Supporting Material - Formula For CO2 Emissions Budget

Bruce Parker (bruce@chesdata.com) 12/2/2019

Calculating the remaining CO2 emission budget for a given global warming level requires estimates for two key factors. The first is the warming that has already occurred since pre-industrial times. The second is the climate sensitivity of the Earth—the relationship between emissions and global mean temperature. There are uncertainties in each of these estimates, and those lead to uncertainties in the CO2 emission budget. Additional uncertainties arise from non-CO_2 gases and climate tipping points (e.g., permafrost melting and resulting methane release).

Development of Formulas

A. CO2 PPM in 2100 based on cumulative CO2 emissions through 2100 (based on 410 scenarios - for calculations for total nonCO2 RF)

The CO2 emissions and CO2 concentration data from 410 scenarios in the "IAMC 1.5°C Scenario Explorer and Data hosted by IIASA, release 2.0" spreadsheet (which can be found from links on the Web page (https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/) was used to create a plot of the atmospheric CO2 concentration in 2100 that results from cumulative CO2 emissions from 2018 through 2100.

> "This Scenario Explorer presents an ensemble of quantitative, model-based climate change mitigation pathways underpinning the Special Report on Global Warming of 1.5°C (SR15) by the Intergovernmental Panel on Climate Change (IPCC) published in 2018. The ensemble was also used and extended in the IPCC's Special Report on Climate Change and Land (SRCCL, 2019)."

Fields used: Emissions|CO2
AR5 climate diagnostics|Concentration|CO2|FAIR|MED
AR5 climate diagnostics|Concentration|CO2|MAGICC6|MED

Sample model data (values in MTCO2):

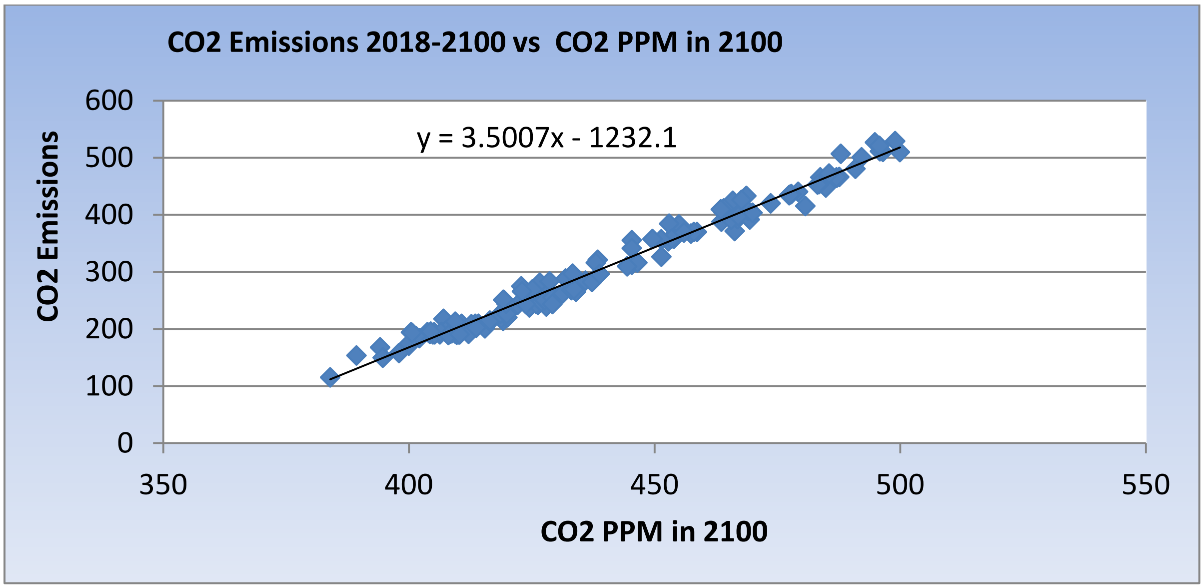
Model	Scenario	2010	2015	2018	2020	2025	2030
AIM/CGE 2.0	ADVANCE_2020_1.5C-2100	38149	41270	42853	43908	30788	21076
AIM/CGE 2.0	ADVANCE_2020_Med2C	38149	41259	42870	43943	31731	23872
AIM/CGE 2.0	ADVANCE_2020_WB2C	38149	41259	42870	43943	31732	23880
AIM/CGE 2.0	ADVANCE_2030_Med2C	38149	41259	42886	43970	43521	41558
AIM/CGE 2.0	ADVANCE_2030_Price1.5C	38102	41725	43424	44557	44252	41746
AIM/CGE 2.0	ADVANCE_2030_WB2C	38149	41259	42886	43970	43521	41558

Values for 2018 were interpolated to simplify the formula for calculating cumulative emissions from 1/1/2018 to 1/1/2100. Scenarios were included where the value for atmospheric CO2 concentration in 2100 was less than 600 PPM.

Sample data for creating the formula:

Scenario ID	Emissions	PPM
1	318.4145	425.994
2	38.20235	366.808
3	40.78784	367.302
4	177.9553	400.035
5	80.92555	375.91
7	64.41205	387.328
8	41.14644	366.646

Excel was use to create the following scatter plot and trend line:



A.1 Formula for CO2 Budgets (For Emissions from 2018-2100)

RF=Radiative Forcing; ET = Equilibrium Temperature; CS=Climate Sensitivity; Ln=Natural Logarithm

A. RF = 5.35 * Ln(1 + ET / CS) *(standard climate model equation)*
CO2RF + NonCO2RF = 5.35 * Ln(1 + ET / CS)
CO2RF = 5.35 * Ln(1 + ET / CS) - NonCO2RF

B. CO2 RF = 5.35 * LN(CO2 PPM/278) *(standard climate model equation)*

C. B=A
5.35 * LN(CO2 PPM/278) = 5.35 * Ln(1 + ET / CS) - NonCO2RF
LN(CO2 PPM/278) = (5.35 * Ln(1 + ET / CS) - NonCO2RF)/5.35
CO2 PPM/278 = e((5.35 * Ln(1 + ET / CS) - NonCO2RF) /5.35)
CO2 PPM = 278 * e((5.35 * Ln(1 + ET / CS) - NonCO2RF) /5.35)

D. CO2 Emissions = 3.5007 * PPM - 1232.1 *(derived above from climate models)*
2100 CO2 PPM = 0.285657 * CO2 Emissions 2018-2100 - 351.95

E. D = C

0.285657 * CO2 Budget + 351.95= 278 * e((5.35 * Ln(1 + ET / CS) - NonCO2RF) /5.35)

0.285657 * CO2 Budget = 278 * e((5.35 * Ln(1 + ET / CS) - NonCO2RF) /5.35) - 351.95

CO2 Budget = (278 * e((5.35 * Ln(1 + ET / CS) - NonCO2RF) /5.35) - 351.95)/ 0.285657

$$\textbf{CO2 Budget} = 3.5007 * \text{CO2OrigPPM} * (1 + ET / CS) * e^{(\ -\ \text{Non-CO2RF} / 5.35)} - 1232.1$$

The formula can be used to create a series of tables that show the carbon emissions budget for various combinations of equilibrium temperature, climate sensitivity, and nonCO2 radiative forcing

		Temp Incr:	1.5	°C	
		Climate Sensitivity			
		2.8	3.0	3.2	3.4
Non-CO2 RF (W/m-2)	0.4	155	123	94	69
	0.5	129	97	70	45
	0.6	104	73	46	22
	0.7	79	49	22	-2
	0.8	55	25	-1	-24
		CO2 Budget 2018-2100			

Figure 2

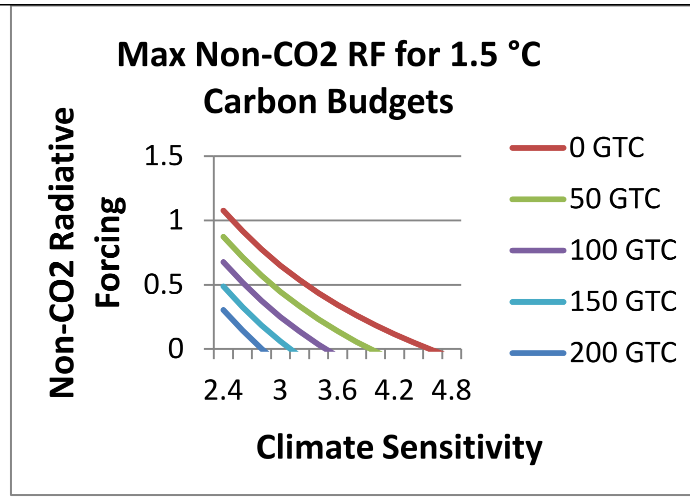
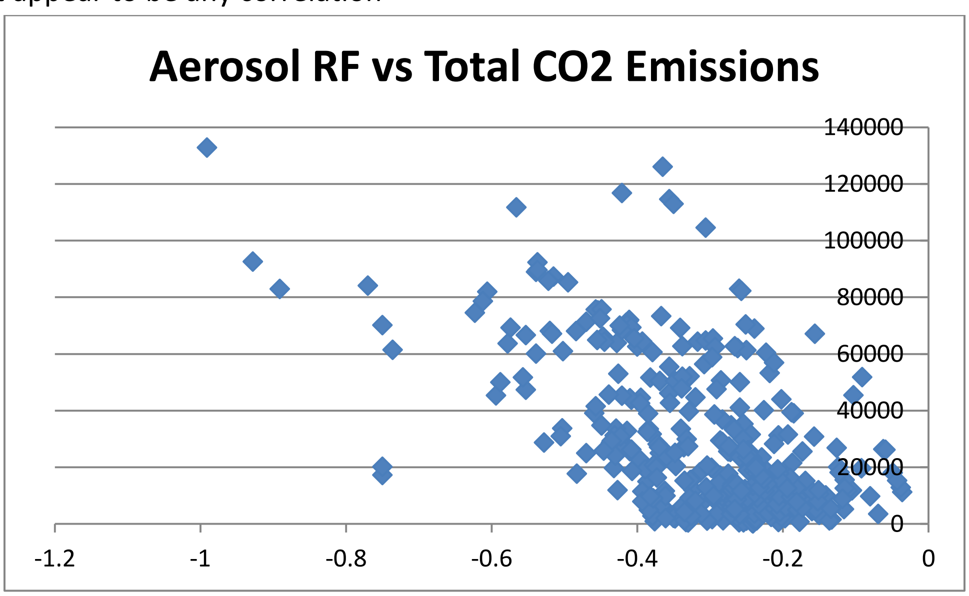


Figure 3

See "Carbon Emissions budget Lookup Tables" for additional examples.

