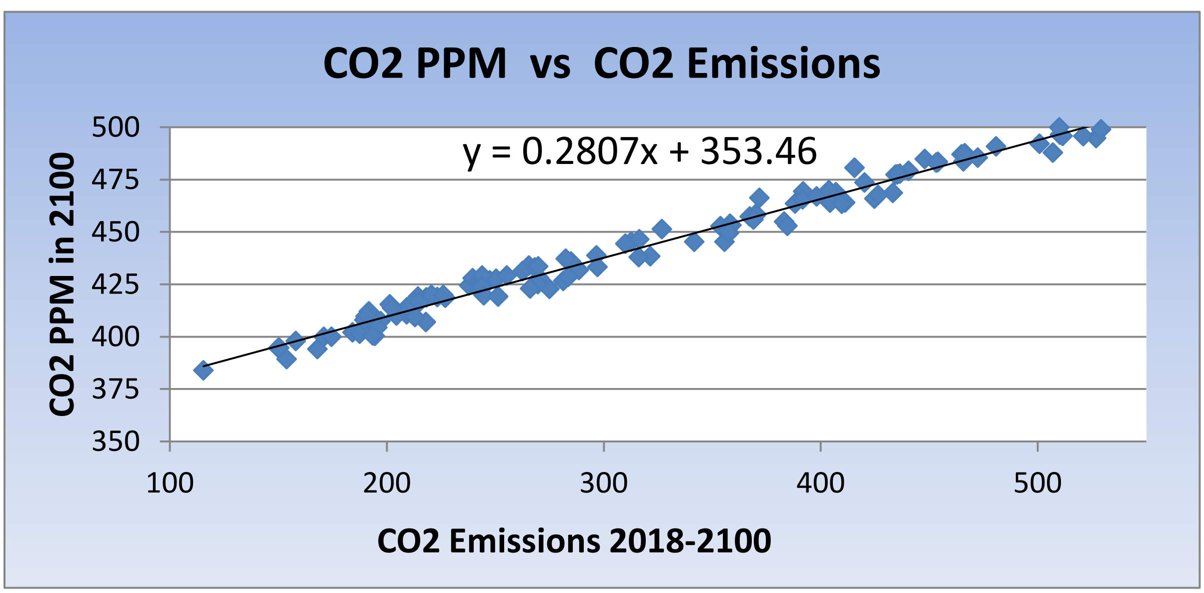
Climate Model Output

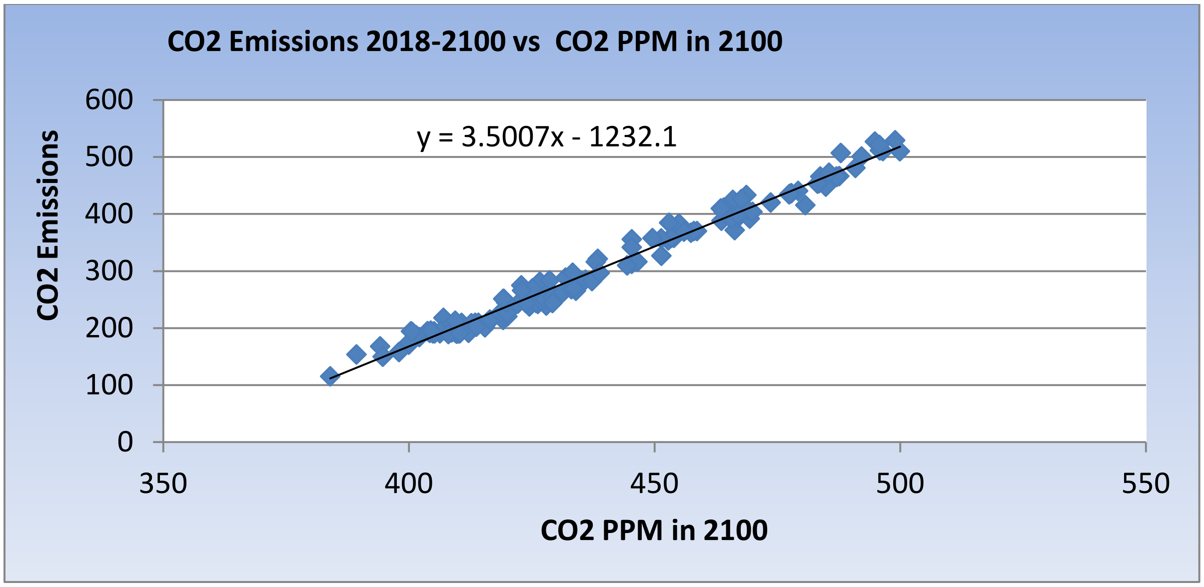
Derive formulas which (1) relate CO2 atmospheric concentration to CO2 emissions and (2) relate other greenhouse gas emissions with their corresponding radiative forcings by using data from 410 scenarios in the "IAMC 1.5°C Scenario Explorer and Data hosted by IIASA, release 2.0" [1] . *(Note that the data include results for both the FAIR and MAGICC computer models. This analysis uses just the results from the FAIR models. The estimated temperature increase at the "P66" level ranges from 0.95°C to 4.68°C)*

A. Relate CO2 Atmospheric PPM to CO2 Emissions

Develop a formula that relates atmospheric CO2 PM and cumulative CO2 emissions by using135 of the 410 scenarios (FAIR P66 temperature increase >1.4, total CO2 emissions > 60GTC, and radiative forcing > - 0.18 w/m2 and < 0.1 w/m2):

