CO2 Emissions Budgets

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http://ccdatacenter.org/documents/CO2EmissionsBudgets.pdf

There are several problems with presenting the IPCC's carbon budget in terms of "there is an XX% chance of meeting the NN° C temperature target if total emissions are less than MM GTC between now and 2100". First of all, even though that is what is almost universally used in discussions of limiting the temperature increase, a more accurate description of the findings is "XX% of the model runs with less than MM GTC emissions resulted in a temperature increase of less than NN° C". So if the models are not accurate (e.g., they do not include natural feedbacks from permafrost, surface waters, etc.) the *anthropogenic* budgets could be way off (and the actual *anthropogenic* budget could be close to zero). And second, there is no discussion (that I am aware of) regarding assumptions about mix of energy generation technologies used (BECCS, CSS, coal, oil, solar, wind, etc.), the non-CO2 radiative forcing, the uptake of CO2 by oceans and the biosphere, and the climate sensitivity implied by the mode results. But I think that the real problem was presenting the results as a "percent chance". In most cases, when we think about climate and the weather, we think of ourselves as "observers". We know that if we change our bad habits that we have a percentage chance of living longer and healthier lives. But when we think of weather forecasts, getting cancer, having a heart attack, being involved in an automobile accident, etc., we basically just go about our daily lives and hope for the best. And most people approach climate change in a similar way - since nothing that we do as individuals directly affects the climate in any measureable way, we sit back and hope the problem will be solved without us individually doing much of anything. (See also Footnote #1)

What I hope the information below (along with additional detail to follow) will do is shed some light on the difficulty of "solving" climate change. It's easy to just "draw a line" to show how much emissions need to be reduced. It is much more difficult to provide a integrated list of "detailed solutions" (along with costs) that are socially and politically acceptable.

The following tables contain CO2 Emissions budget (for both anthropogenic and natural emissions) for temperature increases of 1.5° C and 2.0° C for various climate sensitivities and non-CO2 radiative forcings. Note that N2O and CFCs have combined RFs of .34, .43, and .52 in RCPs 2.0, 4.5, and 6.0 respectively, so getting below a non-CO2 RF of 3 or4 will not be possible unless aerosols (either from coal or solar radiation management) are present in large quantities

CO2 Budget = (278 * e((5.35 * Ln(1 + ET / CS) - NonCO2RF) /5.35) - 342.87)/ 0.2586

	Temp Increase: 1.5															
	Climate Sensititivity															
Non-CO2 RF	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0
0.0	555	482	421	369	325	287	253	223	197	173	152	133	116	100	85	72
0.1	520	449	389	338	294	257	224	195	169	146	125	106	89	73	59	46
0.2	486	416	357	307	264	227	195	167	141	118	98	80	63	47	33	20
0.3	453	383	326	277	235	199	167	139	114	92	72	53	37	22	8	-5
0.4	420	352	295	247	206	170	139	112	87	65	46	28	12	-3	-17	-29
0.5	387	321	265	218	178	143	112	85	61	40	20	3	-13	-28	-41	-53
0.6	356	290	236	189	150	116	86	59	35	14	-5	-22	-37	-52	-65	-77
0.7	325	260	207	161	123	89	59	33	10	-10	-29	-46	-61	-75	-88	-100
0.8	294	231	178	134	96	63	34	8	-14	-35	-53	-70	-85	-98	-111	-122
0.9	264	202	151	107	69	37	9	-16	-39	-59	-77	-93	-108	-121	-133	-145
1.0	235	174	123	80	44	12	-16	-41	-63	-82	-100	-116	-130	-143	-155	-167
1.1	206	146	96	54	18	-13	-40	-65	-86	-105	-122	-138	-152	-165	-177	-188
1.2	177	119	70	29	-7	-37	-64	-88	-109	-128	-145	-160	-174	-187	-198	-209
1.3	150	92	44	4	-31	-61	-88	-111	-131	-150	-167	-182	-195	-208	-219	-230
1.4	122	66	19	-21	-55	-85	-110	-133	-154	-172	-188	-203	-216	-229	-240	-250
	CO2 Budget (Emissoins - GTC)															