B. Aerosol radiative forcing in 2100 from fossil fuel emissions in 2100

There does not appear to be any correlation

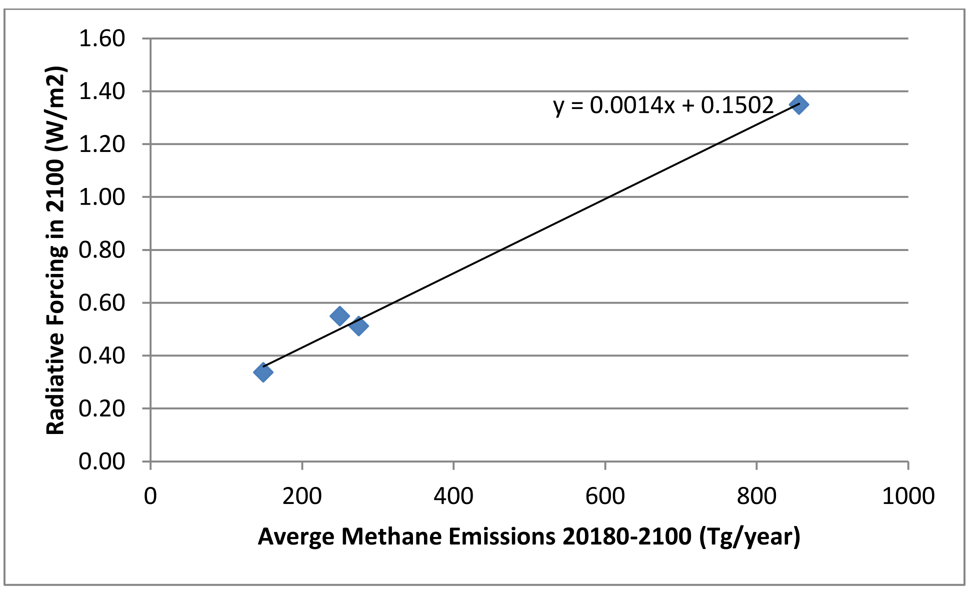


C. CH4 radiative forcing in 2100 based on CH4 emissions 2080-2100

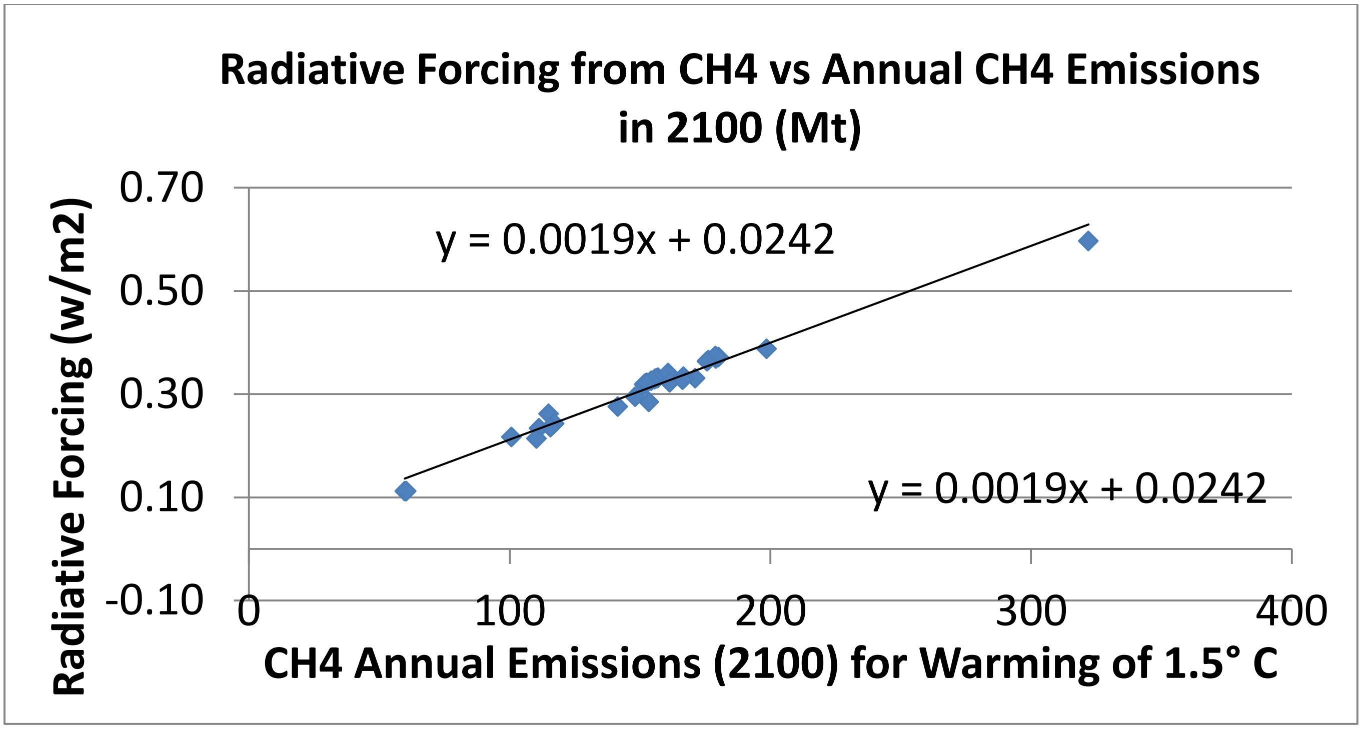
According to a recent article in the Geophysical Research Letters ("Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing" - https://agupubs.onlinelibrary.wiley.com/journal/19448007), the recent IPCC report underestimated the radiative forcing of methane by 25%. Based on increasing the reported radiative forcing values for methane for the four RCP's in the IPCC Physical Basis AR5 by 25%, the following formula can be use to estimate the radiative forcing from methane in 2100 based on the average emissions from 2080 to 2100 (assuming that the annual emissions between 2080 and 2100 do not vary significantly):

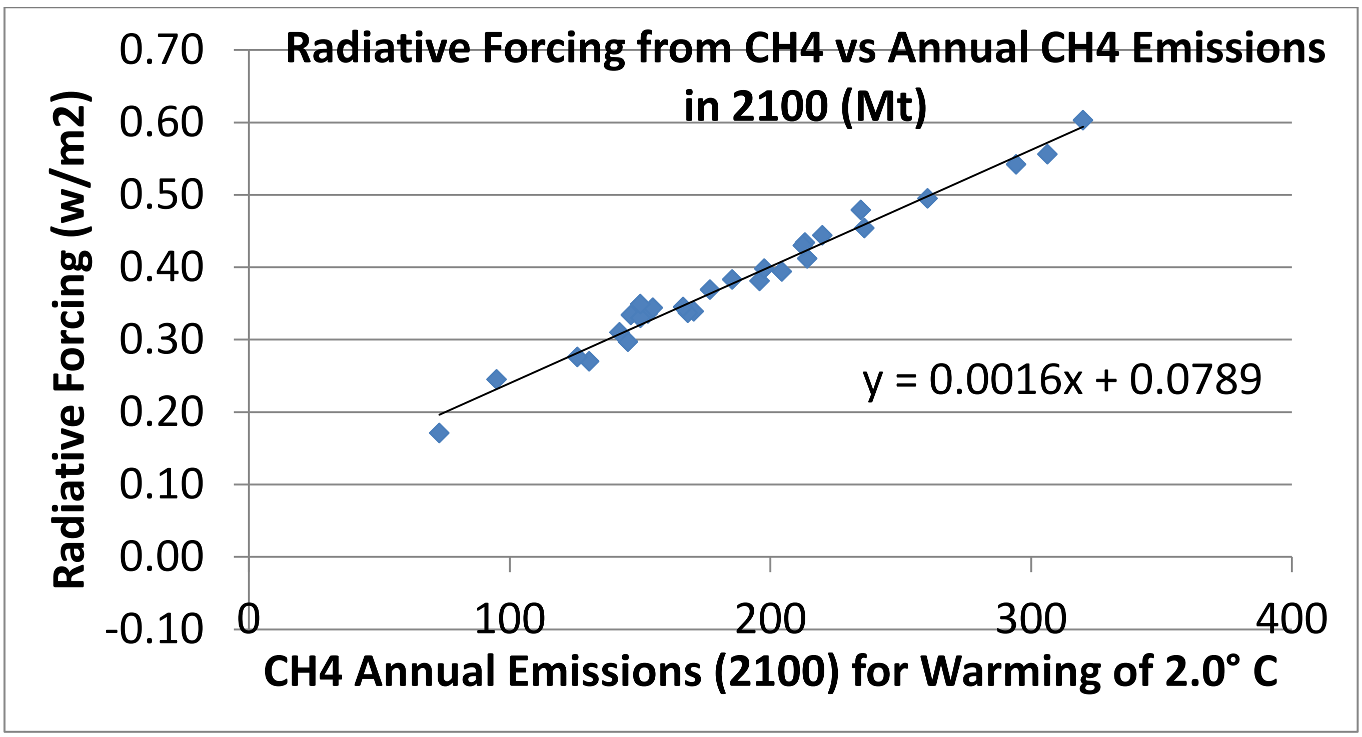
CH4 Radiative Forcing = 0.0014 x Average CH4 Annual Emissions + 0.1502
Average CH4 Annual Emissions = 707.85 x CH4 Radiative Forcing - 104.14

	RCP			
CH4	**2.6**	**4.5**	**6.0**	**8.5**
Emissions	149	275	250	856
Radiative Forcing	0.34	0.51	0.55	1.35



Data from the recent IPCC 1.5° C report show a similar result:





CH4 Emissions	150	200	250	300	350	400	450	500	550	600	650	700	750	800
Radiative Forcing	0.36	0.43	0.50	0.57	0.64	0.71	0.78	0.85	0.92	0.99	1.06	1.13	1.20	1.27

Radiative Forcing	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90
CH4 Emissions	73	108	144	179	214	250	285	321	356	391	427	462	498	533

A4 . CO2 PPM in 2100 based on cumulative CO2 emissions through 2100 (based on 33 scenarios - for calculations for N2O and CH4 emissions)

Since the focus of the report was a 1.5°C temperature increase, 33 FAIR scenarios with a P66 temperature increase between 1.45 and 1.55 were use to the develop the following formula:

CO2 Emissions = 3.5007 * PPM - 1232.1

2100 CO2 PPM = 0.285657 * CO2 Emissions 2018-2100 + 351.9582

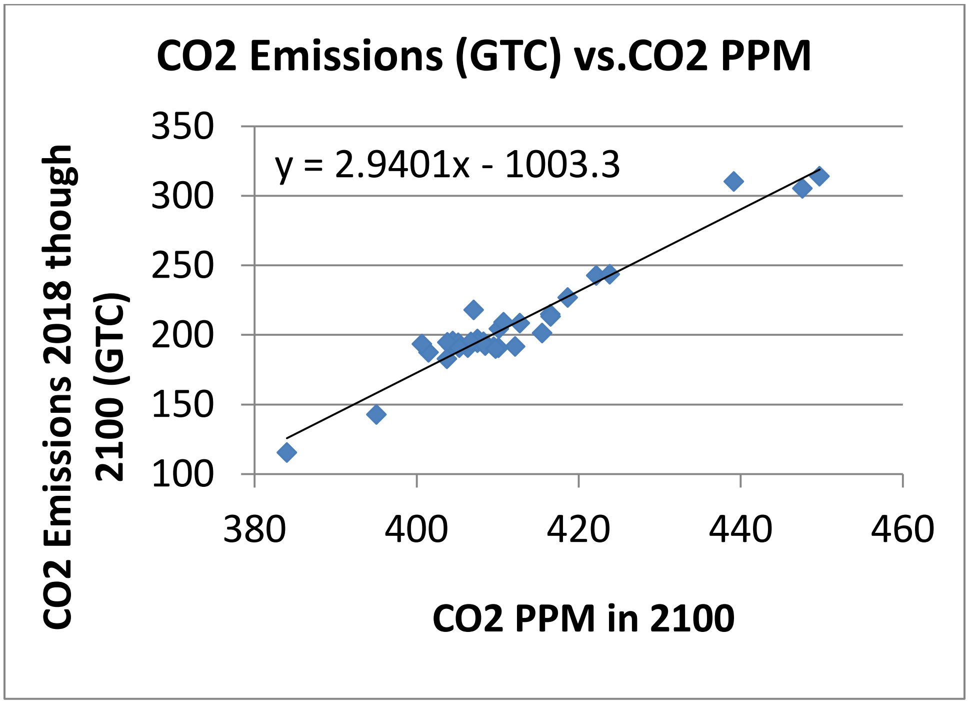


Figure 1

Derivation of the CO2 emission budget Formula for "CO2 Emissions 2018-2100": *(fields substituted in yellow)*