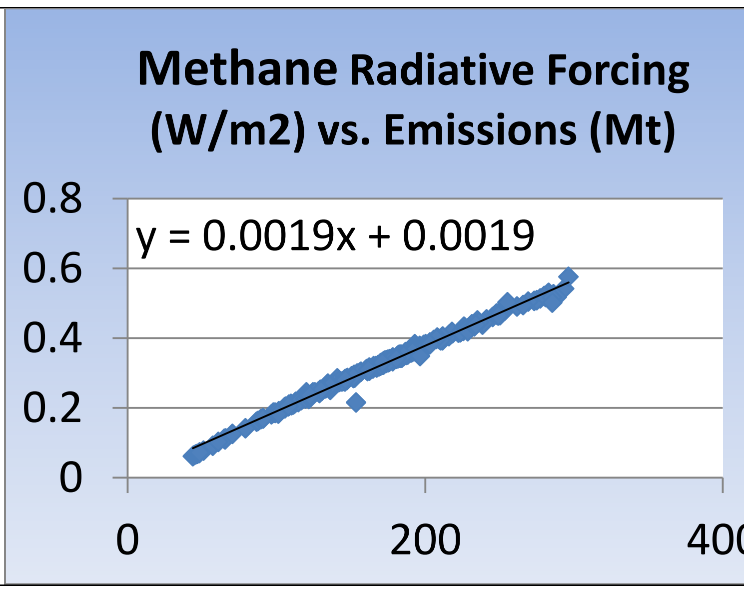
#1. CO2 Emissions = 3.5007 * PPM - 1232.1 (or PPM= 0.285657 * Emissions - 351.9582)
(this formula works better than the CO2 PPM vs CO2 Emissions formula)

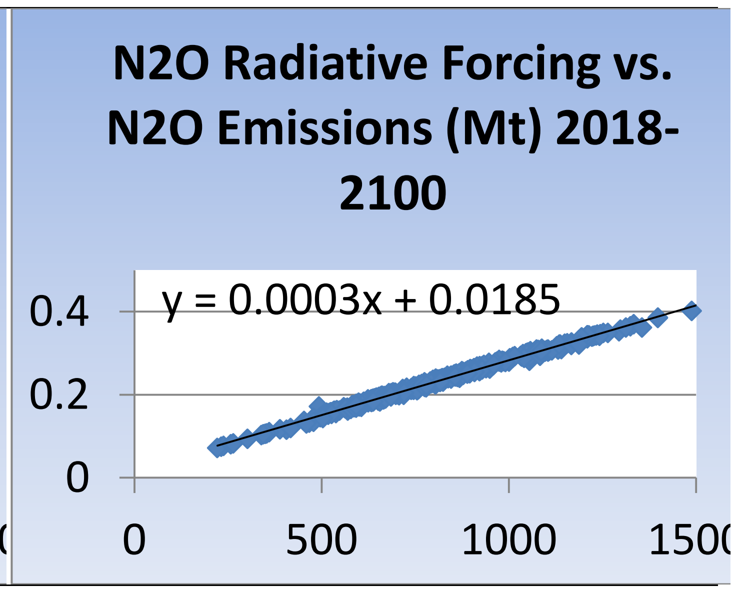




(Note that the computed PPM differs from the scenario PPM by 1.2% to 2.0%.
This reflects differences on the amount of the emitted CO_2 that ends up in the atmosphere.)

B Relating Other Greenhouse Gas Emissions To Their Radiative Forcings in 2100

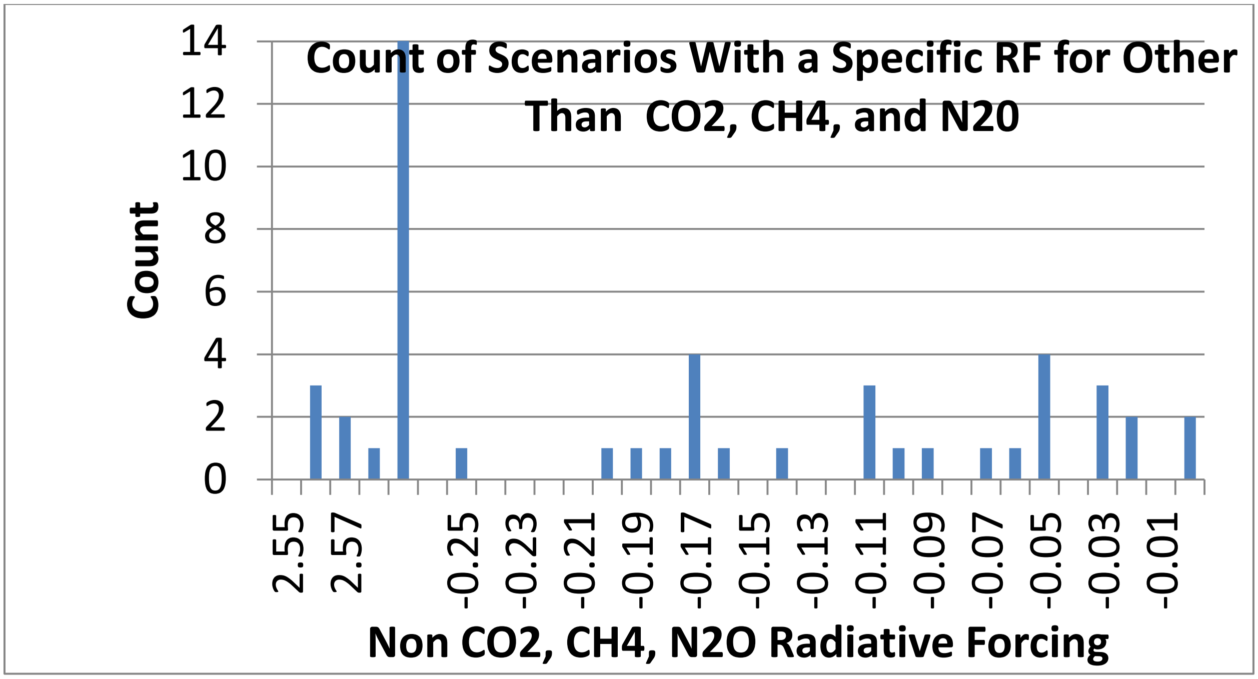




I could not discover a similar correlation for any of the other radiative forcing elements. But a value of -0.05 W/m2 for all the radiative forcing elements other than CO_2, CH_2, and N_2O provides a relatively close estimate for many of the climate scenarios. This results in the following formula:
#5. Non-CO2RF = 0.0019 * CH4Emissions + 0.0003 * N2OEmissions - 0.03

The formula works pretty well for RCP2.6 and RCP6.5. In all cases the formula gives a higher value than the RCPs, so one can assume that the models used by the IPCC for the 1.5°C report did not include the 25% adjustment

RCP:	2.6	4.5	6.0	8.5
RCP Emissions	143	267	250	885
RCP RF	0.27	0.41	0.44	1.08
Calculated RF	0.27	0.51	0.48	1.68



CO2 Budget For Non-CO2 RF

C. CO2 Budget Formula For Non-CO2 Radiative Forcing

Assume that net CO2 emissions will be negligible (or below zero) by 2080, allowing the temperature to reach a near equilibrium value in 2100.