	Temp Increase: 2.0															
	Climate Sensititivity															
Non-CO2 RF	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0
0.0	824	726	645	576	517	466	421	381	346	315	287	261	238	216	197	179
0.1	784	688	608	541	483	433	389	350	315	284	257	232	209	188	169	151
0.2	745	651	573	506	449	400	357	319	285	255	227	203	180	160	141	124
0.3	707	614	537	472	416	368	326	288	255	225	199	174	152	132	114	97
0.4	669	578	503	439	384	337	295	258	226	197	170	147	125	105	87	71
0.5	632	543	469	406	353	306	265	229	197	168	143	119	98	79	61	45
0.6	596	509	436	374	321	276	236	200	169	141	116	93	72	53	35	19
0.7	560	475	403	343	291	246	207	172	141	114	89	66	46	27	10	-5
0.8	525	441	371	312	261	217	178	144	114	87	63	41	21	2	-14	-30
0.9	491	409	340	282	232	188	151	117	87	61	37	15	-4	-22	-39	-54
1.0	458	376	309	252	203	160	123	90	61	35	12	-10	-29	-46	-63	-77
1.1	425	345	279	223	174	133	96	64	36	10	-13	-34	-53	-70	-86	-101
1.2	392	314	249	194	147	106	70	38	10	-15	-37	-58	-76	-93	-109	-123
1.3	360	284	220	166	119	79	44	13	-14	-39	-61	-81	-100	-116	-131	-146
1.4	329	254	191	138	93	53	19	-12	-39	-63	-85	-104	-122	-139	-154	-167
	CO2 Budget (Emissoins - GTC)															

- Yellow cells show combinations of CS and NonCO2 RF for roughly a 230 GTC budget (roughly that put forward but the IPCC and National Academy of Sciences[2].
- Orange cells show combinations of CS and NonCO2 RF for roughly a 100 GTC anthropogenic budget
- Green cells show the total CO2 budget for a value of climate sensitivity slightly above that which was demonstrated by the models that best capture current conditions
- Purple cells show the CO2 budget for the non-CO2 radiative forcing for RCP 4.5

The following tables show the GTC over a 230GTC CO2 budget for various combinations of fossil fuel reductions (without BECCS, CCS, or CDR). It basically shows that meeting a 230 GTC CO2 budget requires "massive" BECCS/CCS/CDR, as we'll be lucky to reduce emissions before 2030 and/or reduce emissions more than 1% 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**

	Peak Yr:	2020			2025			2030		
	Pct Chg to Peak Yr:	0	1	2	0	1	2	0	1	2
Annual Pct Change After Peak Yr	0	881	923	966	881	964	1055	881	1005	1146
	-1	632	661	691	659	718	783	684	776	881
	-2	480	501	523	519	564	613	557	628	709
	-3	383	400	417	428	464	502	472	530	595
	-4	320	333	347	367	397	428	414	462	517
		Emissions 2016-2100			Emissions 2016-2100			Emissions 2016-2100		

	Peak Yr:	2020			2025			2030		
	Pct Chg to Peak Yr:	0	1	2	0	1	2	0	1	2
Annual Pct Change After Peak Yr	0	651	693	736	651	734	825	651	775	916
	-1	402	431	461	429	488	553	454	546	651
	-2	250	271	293	289	334	383	327	398	479
	-3	153	170	187	198	234	272	242	300	365
	-4	90	103	117	137	167	198	184	232	287
		GTC Over Budget in 2100			GTC Over Budget in 2100			GTC Over Budget in 2100		

	Peak Yr:	2020			2025			2030		
	Pct Chg to Peak Yr:	0	1	2	0	1	2	0	1	2
Annual Pct Change of Peak Yr After Peak Yr	0	868	910	953	868	951	1041	868	991	1133
	-1	548	574	600	587	655	731	623	734	862
	-2	321	334	349	370	415	466	419	500	601
	-3	238	248	258	288	319	355	337	395	467
	-4	197	205	213	247	272	300	296	342	399
		Emissions 2016-2100			Emissions 2016-2100			Emissions 2016-2100		