CO2 Emissions = PPM * 3.5007 - 1232.1

OrigPPM*EXP(CO2Forcing/5.35)*3.5007-1232.1

OrigPPM*EXP((TotalRF-NonCO2RF)/5.35)*3.5007-1232.1

OrigPPM*EXP((LN(CO2e Atmo Conc 2100/OrigPPM)*5.35-NonCO2RF)/5.35)*3.5007-1232.1

OrigPPM*EXP((LN(CO2e Atmo Conc 2100/OrigPPM)*5.35-(CH4Rf+N2ORF+OtherRF+TRpoARf+FAdj))/5.35)*3.5007-1232.1

OrigPPM*EXP((LN((OrigPPM*(1+ET/CS))/OrigPPM)*5.35-(CH4Rf+N2ORF+OtherRF+TRpoARf+FAdj))/5.35)*3.5007-1232.1

OrigPPM*EXP((LN((OrigPPM*(1+ET/CS))/OrigPPM)*5.35-(CH4E*0.0019+0.0019+0.0003*N2OE+0.0185-0.061617647))/5.35)*3.5007-1232.1

OrigPPM*EXP((LN((OrigPPM*(1+ET/CS))/OrigPPM)*5.35-(CH4E*0.0019+0.0003*N2OE-0.04122))/5.35)*3.5007-1232.1

278.7*EXP((LN(((1+ET/CS)))*5.35-(CH4E*0.0019+0.0003*N2OE-0.04122))/5.35)*3.5007-1232.1

$$3.5007 * 278.7 * (1 + ET / CS) * e^{\left(-(CH4E*0.0019+0.0003*N2OE-0.04122)/5.35\right)} - 1232.1$$

Create tables based on the carbon emissions budget formula:

		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**	197	193	189	185	181	177	173	169	165	162
	250	147	143	140	136	132	128	124	121	117	113
	350	99	95	92	88	84	81	77	73	70	66
	450	53	49	46	42	38	35	31	28	24	21
	550	8	4	1	-2	-6	-9	-13	-16	-20	-23
	650	-35	-39	-42	-45	-49	-52	-55	-59	-62	-65
	750	-77	-80	-84	-87	-90	-93	-96	-100	-103	-106

CO2 Emissions budget from 2018-2100 For CH4 and N2O(Emissions - GTC)

See "Carbon Emissions budget "Lookup Tables" for additional examples.

H. CO2 Emissions Budget Adjustments

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 (GTC)			
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)

Scenario data from REMIND 1.7 / CEMICS-2.0-CDR8 (calculated CO2 emissions: 185 GTC)			
	Units		Notes
Original Estimate			
Target Temperature	°C	1.5	
Climate Sensitivity		2.45	
Emissions			
CO2	GTC	191	
CH4	Mt	175	
N2O	Mt	913	
Adjustments			
NonCO2 Emissions			
CH4	Tg	103	Surface Waters
CH4	Mt		Other
N2O	Mt		
Climate Sensitivity			
Climate Sensitivity adjustment			
CO2 Emission Equivalents (GTC)			
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	22	=(5.1 GTC/10 Mt CH4)* 175 * 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	116	
Adjusted CO2 emission budget	GTC	75	

Note that anthropogenic methane emissions were over 250 Mt in 1970 and cumulative N2O emissions were about 730 MT in RCP 4.5. This points to the need for the publishing of emission scenarios specifically for methane and N2O.

==

Supporting Material - IPCC Report

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	8
2043	1

Average exceedence year - 2033.5

Supporting Material - Other

A. IPCC Carbon Budget

In a recent IPCC publication ("Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development",https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf) the IPCC reported a remaining carbon emissions budget of 420 GTCO2 for the 57th percentile of TCRE.

Remaining budgets applicable to 2100 would be approximately 100 GtCO2 lower than this to account for permafrost thawing and potential methane release from wetlands in the future, and more thereafter.

Carbon budgets are basically a function of climate sensitivity and no-CO2 radiative forcing. Without some specificity (e.g., sample scenario which has carbon emissions that match the carbon budget) it is difficult to know if a suggested carbon emissions budget is useful. For example, for a 1.5° C carbon emissions budget of 580 GTCO2 (or 150 GTC starting in 2018), the following table shows the non-CO2 radiative forcing for various climate sensitivities (note that the non-CO2 RF for non-CO2 greenhouse gases for RCP 2.6 in 2100 is 0.81)

1.5 °C: CS and Non-CO2 RF for 2018-2100 CO2 Emissions of 150 GTC				
Climate Sensitivity	2.4	2.6	2.8	3.0
Non-CO2 radiative forcing (W/m-2)	0.78	0.62	0.47	0.35

When the media reports on the IPCC carbon budgets, they almost always write something like "we have a 50% chance of not exceeding a temperature increase of 1.5° C if we can limit future emissions to 580 CTCO2". This is both incorrect and misleading on several accounts:

- The IPCC reported the remaining carbon emissions budget as a percentile of TCRE, not a "percent chance".
- When an event is reported as a "percent chance" the assumption is that we have no influence over the event happening so we just sit back and watch (e.g., "there is a 50% chance that a roll of a die will show a 2, 4, or 6); however, we can affect the temperature in 2100 by primarily reducing the radiative forcing of N2O and CH4.
- Since the uncertainties of the estimated emissions budget are huge - larger than the emissions budget itself for .53° C of additional warming (e.g., "we report the emissions budget as being 580 GTCO2, but it could be anywhere between 0 and 1000 GTC") is specifying a emissions budget even useful?

The media also often frames the remaining emissions budget something like "We Have Only 11 Years Left to Prevent Irreversible Damage from Climate Change" . This is also misleading as there is not specific short time span when the we suddenly go from "we can prevent irreversible damage from climate change" to "we cannot prevent irreversible damage from climate change". We are likely on a path towards "irreversible damage from climate change" if we only rely on mitigation. With sufficient use of "negative emission technologies" can effectively "dial back" the atmospheric CO2 to any level we are willing to fund. We will get to "we cannot prevent irreversible damage from climate change" if (and when) we reach the point where we realize that our society will not fund the necessary atmospheric CO2 removal.

Table 2.2 | The assessed remaining carbon budget and its uncertainties. Shaded blue horizontal bands illustrate the uncertainty in historical temperature increase from the 1850–1900 base period until the 2006–2015 period as estimated from global near-surface air temperatures, which impacts the additional warming until a specific temperature limit like 1.5°C or 2°C relative to the 1850–1900 period. Shaded grey cells indicate values for when historical temperature increase is estimated from a blend of near-surface air temperatures over land and sea ice regions and sea-surface temperatures over oceans.

Additional Warming since 2006–2015 [°C]*(1)	Approximate Warming since 1850–1900 [°C]*(1)	Remaining Carbon Budget (Excluding Additional Earth System Feedbacks*(5)) [$GtCO_2$ from 1.1.2018]*(2)			Key Uncertainties and Variations*(4)					
		Percentiles of TCRE *(3)			Earth System Feedbacks *(5)	Non-CO_2 scenario variation *(6)	Non-CO_2 forcing and response uncertainty	TCRE distribution uncertainty *(7)	Historical temperature uncertainty *(1)	Recent emissions uncertainty *(8)
		33rd	*50th*	*67th*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*
0.3		290	160	80						
0.4		530	350	230						
0.5		770	530	380						
0.53	**~1.5°C**	**840**	**580**	**420**	Budgets on the left are reduced by about –100 on centennial time scales	±250	–400 to +200	+100 to +200	±250	±20
0.6		1010	710	530						
0.63		1080	770	570						
0.7		1240	900	680						
0.78		1440	1040	800						
0.8		1480	1080	830						
0.9		1720	1260	980						
1		1960	1450	1130						
1.03	**~2°C**	2030	1500	1170						
1.1		2200	1630	1280						
1.13		2270	1690	1320						
1.2		2440	1820	1430						

Notes:
*(1) Chapter 1 has assessed historical warming between the 1850–1900 and 2006–2015 periods to be 0.87°C with a ±0.12°C *likely* (1-standard deviation) range, and global near-surface air temperature to be 0.97°C. The temperature changes from the 2006–2015 period are expressed in changes of global near-surface air temperature.
*(2) Historical CO_2 emissions since the middle of the 1850–1900 historical base period (mid-1875) are estimated at 1940 $GtCO_2$ (1640–2240 GtCO2, one standard deviation range) until end 2010. Since 1 January 2011, an additional 290 $GtCO_2$ (270–310 $GtCO_2$, one sigma range) has been emitted until the end of 2017 (Le Quéré et al., 2018).
*(3) TCRE: transient climate response to cumulative emissions of carbon, assessed by AR5 to fall *likely* between 0.8–2.5°C/1000 PgC (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker et al., 2013). Values are rounded to the nearest 10 $GtCO_2$.
*(4) Focussing on the impact of various key uncertainties on median budgets for 0.53°C of additional warming.
*(5) Earth system feedbacks include CO_2 released by permafrost thawing or methane released by wetlands, see main text.
*(6) Variations due to different scenario assumptions related to the future evolution of non-CO_2 emissions.
*(7) The distribution of TCRE is not precisely defined. Here the influence of assuming a lognormal instead of a normal distribution shown.
*(8) Historical emissions uncertainty reflects the uncertainty in historical emissions since 1 January 2011.