Combine formula #1 with two standard climate formulas:

#2. Equil. Temp Incr. = Climate Sensitivity * (CO2 PPM - CO2Orig PPM)/ CO2Orig PPM

#3. Radiative Forcing=ln(CO2 PPM / CO2Orig PPM) * 5.35

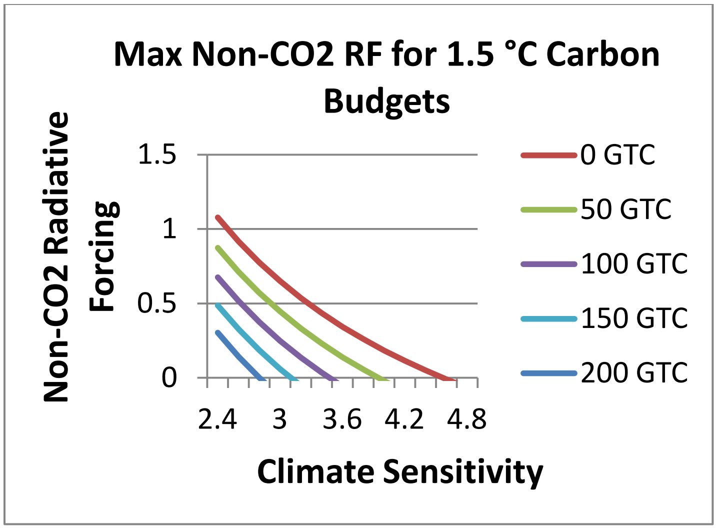
to derive a formula for calculating a CO2 emissions budget for CO2 emissions from 2018-2100 based on non-CO2 radiative forcing:

#4. CO2 budget = 3.5007 * CO2OrigPPM * (1 + ET / CS) * e (- Non-CO2RF /5.35) - 1232.1

D. CO2 Budget "Lookup Table" Based on Non-CO2 RF

The formula with values for non-CO2 RF calculates the CO2 emissions budget within 10% for 95% of the 182 FAIR scenarios where the P66 temperature increase is >= 1.4 and CO2 emissions > 60GTC and atmospheric CO2 in 2100 < 500 PPM

		Temp Increase:		**1.5**	**°C**				
		Climate Sensitivity							
		2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4
Non-CO2 RF (W/m2)	**0.3**	378	315	263	219	181	148	119	94
	0.4	348	287	235	192	155	122	94	69
	0.5	319	259	208	166	129	97	70	45
	0.6	290	231	182	140	104	73	46	22
	0.7	262	204	155	114	79	49	22	-2
		CO2 Budget 2018-2100 (Emissions - GTC)							



E. Equivalences Based on the CO2 Budget Formula

To adjust the CO2 emissions budget for a specific emissions scenario - as more information becomes available - we need to know how sensitive a CO2 emissions budget is to changes in emissions, climate sensitivity, radiative forcing, etc. The following table (derived using formula #4) gives the equivalents for several climate factors for a climate sensitivity of 2.8 and a temperature increase of 1.75°C:

		Climate Sens.	Temp Increase	Radiative Forcing	Atmos. CO2	CO2 Emis	CH4 Ann Emis	N2O Emis	$100/ Ton CO2
Climate Factor	**Amt**		°C	W/m2	PPM	(GTC)	(MT)	(MT)	**$Billion**
Climate Sensitivity	0.1		0.063	0.074	5.685	19.9	39.3	248.8	7,303
°C	0.1	0.156		0.117	8.941	31.3	61.8	391.3	11,487
W/m2	0.1	0.135	0.085		7.713	27.0	53.3	337.5	9,909
PPM CO2	1	0.017	0.011	0.013		3.5	6.9	43.8	1,285
CO2 Emissions (GTC)	10	0.050	0.031	0.037	2.857	10.0	19.7	125.0	3,670
CH4 Ann. Emissions (MT)	10	0.025	0.016	0.019	1.457	5.1		63.8	1,872
NO2 Emissions (MT)	100	0.040	0.025	0.030	2.285	8.0	15.8		2,936

Notes: The CH4 numbers do not include a 25% adjustment - see below
The values in "grey cells" were derived from the CO2 budget formula; "white cell" values were calculated from "grey cell" values

Assuming capture and sequestration costs were $100/Ton CO2 ($365/Ton C):

It could cost about $11 Trillion to decrease the global temperature 0.1°C by removing 31.3 GTC of CO2 from the atmosphere.

The cost of reducing the atmospheric concentration of CO2 is a little over $1Trillion/PPM

CO2 Budget Based on CH4/N2O

F. Develop Formula for a CO2 Emissions Budget

Derive a formula for roughly estimating a CO2 budget that is independent of the radiative forcing estimates for aerosols, tropospheric ozone, and greenhouse gases other than CO2, CH2, and N2O by substituting the value for "Non-CO2RF" in formula #5 in formula #4:

#6. CO2 emissions budget 2018-2100 (based on CH4 and N2O) =

3.5007 * CO2OrigPPM * (1 + ET / CS) * e (- Non-CO2RF /5.35) - 1232.1

where Non-CO2RF =(0.0019*CH4Emissions+0.0003* N2OEmissions -0.03)

How well the calculation compares with the scenario values:

FAIR Scenarios where the P66 Temperature increase is >= 1.4 and CO2 Emissions > 60GTC and atmospheric CO2 in 2100 < 500 PPM					
Number of Scenarios	Percentage of Difference Between Scenario CO2 Emissions and Emissions Calculated Based on CH2 and N2O				
	<5%	<10%	<15%	<20%	<25%
182	29	58	80	92	95
135[*]	40	76	88	96	97
45[*+]	44	71	84	91	91
30[*#]	50	96	100	100	100
	Percentage of scenarios where the calculated emissions differ from the scenario emissions by less than a given percent				
*"Other radiative forcing" between -0.18 and 0.1 W/m2					
+ P66 Temperature increase between 1.45 and 1.55					
# 30 of 35 scenarios which used the 'AIM/CGE 2.0' model					