B. Temperature Increase Target

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

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

Background on "selection" of 2.0°C temperature increase limit

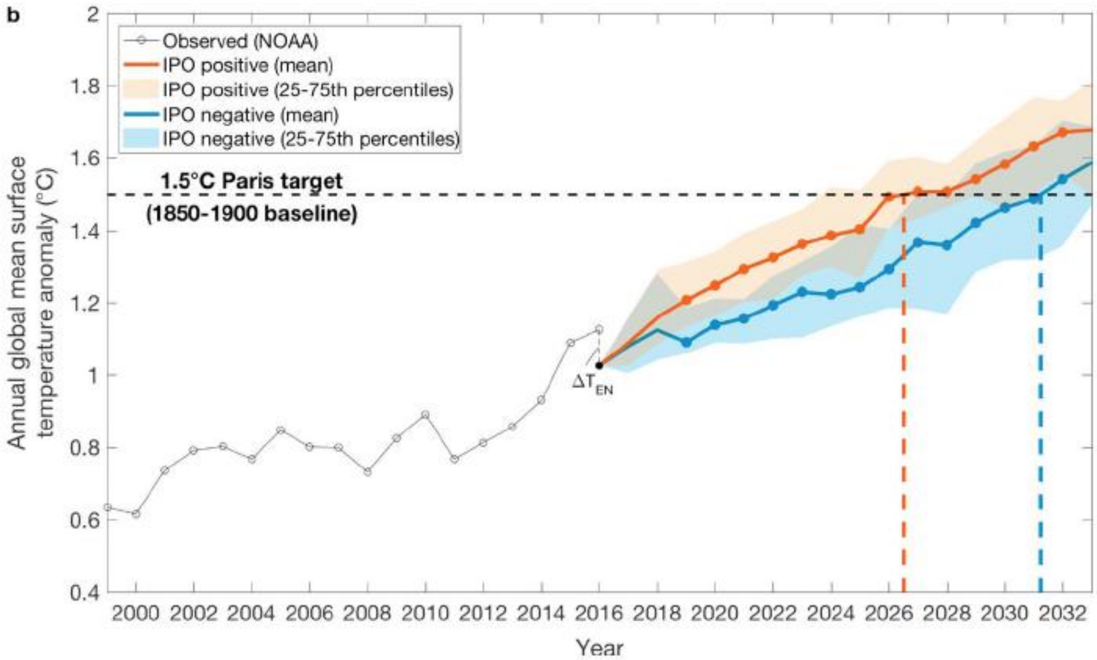
"In his 1975 paper "Can We Control Carbon Dioxide?," Nordhaus, "thinks out loud" as to what a reasonable limit on CO2 might be. He believed it would be reasonable to keep climatic variations within the "normal range of climatic variation." He also asserted that science alone cannot set a limit; importantly, it must account for both society's values and available technologies. He concluded that a reasonable upper limit would be the temperature increase one would observe from a doubling of preindustrial CO2 levels, which he believed equated to a temperature increase of about 2°C.

Nordaus himself stressed how "deeply unsatisfactory" this thought process was. It's ironic that a back-of-the-envelope, rough guess ultimately became a cornerstone of international climate policy.

This fear of abrupt climate change also drove the political acceptance of a defined temperature limit. The 2°C limit moved into the policy and political world when it was adopted by the European Union's Council of Ministers in 1996, the G8 in 2008 and the UN in 2010. In 2015 in Paris, negotiators adopted 2°C as the upper limit, with a desire to limit warming to 1.5°C."

http://theconversation.com/why-is-climate-changes-2-degrees-celsius-of-warming-limit-so-important-82058

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."

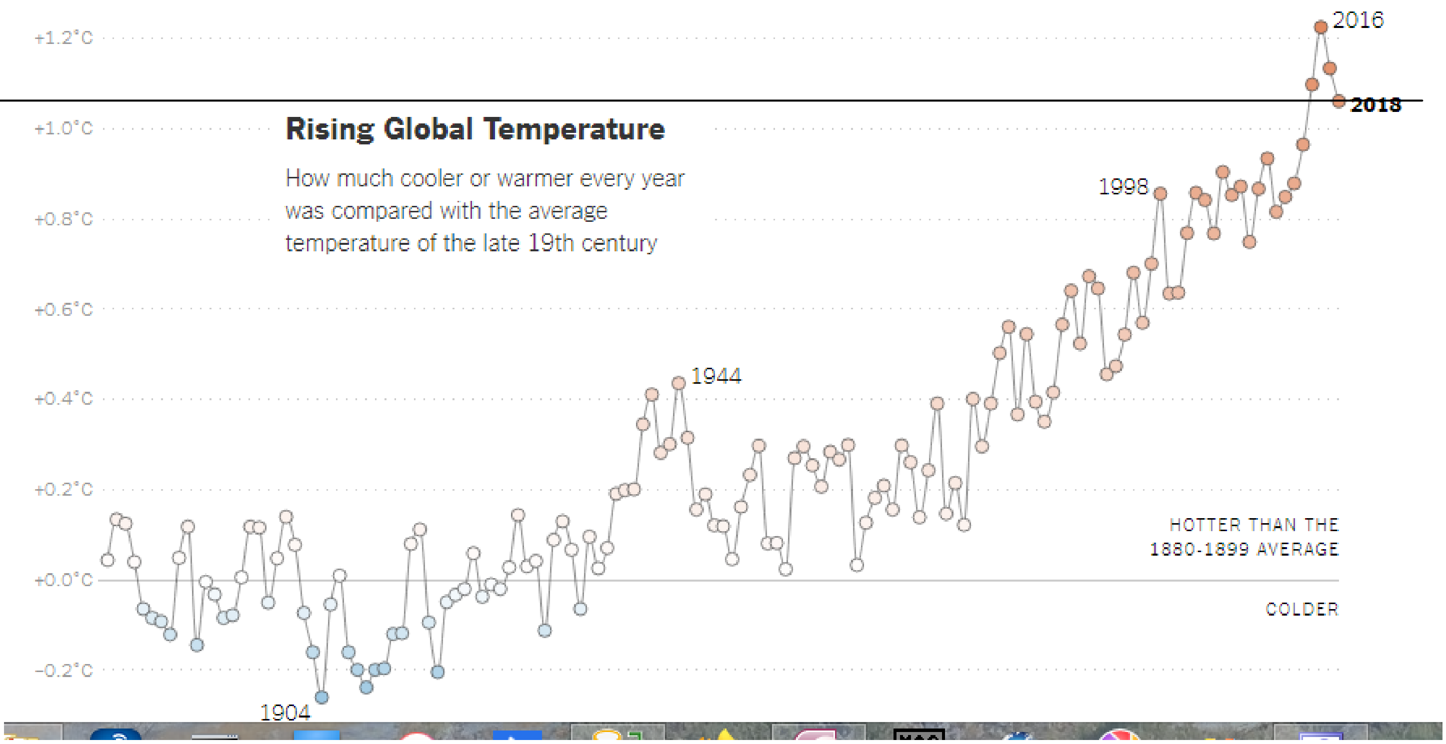
KONG AND WANG: the threshold of 1.5°C warming will be reached in 2027, 2026, and 2023 under RCP2.6, RCP4.5, RCP8.5, respectively.

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

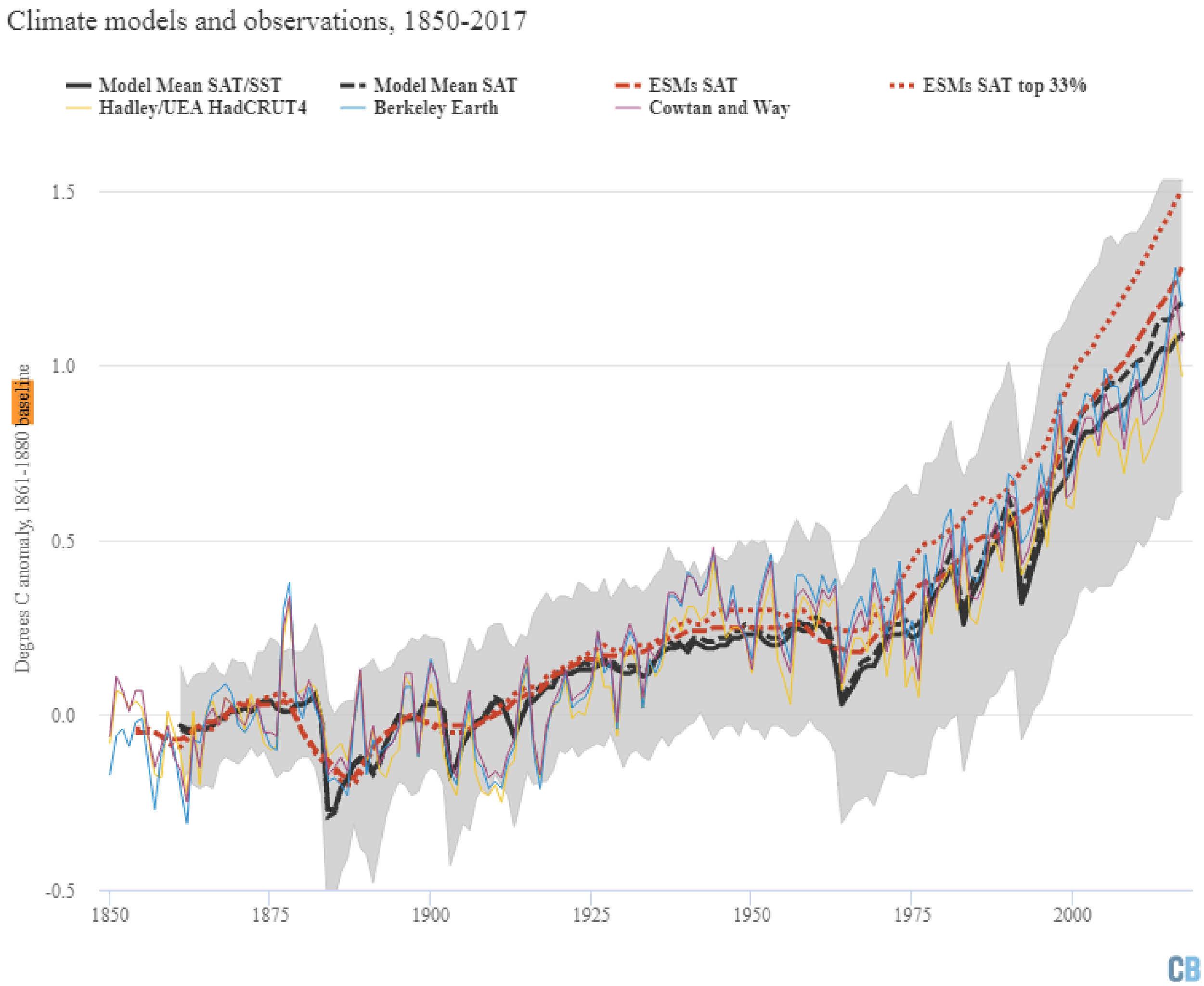
ROGELJ et al: then SSP5 exceeds 1.5°C in 2029 and SSP4 by 2031.
https://www.resilience.org/stories/2018-04-05/1-5c-of-warming-is-closer-than-we-imagine-just-a-decade-away/
Note: The graph shows a 1.1°C temperature increase in 2015, about 0.075°C above the mean for MAGICC in the IPCC 1.5°C report, the "exceedence year" for 1.5°C would be increased by about 2 years to 2028-2033

It's Official: 2018 Was the Fourth-Warmest Year on Record

By JOHN SCHWARTZ and NADJA POPOVICH FEB. 6, 2019



https://www.nytimes.com/interactive/2019/02/06/climate/fourth-hottest-year.html - for 2018 - increase is 1.12°C



RCP4.5 CMIP5 blended SAT/SST multimodel mean (solid black), two-sigma model range (in grey), CMIP5 SAT multimodel mean (dashed black), ESM SAT multimodel mean (dashed red) and mean of the 33% of ESMs with the smallest 1.5C carbon budget (dotted red). Observational temperature records from HadCRUT, Cowtan and Way and Berkeley Earth. Data plotted as anomalies with respect to the 1861-1880 period. Chart by Carbon Brief using Highcharts.