(The IPCC emissions for the 67 percentile for 1.5°C were 115 GTC - 10% of this is 11 GTC)

Comparing the model to the RCPs

Scenario Values	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
50% Temp Incr 2100 (°C)	1.55	2.29	2.64	4.18
CO2 PPM 2100	420	538	670	936
Emissions				
CO2 (GTC - Cumulative)	274	726	1035	1746
CH4 (MT - 2100)	143	143	143	143
N2O (Mt- Cumulative)	528	697	874	1049
Radiative Forcing (W/M2)				
Carbon dioxide	2.22	3.54	4.70	6.49
Methane	0.27	0.41	0.44	1.08
Nitrous oxide	0.23	0.32	0.41	0.49
CFCs (Montreal Protocol)	0.10	0.10	0.10	0.10
HFCs	0.13	0.08	0.05	0.18
PFCs and SF6	0.02	0.026	0.05	0.04
Tropospheric O3	0.17	0.27	0.27	0.60
Aerosol	-0.12	-0.12	-0.12	-0.12
Other Factors*	-0.41	-0.13	0.11	-0.37
Non-CO2 RF	0.110	0.550	0.860	0.930
Non CO2, CH4, N2O RF	-0.120	0.230	0.450	0.440
Total	2.600	4.500	6.000	8.500

#	Calculations				
	50% RCP Temp Incr Rel 1986–2005	0.94	1.68	2.03	3.57
1	Temp Incr rel 1870	1.55	2.29	2.64	4.18
2	CO2 PPM 2100	430	559	648	851
3	CO2 PPM 2100	421	539	669	935
4	PPM Percent Increase Diff	6	8	-6	-13
5	CO2e PPM 2100	452	645	853	1361
6	Climate Sensitivity	2.48	1.74	1.28	1.07
7	CO2 Emissions budget (NonCO2 RF)	318	804	1311	2773
8	CO2 Emissions budget %Diff From Emissions	16	11	27	59
9	CO2 Emissions budget (CH4 and N2O)	243	852	1499	3083
10	CO2 Emissions budget %Diff From Emissions	-11	17	45	77

#	Calculation Formula
1	global mean surface temperature change (°C) relative to 1870 (50%)
2	0.285657 * CO2 Emissions 2018-2100 + 351.95
3	PPM CO2 =278 * Power(2.718,CO2 Radiative Forcing/5.35)
5	PPM CO2 =278 * Power(2.718,CO2e Radiative Forcing/5.35)
6	Climate Sensitivity = Equilibrium Temperature/((PPM/278)-1)
7	(278 * e((5.35 * Ln(1 + ET / CS) - NonCO2RF) /5.35) - 351.95)/ 0.285657
9	278.7*EXP((LN(((1+ET/CS)))*5.35-(CH4E*0.0019+0.0003*N2OE-0.04122))/5.35)*3.5007-1232.1

G. CO2 Budget "Lookup Table" Based on CH4 and N2O

		Climate Sensitivity:2.6									
		Temp Increase: 1.5 °C									
		Cumulative N2O Emissions (Mt)									
		500	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**
CH4 Emissions 2100	**150**	200	196	192	188	184	180	176	172	168	164
	250	150	146	142	138	134	130	127	123	119	115
	350	101	98	94	90	87	83	79	75	72	68
	450	55	51	48	44	41	37	33	30	26	23
	550	10	6	3	0	-4	-7	-11	-14	-18	-21
	650	-33	-37	-40	-43	-47	-50	-53	-57	-60	-63
	750	-75	-78	-82	-85	-88	-91	-94	-98	-101	-104
		CO2 budget from 2018-2100 (Based on CH4 and N2O - GTC)									

(The range shown above is roughly emissions range in the RCP scenarios)

H. CO2 Emissions Budget Adjustments

A recent report found that freshwaters emit at least 103Mt of CH4 per year[2].

Another recent article reported that a recent IPCC report underestimated the radiative forcing of methane by 25%[3].

The following is an example of adjusting a CO2 emissions budget (where the climate sensitivity is 2.8 and temperature increase is 1.75°C) based on this new information:

CO2 Cumulative Emissions	GTC	115	Initial CO2 emissions budget
CH4 2100 Emissions	Mt	250	
N2O Cumulative Emissions	Mt	950	
IPCC 1.5°C report feedbacks	GTC	-30	
CH4 - 25% additional forcing	GTC	-32	=(5.1 GTC/10 Mt CH4) * 250 * 0.25
CH4 - Additional emissions	GTC	-64	=(5.1 GTC/10 Mt CH4) * 100 * 1.25
Adjusted CO2 Budget	GTC	-11	(Adjusted anthropogenic CO2 emissions budget)

With adjustments likely needed for climate sensitivity, CH4, and natural emissions, there is likely no anthropogenic carbon emissions budget left.

CO2 Emissions Budget Adjustment Worksheet

Emissions for CH4 and N2O chosen to have CO2 Emissions budget about 115 GTC (P66 for IPCC results)			
	Units		Notes
Original Estimate			
Target Temperature	°C	1.5	
Climate Sensitivity		2.6	
Emissions			
CO2	GTC	114	
CH4	Mt	280	
N2O	Mt	950	
Adjustments			
NonCO2 Emissions			
CH4	Tg	103	Surface Waters[1]
CH4	Mt		Other
N2O	Mt		
Climate Sensitivity			
Climate Sensitivity adjustment			
CO2 Emission Equivalents			
IPCC report feedbacks	GTC	30	
CO2	GTC		Amazon changes to savannah
Peat	GTC		
Soils	GTC		
Permafrost	GTC		
Forests	GTC		
CH4 - 25% add'l forcing	GTC	36	=(5.1 GTC/10 Mt CH4)* 280 * 0.25
CH4 - Additional emissions	GTC	64	=(5.1 GTC/10 Mt CH4)* 100 * 1.25
N2O	GTC	0	Additional emissions
Climate Sensitivity	GTC	0	
Total Adjustments	GTC	130	
Adjusted CO2 emission budget	GTC	-16	(Adjusted anthropogenic CO2 budget)

CO2 Budget Equation Variables

I. Temperature Target

IPCC goal: hold the increase to well below 2°C and purse efforts to limit the temperature increase to 1.5°C

James Hansen believes that a better target would be a 1.0° C temperature increase[4].