https://www.carbonbrief.org/analysis-why-the-ipcc-1-5c-report-expanded-the-carbon-budget

Note: The average "mean" temperature increase (°C) for all 1.5°C report model runs for 2015 is less than the lowest value for any of the model runs above

	Average Temp Incr (°C)	
IPCC Report Variable	FAIR	MAGICC
Mean 2015	0.97	1.026306
Mean 2015 - P66	0.98	1.056042
Mean 2018	1.04	1.113965
Mean 2018 - P66	1.06	1.152839

C. Climate Sensitivity

New Models Point to More Global Warming than Expected

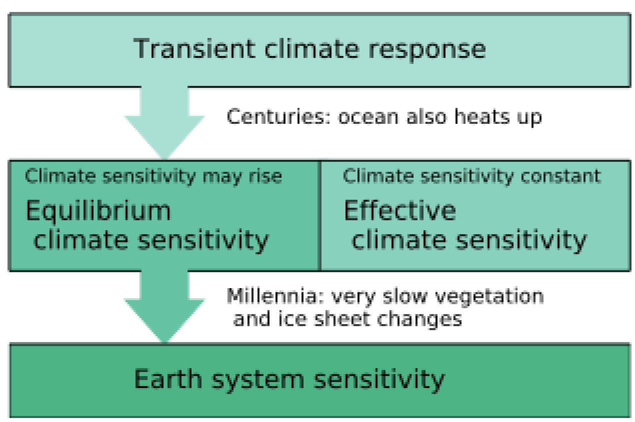
"Global climate models for the next major IPCC assessment show more warming than expected, bucking decades of consensus. Scientists are working to confirm and unravel the potential big shift….
Our planet's climate may be more sensitive to increases in greenhouse gas than we realized, according to a new 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/

From Wikipedia

Different forms of climate sensitivity



Schematic of how different measures of climate sensitivity relate to one another

A component of climate sensitivity is directly due to radiative forcing, for instance by CO_2, and a further contribution arises from climate feedback, both positive and negative. Without feedbacks the radiative forcing of approximately 3.7 W/m^2, due to doubling CO_2 from the pre-industrial 280 ppm, would eventually result in roughly 1 °C global warming. This is easy to calculate[note 2][7] and undisputed.[8] The uncertainty is due entirely to feedbacks in the system: the water vapor feedback, the ice-albedo feedback, the cloud feedback, and the lapse rate feedback.[8] Due to climate inertia, the climate sensitivity depends upon the timescale in which one is interested. The *transient response* is defined by scientists as the temperature response over human time scales of around 70 years, the *equilibrium climate sensitivity* over centuries, and finally the *Earth system sensitivity* after multiple millennia.[9]

Equilibrium climate sensitivity

The equilibrium climate sensitivity (ECS) refers to the equilibrium change in global mean near-surface air temperature that would result from a sustained doubling of the atmospheric equivalent CO
2 concentration ($\Delta T_{2\times}$). A comprehensive model estimate of equilibrium sensitivity requires a very long model integration; fully equilibrating ocean temperatures requires the integration of thousands of model years, although it is possible to produce an estimate more quickly using the method of Gregory et al. (2004).[10] As estimated by the IPCC Fifth Assessment Report (*AR5*), "there is high confidence that ECS is extremely unlikely less than 1°C and medium confidence that the ECS is likely between 1.5°C and 4.5°C and very unlikely greater than 6°C".[11]

Effective climate sensitivity

The effective climate sensitivity is an estimate of equilibrium climate sensitivity using data from a climate system, either in a model or real-world observations, that is not yet in equilibrium.[12] Estimation is done by using the assumption that the net effect of feedbacks as measured after a period of warming remains constant afterwards.[13] This is not necessarily true, as feedbacks can change with time, or with the particular starting state or forcing history of the climate system.[14][12]

Transient climate response

The transient climate response (TCR) is defined as the average temperature response over a twenty-year period centered at CO2 doubling in a transient simulation with CO2 increasing at 1% per year (compounded), i.e., 60 to 80 years following initiation of the increase in CO2.[15] The transient response is lower than the equilibrium sensitivity because the deep ocean, which takes many centuries to reach a new steady state after a perturbation, continues to serve as a sink for heat from the upper ocean.[16] The IPCC literature assessment estimates that TCR likely lies between 1 °C and 2.5 °C.[17] A related concept is the transient climate response to cumulative carbon emissions, which is the globally averaged surface temperature change per unit of CO
2 emitted.[18]

Earth system sensitivity

The Earth system sensitivity (ESS) includes the effects of slower feedback loops, such as the change in Earth's albedo from the melting of large ice sheets that covered much of the northern hemisphere during the last glacial maximum. These extra feedback loops make the ESS larger than the ECS – possibly twice as large. Data from Earth's history is used to estimate ESS, but climatic conditions were quite different which makes it difficult to infer information for future ESS.[19] ESS includes the entire system except the carbon cycle.[20] Changes in albedo as a result of vegetation changes are included.[21]

Perhaps long-term ECS is over 4

https://www.resilience.org/stories/2019-08-13/new-models-point-to-more-global-warming-than-expected/

In theory, climate models can provide the best estimates of climate sensitivity. However, climate sensitivity is a really "fuzzy" concept that is not always used in a "consistent" manner. For instance, most "definitions" of climate sensitivity only refer to CO2. But both the transient climate response (TCR) and equilibrium climate sensitivity (ECS) really include non-CO2 radiative forcing. In addition, if the PPM is stabilized, the formula

Equilibrium Temperature Increase = Climate Sensitivity * (Stable PPM - Initial PPM)/Initial PPM
(e.g., if CS = 3 then 3 * (560-280)/280 --> a 3° temperature increase)

is generally expected to work for any "Stable PPM", so all that we need to know is the initial PPM and climate sensitivity to determine the expected temperature increase for any "stable ppm". This works relatively well if the temperature increases relatively linearly (or slightly logarithmically) for a PPM increase, but this is not the case we find ourselves in today as the albedo change in the Arctic will not be linear for the years 1980 - 2100 as Arctic Sea ice started melting significantly in the summer around 1980 and will likely completely melt by 2100. So the value for climate sensitivity for an initial PPM will be different for various "stable PPMs" in the range that we can expect this century.

And finally, if permafrost emissions become significant (1 GTC/year??) then atmospheric PPM will not stabilize for centuries (assuming "negative emission technologies" are not used at scale), so what is an appropriate value of climate sensitivity? Or is the concept even useful?

D. Future Anthropogenic CO2 Emissions

Estimating future emissions based on a peak year and percent changes per year

The tables below show cumulative CO2 emissions from 2019-2100 for fossil fuel , cement, and land use changes for various combinations of emission reductions (without BECCS, CCS, or CDR) based on the following values:

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)**

Emissions 2019-2100: After the peak year, emissions are reduced by the same value (percent of peak year emissions) each year

	Peak Yr:	2020			2030			2040			2050		
	Pct Chg to Peak Yr:	0	1	2	0	1	2	0	1	2	0	1	2
Annual Pct Change of Peak Yr After Peak Yr	0	846	888	931	846	970	1111	846	1048	1301	846	1121	1497
	-1	527	552	579	601	712	841	666	859	1102	721	989	1358
	-2	299	313	327	398	479	580	487	644	862	557	781	1121
	-3	217	227	237	316	374	445	400	509	664	455	604	837
	-4	176	183	191	274	321	378	355	441	562	397	509	684

Emissions 2019-2100: After the peak year, emissions are reduced by the percentage of the value of the previous year

	Peak Yr:	2020			2030			2040			2050		
	Pct Chg to Peak Yr:	0	1	2	0	1	2	0	1	2	0	1	2
Annual Pct Change After Peak Yr	0	846	888	931	846	970	1111	846	1041	1282	846	1121	1497
	-1	597	626	656	649	741	846	692	845	1034	739	969	1282
	-2	445	466	488	522	593	674	587	711	865	660	858	1125
	-3	348	365	382	437	495	560	514	618	747	603	776	1010
	-4	285	298	312	379	427	482	462	552	663	559	715	923

Estimates of future Anthropogenic CO2 Emissions

"For atmospheric CO_2 concentrations to remain below a "dangerous" level of 450 ppmv (Hansen et al., 2007), model forecasts suggest that there will have to be some combination of an unrealistically rapid rate of energy decarbonization and nearly immediate reductions in global civilization wealth. Effectively, it appears that civilization may be in a double-bind. If civilization does not collapse quickly this century, then CO_2 levels will likely end up exceeding 1000 ppmv; but, if CO_2 levels rise by this much, then the risk is that civilization will gradually tend towards collapse."
https://www.earth-syst-dynam.net/3/1/2012/

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

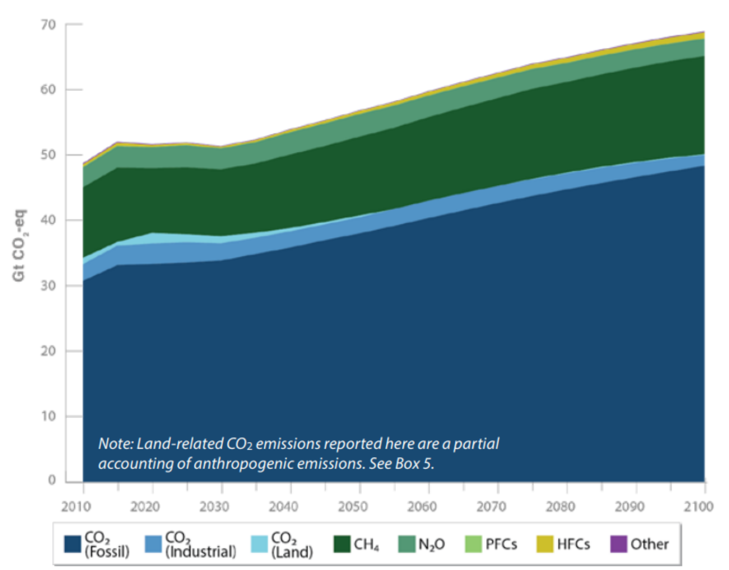


Figure 19. Global annual greenhouse gas emissions

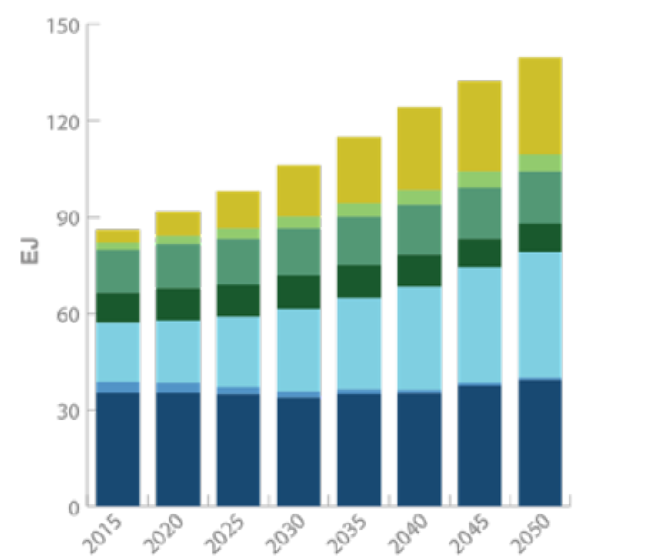
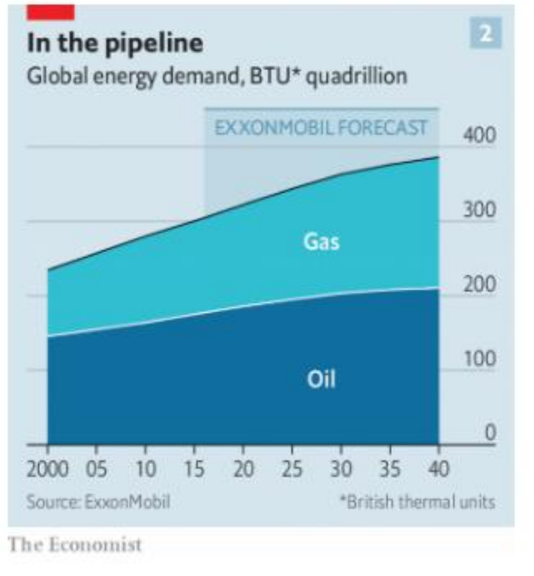