The temperature increase will almost certainly exceed 1.5°C by mid-century and will very likely exceed 2.0° C well before 2100. The best that we can hope for is that the number of years of "overshoot" will be short (decades at most) and that the temperature will start decreasing well before 2100. What we need to avoid are significant CO2 emission-equivalents from natural feedbacks*, as we will need to remove CO2 from the atmosphere to compensate for them.*

By capturing and sequestering enough carbon, any temperature target can be met.

J. Anthropogenic CO2 Emissions

In estimating likely future anthropogenic emissions, consider

- Historically, CO2 emissions have been correlated to global GDP (atmospheric CO2 would be about 900PPM in 2100 if the ratio continues to hold as the GDP increases from $88 Trillion to $480 Trillion)5
- Greenhouse gas emissions will increase about 1% per year through 2030 under current policies (latest UN “Emissions Gap Report”)[6]
- A recent MIT report forecast that annual anthropogenic CO2 emissions would increase from about 10 GTC today to about 14 GTC in 2100[7]
- According to ExxonMobil, global oil and gas demand will rise by 13% by 2030[8]
- Entrenched interests (fossil fuels, etc.) are interested in maintaining the status quo
- Our society has not taken any really serious steps to reduce greenhouse gas emissions
- Deforestation continues to increase
- The fossil fuel share of total energy has only declined to about 86% from 88% in 1990
- World energy consumption of fossil fuels has been growing about 2%/year since 1965
- The global temperature increase could reach 1.5° C as early as 2026
- There are, for all practical purposes, almost no policies either in place or planned (other than a carbon tax and renewable portfolio standards) that will have a significant impact on future greenhouse gas emissions - we are relying on the "free market" (with a little "tweaking" and perhaps a carbon tax) to be sufficient

Estimating 2018-2100 CO2 emissions based on a peak year and percent change per year

9.86	**2015 Fossil Fuel Emissions (GTC)**
1.6	**2015 land use emissions (GTC)**
2070	**Year when land use emissions reach zero**
0.029	**Land use decline/year (GTC**
43.00	**Land use emissions 2016-2070 (GTC)**
35.00	**CO2 Emissions 2016-2018 (GTC)**

	Peak Yr:	2020			2030			2050		
% Chg to Peak Yr:		0	1	2	0	1	2	0	1	2
Annual % Change After Peak Yr	0	858	900	943	858	982	1123	858	1133	1509
	-1	609	638	668	661	753	858	751	981	1294
	-2	457	478	500	534	605	686	672	870	1137
	-3	360	377	394	449	507	572	615	788	1022

With a lot of momentum in our energy system, quick reductions are unlikely.

K. CH4 and N2O Emissions

For CH4, the difference between RCP 2.6 and RCP 8.5 is equivalent to about 290 GTC of CO2, so our emphasis also needs to be on ways to reduce CH4 emissions

It would be very helpful to have some detailed scenarios on possible emission pathways for CH4 and N2O from now to 2100 in order to help understand what the tradeoffs are.

(Units: Mt)		RCP 2.6			RCP 4.5			RCP 8.5		
	2010	2050	2100	2018- 2100	2050	2100	2018- 2100	2050	2100	2018- 2100
CH4	322	192	143	16,310	331	267	26,130	669	885	54,780
N2O	7.7	6.3	5.3	528	8.6	8.1	697	12.7	15.7	1,049

L. Climate Sensitivity

The "IPCC 1.5°C Report" uses "transient climate response" (TCR) - the amount of warming that might occur at the time when CO2 doubles, having increased gradually by 1% each year.

The average value of the calculated TCR for 45 scenarios where the temperature increase was between 1.45°C and 1.55°C is 2.46.

Newer global climate models indicate that our climate is more sensitive to GHG emissions[9].

In the "IPCC 1.5°C Report" the average year when the models predict that 1.5°C will be exceeded is 2033. A recent report shows this happening 2 1/2 years earlier[10].

M. Natural Emissions[11]

- The *anthropogenic* CO2 emissions budget is calculated by subtracting an estimate of CO2-equivalent emissions from natural feedbacks from the derived CO2 emission budget
- The recent 1.5° C IPCC report estimated that non-anthropogenic greenhouse gas emissions would be equivalent of about 27 GTC from 2018 through 2100.
- Many of the emissions from natural feedbacks are temperature-dependent. Given a likely temperature increase of at least 2° C by 2050 it seems possible that cumulative emissions through 2100 from natural feedbacks could be in the range of 120-200 GTC (not including methane from methyl hydrates).

Feedbacks - GHGs	Carbon Store (GTC)	Possible emissions through 2100 (GTC/GTCe)
IPCC 1.5° Report - All		27
Permafrost	1,600	120
Soils		55
Peat	270 to 370	100
Surface waters	CH4 - 100Mt/yr	60
Forests		Forests will likely turn from sinks to sources (as is currently happening in the Arctic)
Methyl Hydrates	5,000 to 20,000	
Amazon	86	The Amazon Forest could transition to a savannah

Observations

N. Carbon Capture and Sequestration Costs

The average quantity of carbon sequestered was about one-half of the net CO2 emissions for 45 scenarios where the temperature increase was between 1.4°C and 2.6°C.

Because of likely tipping points for natural feedbacks, a significant portion the sequestration needs to happen prior to 2050.

There are many way to capture and sequester carbon - carbon capture and storage (CCS), direct air capture (DAC), iron ocean fertilization, reforestation, rebuilding soils, etc.

Average carbon capture and sequestration costs are hard to come by. An average cost of $100/ton CO2 seems like a good estimate for the period 2018-2050.

If our global society is not willing to fund very significant carbon sequestration (due to possible high costs at the scale needed) there is a reasonable chance that we could eventually end up with a "hothouse Earth" that is incompatible with life as we know it.

(With BAU, CO2e could be over 750 PPM in 2100. With a temperature increase over 5°C there could be quite significant CH4 emissions from methyl hydrates.)