Figure 13. World electricity production (exajoules)

Annual greenhouse emissions projected thru 2100	World electricity production projected through 2050

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

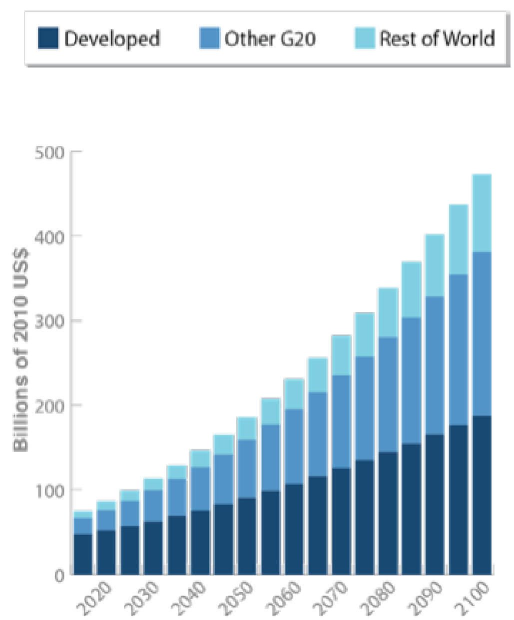
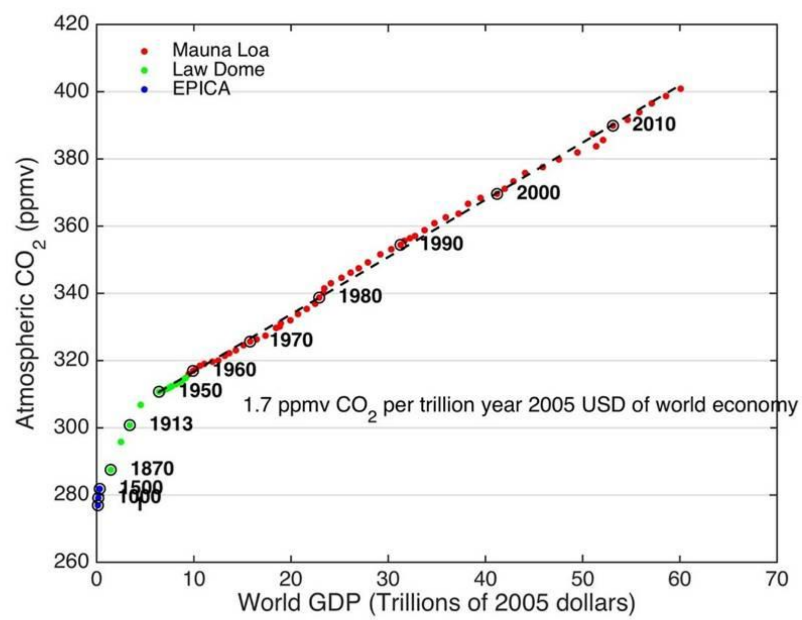
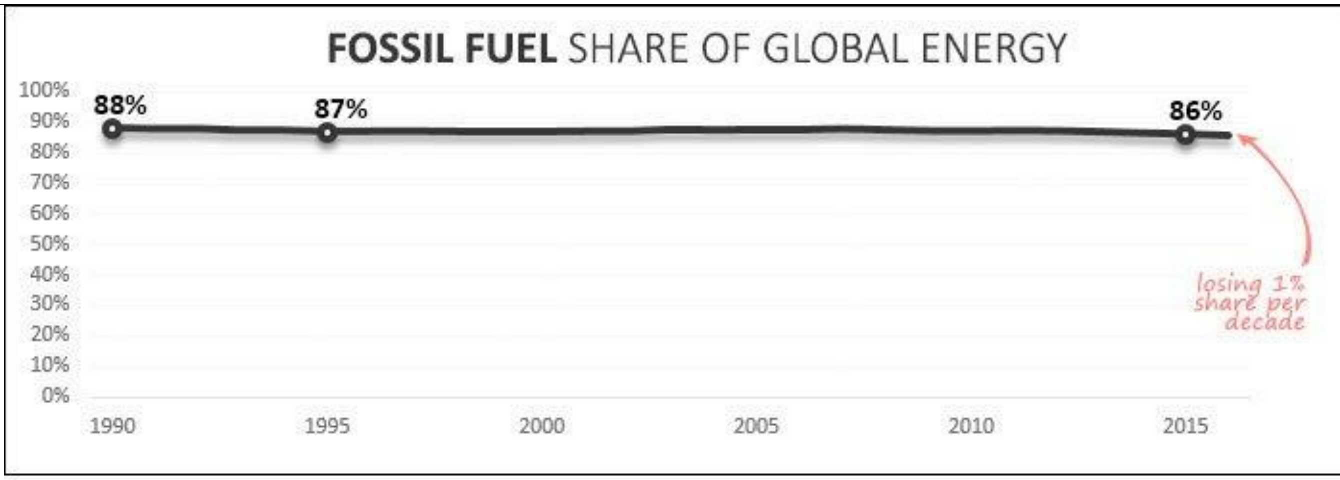


Figure 3. World GDP



https://globalchange.mit.edu/sites/default/files/newsletters/files/2018-JP-Outlook.pdf
(left axis should be Trillions of $US)

<u>(need source)</u>
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



GLOBAL FOSSIL FUEL CONSUMPTION, 1990 - 2016. Percent of total energy consumption. SOURCE: Sum of Oil, Gas and Coal consumption vs total energy in BP Statistical Review of World Energy June 2017. CHART by Barry Saxifrage at VisualCarbon.org. June 2017

https://twitter.com/kencaldeira/status/948093886508892160

MIT Outlook 2018 has fossil fuel share of global energy decreasing from 84% (93 exajoules) in 2015 to 78% (114 exajoules) in 2050

https://globalchange.mit.edu/sites/default/files/newsletters/files/2018-JP-Outlook.pdf (Page 10)

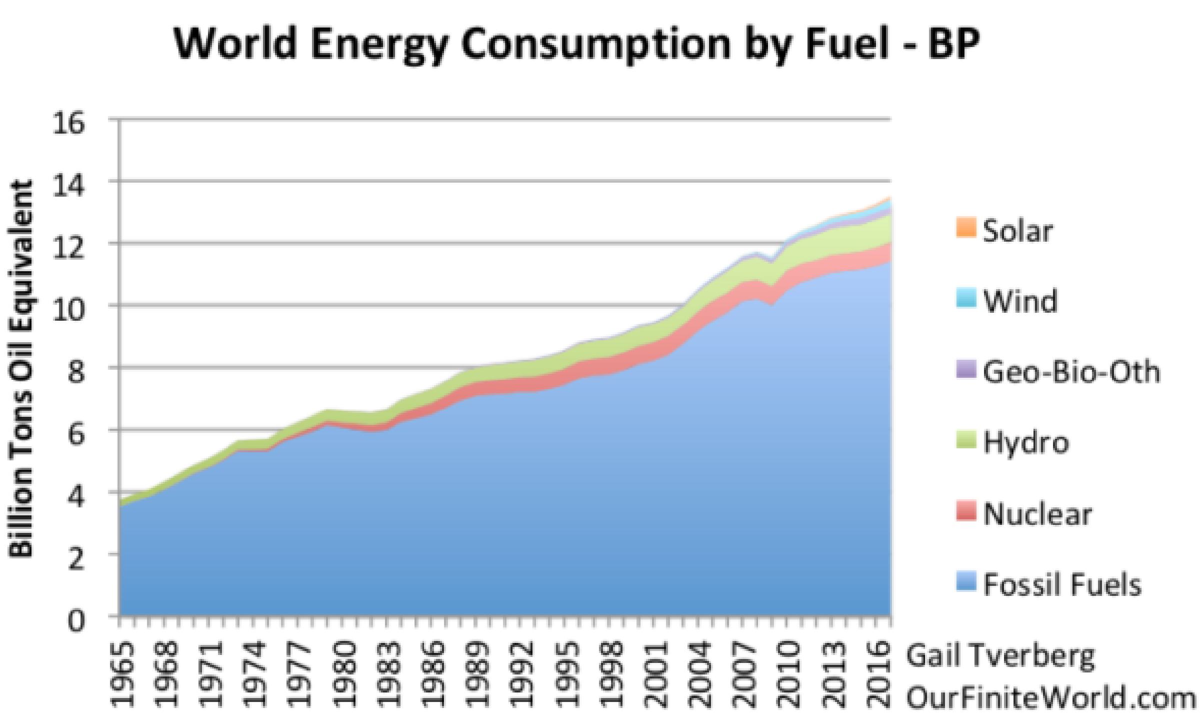
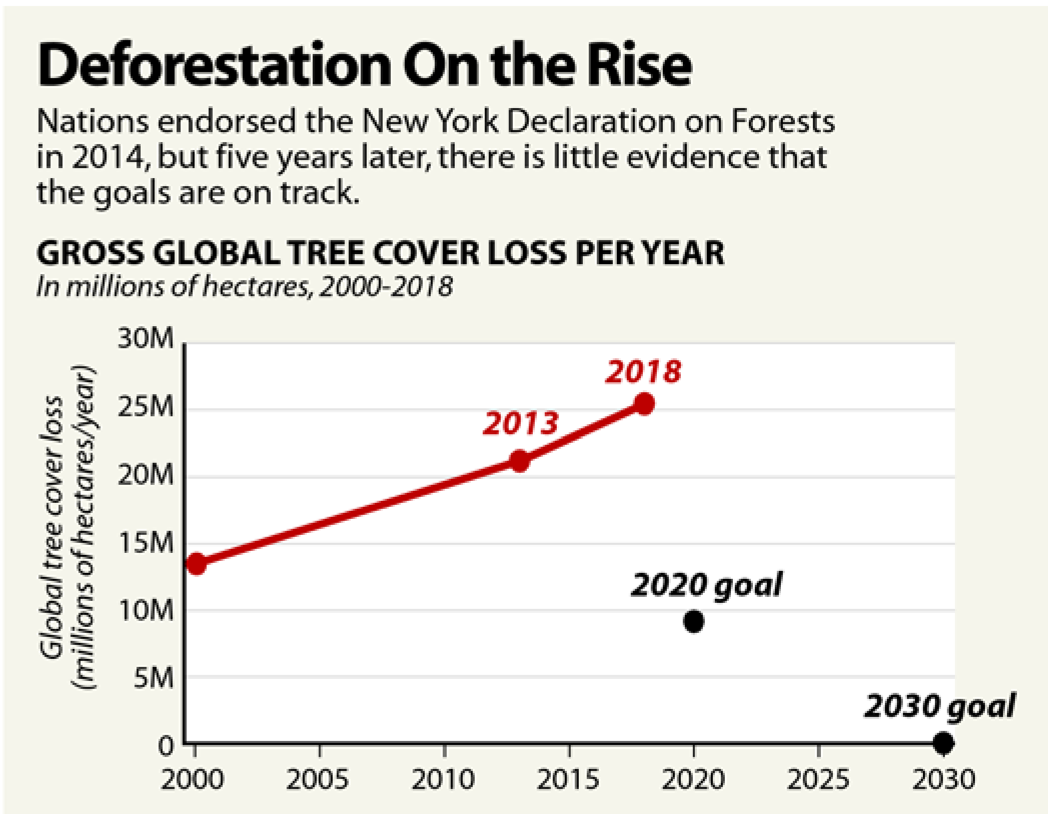


Figure 1. World energy consumption divided between fossil fuels and non-fossil fuel energy sources, based on data from BP 2018 Statistical Review of World Energy 2018.