We are currently at about 500 PPM CO2e. If anthropogenic and natural emissions are about 880 GT though 2100, CO2e PPM would be about 750 PPMCO2e (500 + 880 GTC * .286 PPM/GTC) (assuming the RF from other GHGs remained the same as today). If natural emissions (not including those surface waters, as those emissions are about the same as the carbon budget) are about 250 GTC, then only 630 GTC of anthropogenic emissions are needed. We will almost certainly exceed that.

O. United States Share of Total Carbon Budget

The global carbon emissions budget for 1800 to 2100 is approximately 3270 GTCO2 (for the 50th percentile of model runs for a 1.75° temperature increase: 1940 + 290 + 1040)[1]

Historical US emissions have been about 17% of this budget.

With about 4% of the world's population, what is our "fair share"?

If future US emissions are 100 GTCCO2 and average capture and sequestration costs are $100/Ton CO2, then the US would need to spend at least $10 Trillion (about 1/2 of the total US debt) in the next 40 years to capture future CO2 emissions.

- Because of "embodied" emissions, US CO2 emissions have not declined significantly in the last 20 years
- We cannot deny significant additional fossil fuel emissions to people in other countries who would like to have our standard of living
- According to the IPPC, historical CO2 emissions have been about 2230 GTCO2. If another 800 GTCO2 can be added (to keep the total temperature increase well below 2°), then the total CO2 emissions budget is about 3000 GTCO2.
- Historic US emissions have been about 25% of global emissions, or about 550 GTCO2. If US emissions decline from about 5 GTCO2 to zero in 40 years, our total will be about 650 GTCO2.
- US has about 4.25 percent of the world's population, and we'd be using 22% of the total world budget
- Assuming the "polluter's pay" principle, what is the US's "fair share" of the total budget?

- Historical US emissions are about 18% of the 3000 GTCO2 total budget. So if our "fair share" is anything less than 18% we would need to capture and sequester *at least* all future emissions.
- If future US emissions are 100 GTCCO2 and capture and sequestration costs are $100/Ton CO2, then the US would need to spend at least $10 Trillion (about 1/2 of the total US debt) on "negative emission technologies" in the next 40 years just to capture future emissions

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Additional Analysis

Is a CO2 emissions budget Really Useful?

Are we wasting our time analyzing and worrying about carbon budgets and climate sensitivity? We have a good enough understanding of climate science and human nature to know that we are well past the point where it is reasonable to expect that we can prevent a "climate crisis" through mitigation alone. With a total temperature increase of about 1.5° C expected in the next ten years, with catastrophic sea level rise being unavoidable, with the recent drop in the costs of renewable energy, and knowing that we will overshoot our temperature increase target, we know what we need to do: decarbonize our economies as fast as possible and ramp up removing CO2 from the atmosphere as fast as possible. A difference of a few hundred gigatons in an estimated CO2 emissions budget or the difference of 10-20 percent in a scientific estimate of climate sensitivity won't provide an impetus to do anything differently.

Developing Climate Policies

If our society were really interested in meeting the temperature goals of the Paris agreement, it would

1. Impose a relatively high tax on carbon (over $100/Ton CO2?)
2. Stop subsidizing fossil fuels
3. Stop building fossil fuel power plants by subsidizing renewable energy projects
4. Stop deforestation and rapidly increase reforestation
5. Develop policies to speed up energy efficiency improvements
6. Work on other projects to remove carbon dioxide from the atmosphere
7. Work to reduce the cost of removing carbon dioxide from the atmosphere
8. Work with financial institutions to determine how to pay for the removing carbon dioxide from the atmosphere
9. etc.
10.

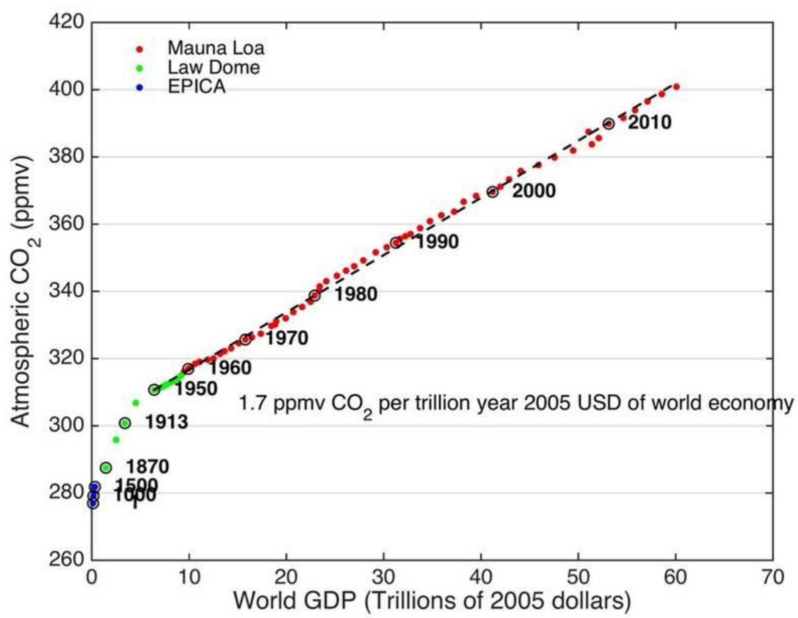
The Cost of Avoiding Catastrophic Climate Change

1. Given (1) that our society has not taken any serious steps to reduce greenhouse gas emissions (and does not seem likely to do so in the near future), (2) entrenched interests (fossil fuels, agricultural, industrial, etc.) in maintaining the status quo, (3) a growing GDP, (4) our continued reliance on the "free market" to reduce emissions, etc., it seems quite likely that total CO2 emissions (anthropogenic + natural) through 2100 will exceed any reasonable CO2 emissions budget by at least 1,000 GTC.

2. And given that (1) there are so many uncertainties about climate sensitivity, emissions from natural feedbacks, anthropogenic greenhouse gas emissions, GDP, aerosols, etc., and (2) the need to rapidly remove CO2 from the atmosphere to prevent the feedbacks in the Arctic from becoming significant, an accurate estimate of the costs of avoiding catastrophic climate change is almost impossible to make.
3. As a "thought experiment", assume that 2018 CO2 emissions are 10 GTC, that emissions are reduced linearly to 5 GTC in 2050, that we need to remove three-fourths of these emissions, and that the average removal costs will be $300/Ton C ($80/Ton CO2). The resulting cost would be $54 Trillion.
4. One percent of the world's population holds over one half of the world's $320 trillion wealth, while adults with less than $10,000 in wealth make up 64 percent of the world's population but hold less than 2 percent of global wealth. Keeping the temperature increase below a catastrophic level will be very expensive, at least many tens of trillions of dollars and possibly hundreds of trillions of dollars. So our basic problem is to get the 1% to understand that if they commit to paying about 1.0% of their wealth every year ($1.6 Trillion) for the at least the next 30 years for emissions reduction and removing CO2 from the atmosphere, we might be able to leave a habitable planet to our children. (E.g., "US Military Could Collapse Within 20 Years Due To Climate Change" (report commissioned by the Pentagon))

Foototes

1	IAMC 1.5°C Scenario Explorer and Data hosted by IIASA, release 2.0 https://zenodo.org/record/3363345#.Xc7_UtVKiUk
2	**Freshwaters emit at least 103 Tg of CH4 yr-1** *(or about 25 percent of anthropogenic emissions if these count as anthropogenic emissions)* Inland waters (lakes, reservoirs, streams and rivers) are often substantial methane (CH4) sources in the terrestrial landscape. They are, however, not yet well integrated in global greenhouse gas (GHG) budgets. Data from 474 freshwater ecosystems and the most recent global water area estimates indicate that freshwaters emit at least 103 Tg of CH4 yr-1 corresponding to 0.65 Pg C as CO2 equivalents yr-1 , offsetting 25% of the estimated land carbon sink. Thus, the continental GHG sink may be considerably overestimated and freshwaters need to be recognized as important in the global carbon cycle https://science.sciencemag.org/content/331/6013/50 January 2011
3	According to a recent article in the Geophysical Research Letters ("Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing" - https://agupubs.onlinelibrary.wiley.com/journal/19448007), the recent IPCC report underestimated the radiative forcing of methane by 25%.
4	**The following implies that a better target would be a 1.0° C temperature increase:** **"** We assess climate impacts of global warming using ongoing observations and paleoclimate data. We use Earth's measured energy imbalance, paleoclimate data, and simple representations of the global carbon cycle and temperature to define emission reductions needed to stabilize climate and avoid potentially disastrous impacts on today's young people, future generations, and nature. A cumulative industrial-era limit of ∼500 GtC fossil fuel emissions and 100 GtC storage in the biosphere and soil would keep climate close to the Holocene range to which humanity and other species are adapted. Cumulative emissions of ∼1000 GtC, sometimes associated with 2°C global warming, would spur "slow" feedbacks and eventual warming of 3–4°C with disastrous consequences. Rapid emissions reduction is required to

	restore Earth's energy balance and avoid ocean heat uptake that would practically guarantee irreversible effects. Continuation of high fossil fuel emissions, given current knowledge of the consequences, would be an act of extraordinary witting intergenerational injustice. Responsible policymaking requires a rising price on carbon emissions that would preclude emissions from most remaining coal and unconventional fossil fuels and phase down emissions from conventional fossil fuels." " These growing climate impacts, many more rapid than anticipated and occurring while global warming is less than 1°C, imply that society should reassess what constitutes a "dangerous level" of global warming. Earth's paleoclimate history provides a valuable tool for that purpose." " Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature" James Hansen, et al. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0081648
5	Historically, CO2 emissions have been correlated to global GDP  With global GPD of $88Trillion in 2019 ($67 Trillion in 2005 dollars) and approaching $480 trillion in 2100 ($365 Trillion in 2005 dollars) CO2 would be about 900PPM in 2100 if the ratio continues to hold
6	UN "Emissions Gap Report" https://www.unep-wcmc.org/news/2019-emissions-gap-report
7	MIT report forecast that annual anthropogenic CO2 emissions would increase today to about 14 GTC in 2100