World energy consumption of fossil fuels has been growing about 2%/year since 1965

E. Deforestation

The "CO2 emission budget" formula assumes that 32 GTC will be emitted from deforestation from 2016 through 2100. Current emissions are around 1.3 GTC/year (https://news.mongabay.com/2018/10/tropical-deforestation-now-emits-more-co2-than-the-eu/) and rising. Given efforts to address global warming and deforestation, it can be assumed that emissions from deforestation through 2100 will be close enough to 32 GTC that they can be ignored when calculating the anthropogenic CO2 emissions budget.

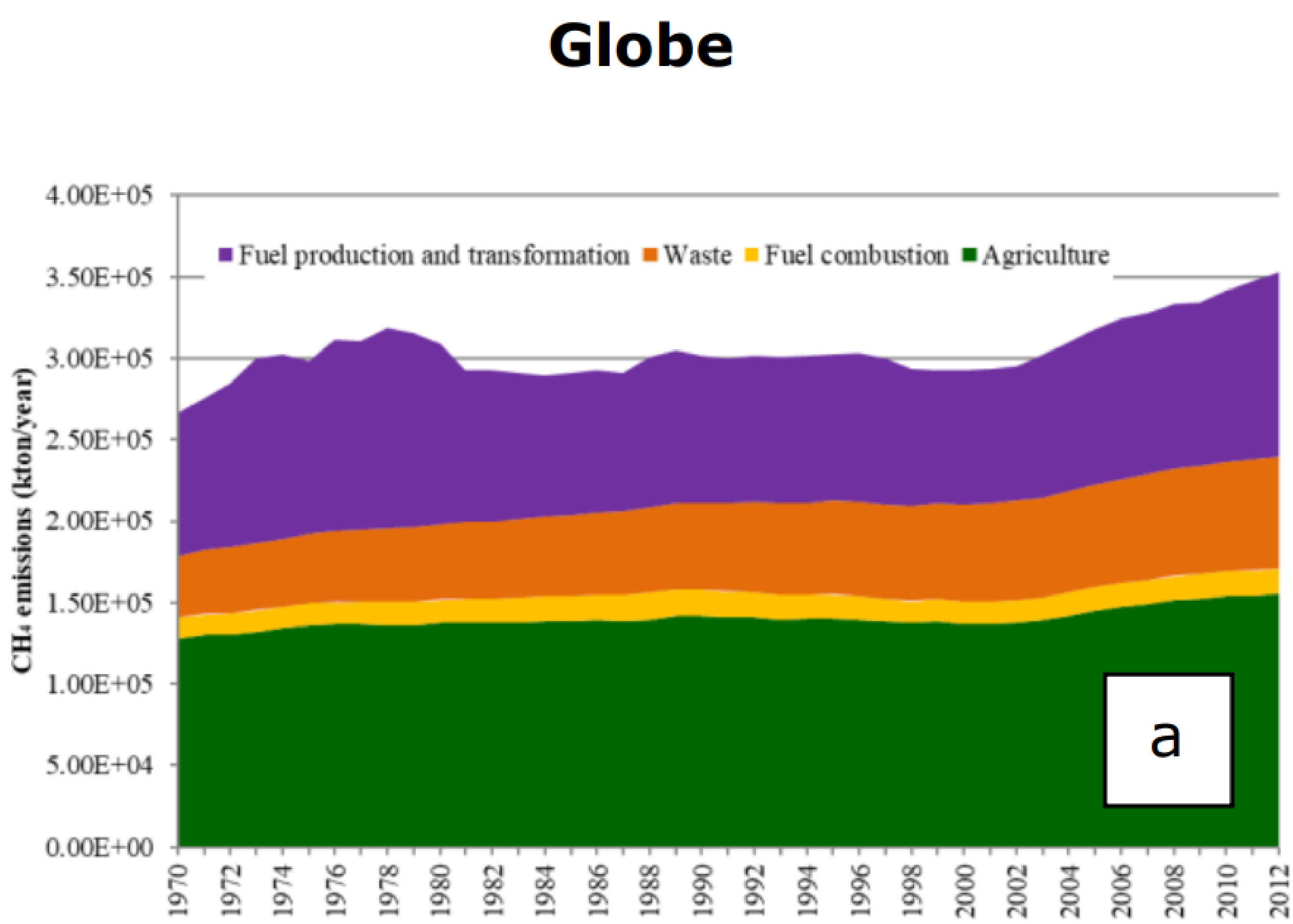


SOURCE: New York Declaration on Forests 2019 report InsideClimate News

https://insideclimatenews.org/news/13092019/forest-loss-rate-global-deforestation-amazon-fires-corporate-agribusiness-international-declaration

F. Emissions from Methane

Global methane emissions



https://espas.secure.europarl.europa.eu/orbis/sites/default/files/generated/document/en/KJNA29394ENN.en_.pdf

(Units are hundreds of metric tons (hundreds of Teragrams - Tg)

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

G. Emissions from Natural Feedbacks

Many of the emissions from natural feedbacks are temperature-dependent. Given a likely temperature increase of at least 2° C by 2050 (see http://ccdatacenter.org/documents/TempIncreaseExpectations.pdf) it seems reasonable that cumulative emissions through 2100 from natural feedbacks will likely be in the range of 120-200 GTC (not including methane from methyl hydrates).

GHG Source	Carbon Store (GTC)	Notes	Likely Temp Change by 2100 (°C)	Likely Temp Change by 2200 (°C)
Feedbacks - GHGs				
Permafrost	1,600	Cumulative permafrost and wetland emissions (about 55 GTC) could cut 1.5C carbon budget 'by five years' Cumulative permafrost emissions could be 120 GTC by 2100	.5	1.5
Soils		Cumulative emissions from soil carbon could be as high as 55 GTC through 2050		
Peat	270 to 370	40% loss by 2100 (100 GTC) 80% loss by 2200 (220 GTC)	.2	.5
Surface waters		Cumulative methane emissions from reservoirs could be about 30 GTC through 2060 and 60 GTC through 2100[11] "[G]lobally, lakes and manmade "impoundments" like reservoirs emit about one-fifth the amount of greenhouse gases emitted by the burning of fossil fuels" "[S]cientists have found that this surge in aquatic plant growth could double the methane being emitted from lakes [(to 40% of current fossil fuel emissions)] ... over the next 50 years."		
Forests		Forests will likely turn from sources to sinks		
Methyl Hydrates	5,000 to 20,000			
Amazon	86			

Source: http://ccdatacenter.org/documents/ NaturalEmissionsExpectations.pdf

H. IPCC AR5 Estimate Non-CO2 Radiative Forcing in 2100

			IPCC Radiative Forcing Estimates				
Greenhouse Gas	Chemical Formula	Residency Time	2011	2100 - RCP 2.6	2100 - RCP 4.5	2100 - RCP 6.0	2100 - RCP 8.5
Carbon dioxide	CO_2	5-200	1.68	2.22	3.54	4.70	6.49
Nitrous oxide	N_2O	114	0.17	0.23	0.32	0.41	0.49
CFCs		45-85	0.34	0.10	0.10	0.10	0.10
Methane	CH_4	12	0.48	0.27	0.41	0.44	1.08
Other Climate Factors			-0.38	-0.22	0.13	0.35	0.34
Non-CO2 Rad. Forc.			0.61	0.38	0.96	1.30	2.01
Total			2.29	2.60	4.50	6.00	8.50
CO2 % of Total RF			**73.36**	**85.38**	**78.67**	**78.33**	**76.35**
Methane Emissions 2090 (Tg/Year)				149	275	250	856
CFC in 2011 from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-3-4.html							

- N2O - mostly comes from agriculture, fuel combustion, wastewater management, and industrial processes and the RF can only increase
- CFCs - Banned by the Montreal protocol, so should only go down as indicted (unless there is illegal production)
- CH4 - (RF reported by IPCC increased by 25% based on latest science) With a short life time the value for 2100 depends primarily on what is emitted in the decade prior to 2100. Atmospheric methane come from natural sources and anthropogenic such as landfills, livestock and exploitation of fossil fuels. Most 1.5 and 2.0 pathways assume a huge drop in anthropogenic CH4 and do not consider the possibility of additional natural CH4 emissions.
- LUC - includes land use land cover change
- Other Factors - for 2011 these are detailed in the AR5. For RCP 2.6 a better explanation is needed

I. Current Situation

If the following statement does not describe our current situation accurately, what is a better description?

Scientists' Declaration of Support for Non-Violent Direct Action Against Government Inaction Over the Climate and Ecological Emergency
THIS DECLARATION SETS OUT THE CURRENT SCIENTIFIC CONSENSUS CONCERNING THE CLIMATE AND ECOLOGICAL EMERGENCY AND HIGHLIGHTS THE NECESSITY FOR URGENT ACTION TO PREVENT FURTHER AND IRREVERSIBLE DAMAGE TO THE HABITABILITY OF OUR PLANET.

As scientists, we have dedicated our lives to the study and understanding of the world and our place in it. We declare that scientific evidence shows beyond any reasonable doubt that human-caused changes to the Earth's land, sea and air are severely threatening the habitability of our planet. We further declare that overwhelming evidence shows that if global greenhouse gas emissions are not brought rapidly down to net zero and biodiversity loss is not halted, we risk catastrophic and irreversible damage to our planetary life-support systems, causing incalculable human suffering and many deaths.