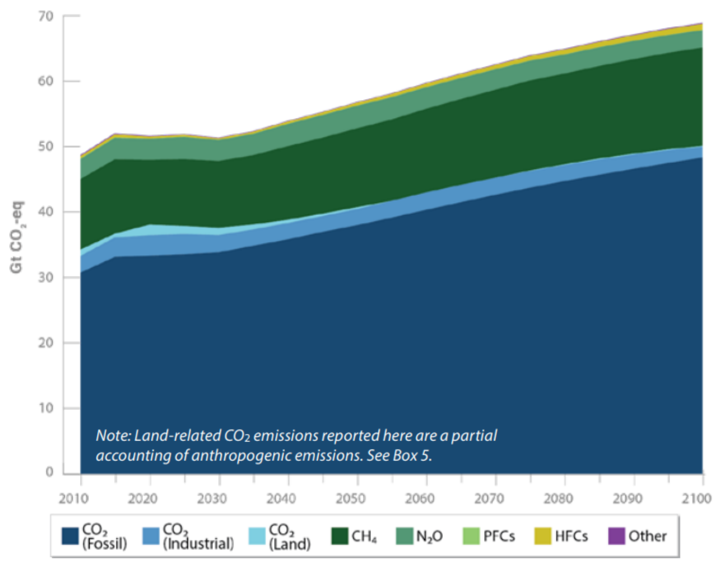
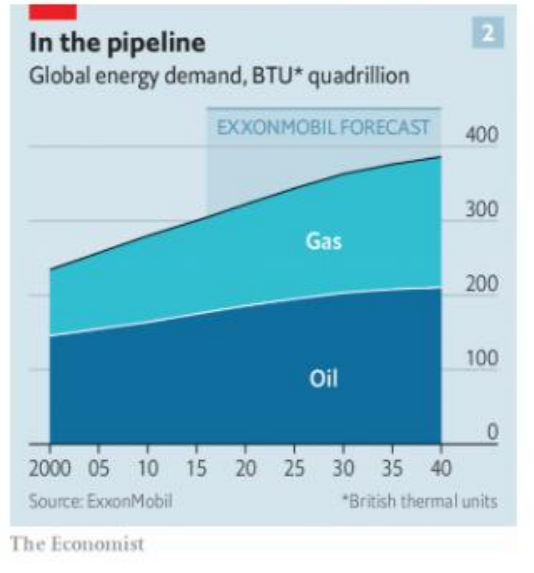
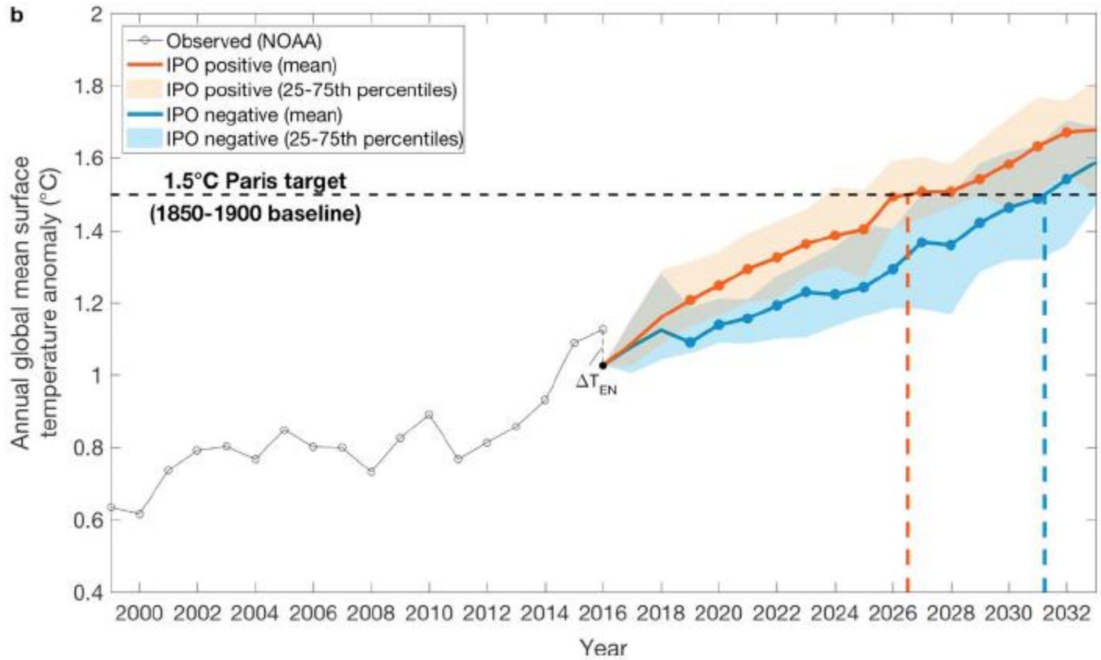


Figure 19. Global annual greenhouse gas emissions

MIT - https://globalchange.mit.edu/sites/default/files/newsletters/files/2018-JP-Outlook.pdf

8	The Economist- Global demand for oil and natural gas projected through 2040 "According to ExxonMobil, global oil and gas demand will rise by 13% by 2030. All of the majors, not just ExxonMobil, are expected to expand their output. Far from mothballing all their gasfields and gushers, the industry is investing in upstream projects from Texan shale to high-tech deep-water wells. Oil companies, directly and through trade groups, lobby against measures that would limit emissions. The trouble is that, according to an assessment by the ipcc, an intergovernmental climate-science body, oil and gas production needs to fall by about 20% by 2030 and by about 55% by 2050, in order to stop the Earth's temperature rising by more than 1.5°C above its pre-industrial level."  **https://www.economist.com/leaders/2019/02/09/the-truth-about-big-oil-and-climate-change**
9	Newer global climate models indicate that our climate is more sensitive to GHG emissions "Global climate models for the next major IPCC assessment show more warming than expected, bucking decades of consensus. Scientists are working to confirm and unravel the potential big shift…. Our planet's climate may be more sensitive to increases in greenhouse gas than we realized, according to a new generation of global climate models being used for the next major assessment from the Intergovernmental Panel on Climate Change (IPCC). The findings—which run counter to a 40-year consensus—are a troubling sign that future warming and related impacts could be even worse than expected. One of the new models, the second version of the Community Earth System Model (CESM2) from the National Center for Atmospheric Research (NCAR), saw a 35% increase in its equilibrium climate sensitivity (ECS), the rise in global temperature one might expect as the atmosphere adjusts to an instantaneous doubling of atmospheric carbon dioxide. Instead of the model's previous ECS of 4°C (7.2°F), the CESM2 now shows an ECS of 5.3°C (9.5°F)" https://www.resilience.org/stories/2019-08-13/new-models-point-to-more-global-warming-than-expected/

10A **The global temperature could reach 1.5° C as early as 2026**



Projected temperature rises with IPO in positive mode (red) and negative mode (blue) (Henley and King, 2017)

JACOB et al: the world is likely to pass the +1.5°C threshold around 2026 for RCP8.5, and "for the intermediate RCP4.5 pathway the central estimates lie in the relatively narrow window around 2030. In all likelihood, this means that a +1.5°C world is imminent."

KONG AND WANG: the threshold of 1.5°C warming will be reached in 2027, 2026, and 2023 under RCP2.6, RCP4.5, RCP8.5, respectively.

XU and RAMANTHAN: suggesting that the 1.5°C would be exceed around 2028.

ROGELJ et al: then SSP5 exceeds 1.5°C in 2029 and SSP4 by 2031.
https://www.resilience.org/stories/2018-04-05/1-5c-of-warming-is-closer-than-we-imagine-just-a-decade-away/

10B 1.5°C Excedence Year for P66 temp increase 1.45-1.55 (45 scenarios)

exceedance year|15°C	Count
2030	12
2031	1
2032	9
2033	10
2034	2
2035	2
>=2040	9

Average exceedence year - 2033.5

10C By adjusting the 2015 temperature increase in the above graph (1.1°C) to match the 2015 temperature increase in the IPCC 1.5°C report (1.026), the average exceedence year in the above graph would be 2031 - 2 1/2 years earlier than the IPCC reported

11	Natural emissions http://ccdatacenter.org/documents/GlobalWarmingFeedbacks.pdf