We note that despite the scientific community first sounding the alarm on human-caused global warming more than four decades ago, no action taken by governments thus far has been sufficient to halt the steep rise in greenhouse gas emissions, nor address the ever-worsening loss of biodiversity. Therefore, we call for immediate and decisive action by governments worldwide to rapidly reduce global greenhouse gas emissions to net zero, to prevent further biodiversity loss, and to repair, to the fullest extent possible, the damage that has already been done. We further call upon governments to provide particular support to those who will be most affected by climate change and by the required transition to a sustainable economy.

As scientists, we have an obligation that extends beyond merely describing and understanding the natural world to taking an active part in helping to protect it. We note that the scientific community has already tried all conventional methods to draw attention to the crisis. We believe that the continued governmental inaction over the climate and ecological crisis now justifies peaceful and nonviolent protest and direct action, even if this goes beyond the bounds of the current law.

We therefore support those who are rising up peacefully against governments around the world that are failing to act proportionately to the scale of the crisis.

We believe it is our moral duty to act now, and we urge other scientists to join us in helping to protect humanity's only home.

https://docs.google.com/document/d/1FuZYG-gT5EPTLDyvgNnlYIS5dAy43TM1MnvOls48qIc/mobilebasic

J. RCP Background Information

RCP 2.6:

The RCP 2.6 is developed by the IMAGE modeling team of the Netherlands Environmental Assessment Agency. The emission pathway is representative for scenarios in the literature leading to very low greenhouse gas concentration levels. It is a so-called "peak" scenario: its radiative forcing level first reaches a value around 3.1 W/m2 mid-century, returning to 2.6 W/m2 by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially over time. The final RCP is based on the publication by Van Vuuren et al. (2007).

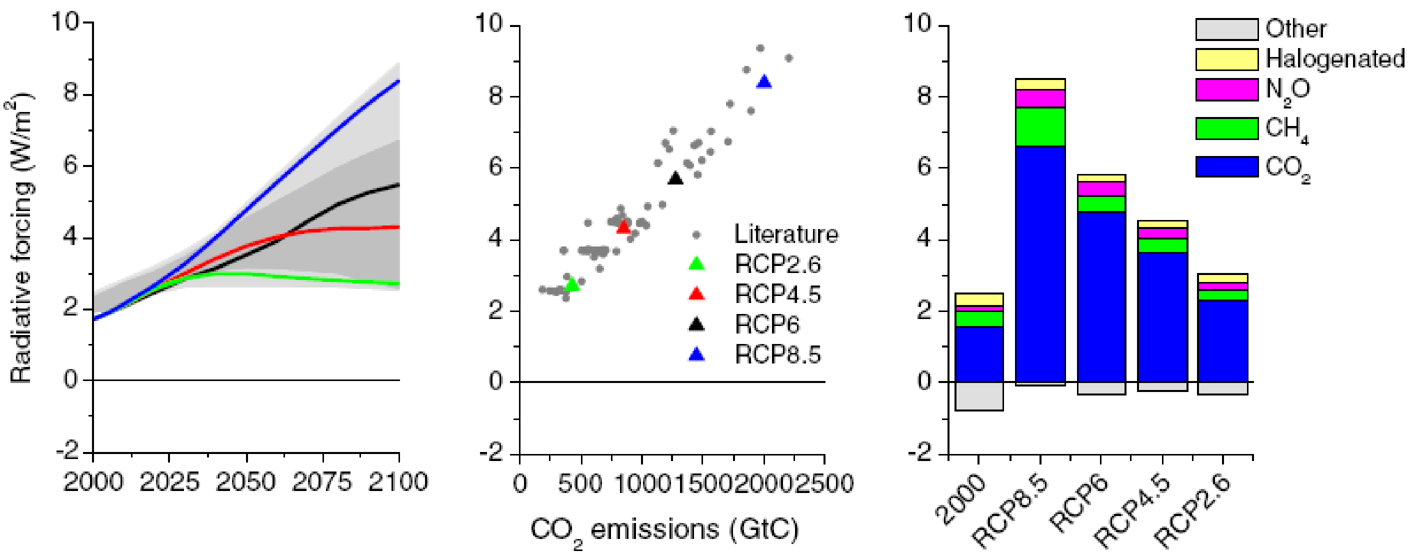


Figure 11: Trends in radiative forcing (left), cumulative 21st centuryCO2 emissions vs 2100 radiative forcing (middle) and 2100 forcing level per category (right). *Grey area indicates the 98th and 90th percentiles (light/dark grey) of the literature. The dots in the middle graph also represent a large number of studies. Forcing is relative to pre-industrial values and does not include land use (albedo), dust, or nitrate aerosol forcing (van Vuuren 2011).* ***Click image for larger version***

Energy sources at years 2000 and 2100

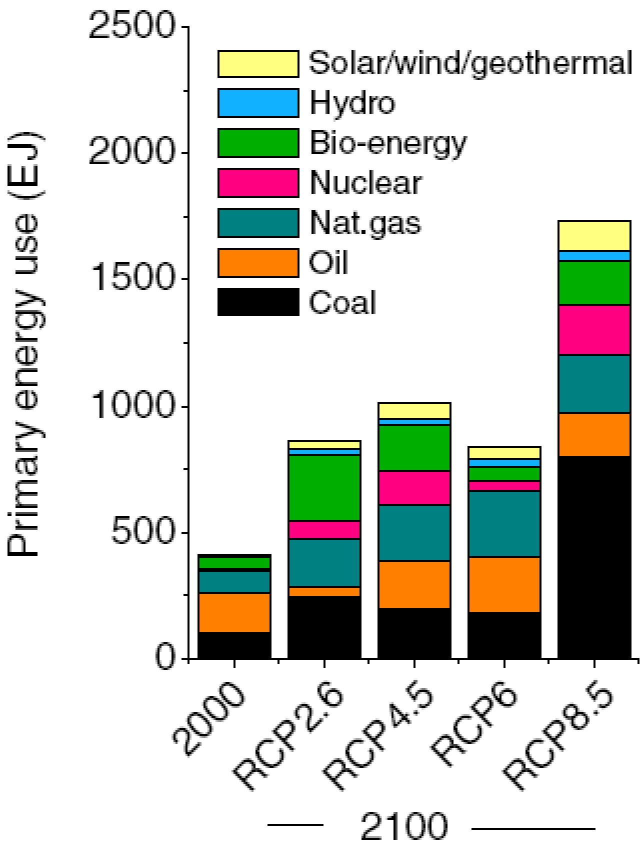


Figure 14: Energy sources by sector (van Vuuren et.al. 2011)

> "In terms of the mix of energy carriers, there is a clear distinction across the RCPs given the influence of the climate target. Total fossil- fuel use basically follows the radiative forcing level of the scenarios; however, due to the use of carbon capture and storage (CCS) technologies (in particular in the power sector), all scenarios, by 2100, still use a greater amount of coal and/or natural gas than in the year 2000. The use of oil stays fairly constant in most scenarios, but declines in the RCP2.6 (as a result of depletion and climate policy).
>
> The use of non-fossil fuels increases in all scenarios, especially renewable resources (e.g. wind, solar), bio-energy and nuclear power. The main driving forces are increasing energy demand, rising fossil-fuel prices and climate policy. An important element of the RCP2.6 is the use of bio-energy and CCS, resulting in negative emissions (and allowing some fossil fuel without CCS by the end of the century)". ***(van Vuuren et.al. 2011).***

Atmospheric Air Pollutants

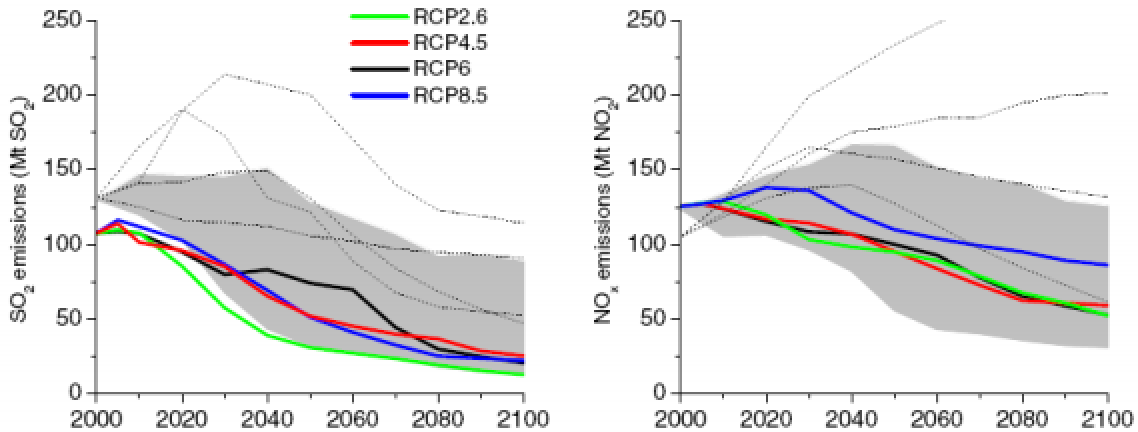


Figure 10: Emissions of SO_2 and NO_x across the RCPs*. Grey area indicates the 90th percentile of the literature (only scenarios included in Van Vuuren et al. 2008b, i.e. 22 scenarios; the scenarios were also harmonized for their starting year—but using a different inventory). Dotted lines indicate SRES scenarios. The different studies use slightly different data for the start year. (van Vuuren et.al. 2011)*

"The RCPs generally exhibit a declining trend of air polluting emissions. The emission trends for air pollutants are determined by three factors: the change in driving forces (fossil- fuel use, fertilizer use), the assumed air pollution control policy, and the assumed climate policy (as the last induces changes in energy consumption leading to changes (generally reductions) in air polluting emissions). We have illustrated the trends in air pollutants by looking at SO2 and NOx (Fig. 10). In general, similar trends can be seen for other air pollutants.

"All RCPs include the assumption that air pollution control becomes more stringent, over time, as a result of rising income levels. Globally, this would cause emissions to decrease, over time—although trends can be different for specific regions or at particular moments in time. A second factor that influences the results across the RCPs is climate policy. In general, the lowest emissions are found for the scenario with the most stringent climate policy (RCP2.6) and the highest for the scenario without climate policy (RCP8.5), although this does not apply to all regions, at all times". ***(van Vuuren et.al. 2011).***

CCS Costs

Part of Sintef's research has involved calculating the costs to global industry of capturing the carbon it produces – US$97 a tonne for coal-fired power stations. This, Sintef says, is far less than the cost to the planet of releasing the carbon into the atmosphere.
https://www.truthdig.com/articles/carbon-capture-could-save-the-planet/

The study, just published in the journal *Nature*, was conducted by researchers from UCLA, the University of Oxford and elsewhere. They found about half a gigaton, on average, of carbon could be captured

from fossil fuel sources and the atmosphere per year that could be used for fuel and other purposes. At peak projections, over 10 gigatons could be captured annually annually. The researchers believe it would cost around $100 per ton. They note that IPCC reports have cited carbon capture as a necessary technology if we're going to avoid the possibly catastrophic effects of climate change.
https://www.inverse.com/article/60819-carbon-capture-profitable-cost-climate

A top-end scenario could see more than 10 gigatonnes of carbon dioxide a year used, at a theoretical cost of under $100 per tonne of carbon dioxide
https://www.sciencedaily.com/releases/2019/11/191107093927.htm