	Peak Yr:	2020			2025			2030		
	Pct Chg to Peak Yr:	0	1	2	0	1	2	0	1	2
Annual Pct Change of Peak Yr After Peak Yr	0	638	680	723	638	721	811	638	761	903
	-1	318	344	370	357	425	501	393	504	632
	-2	91	104	119	140	185	236	189	270	371
	-3	8	18	28	58	89	125	107	165	237
	-4	-33	-25	-17	17	42	70	66	112	169

The following tables show the expected equilibrium temperature for specific climate sensitivities (3 and 4) for a range of CO2 emissions and Non-CO2 radiative forcings:

	Climate Sensititivity	3.0														
	CO2 Emissions															
Non-CO2 RF	-50	0	50	100	150	200	250	300	350	400	450	500	550	600	650	700
0.0	0.56	0.70	0.84	0.98	1.12	1.26	1.40	1.54	1.68	1.82	1.96	2.10	2.23	2.37	2.51	2.65
0.1	0.63	0.77	0.91	1.05	1.20	1.34	1.48	1.62	1.76	1.91	2.05	2.19	2.33	2.48	2.62	2.76
0.2	0.70	0.84	0.99	1.13	1.28	1.42	1.57	1.71	1.85	2.00	2.14	2.29	2.43	2.58	2.72	2.87
0.3	0.77	0.91	1.06	1.21	1.36	1.50	1.65	1.80	1.95	2.09	2.24	2.39	2.54	2.68	2.83	2.98
0.4	0.84	0.99	1.14	1.29	1.44	1.59	1.74	1.89	2.04	2.19	2.34	2.49	2.64	2.79	2.94	3.09
0.5	0.91	1.06	1.22	1.37	1.52	1.68	1.83	1.98	2.13	2.29	2.44	2.59	2.75	2.90	3.05	3.21
0.6	0.98	1.14	1.30	1.45	1.61	1.76	1.92	2.08	2.23	2.39	2.54	2.70	2.86	3.01	3.17	3.32
0.7	1.06	1.22	1.38	1.54	1.69	1.85	2.01	2.17	2.33	2.49	2.65	2.81	2.97	3.13	3.28	3.44
0.8	1.13	1.30	1.46	1.62	1.78	1.94	2.11	2.27	2.43	2.59	2.75	2.92	3.08	3.24	3.40	3.56
0.9	1.21	1.38	1.54	1.71	1.87	2.04	2.20	2.37	2.53	2.70	2.86	3.03	3.19	3.36	3.52	3.69
1.0	1.29	1.46	1.63	1.80	1.96	2.13	2.30	2.47	2.64	2.81	2.97	3.14	3.31	3.48	3.65	3.81
1.1	1.37	1.54	1.72	1.89	2.06	2.23	2.40	2.57	2.74	2.92	3.09	3.26	3.43	3.60	3.77	3.94
1.2	1.46	1.63	1.80	1.98	2.15	2.33	2.50	2.68	2.85	3.03	3.20	3.38	3.55	3.73	3.90	4.07
1.3	1.54	1.72	1.90	2.07	2.25	2.43	2.61	2.78	2.96	3.14	3.32	3.50	3.67	3.85	4.03	4.21
1.4	1.63	1.81	1.99	2.17	2.35	2.53	2.71	2.89	3.08	3.26	3.44	3.62	3.80	3.98	4.16	4.34
	Equilibrium Temperature															

	Climate Sensititivity	3.4														
	CO2 Emissions															
Non-CO2 RF	100	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900
0.0	1.11	1.43	1.58	1.74	1.90	2.06	2.22	2.37	2.53	2.69	2.85	3.01	3.16	3.32	3.48	3.64
0.1	1.19	1.52	1.68	1.84	2.00	2.16	2.32	2.48	2.64	2.81	2.97	3.13	3.29	3.45	3.61	3.77
0.2	1.28	1.61	1.77	1.94	2.10	2.27	2.43	2.59	2.76	2.92	3.09	3.25	3.42	3.58	3.74	3.91
0.3	1.37	1.70	1.87	2.04	2.21	2.37	2.54	2.71	2.87	3.04	3.21	3.38	3.54	3.71	3.88	4.05
0.4	1.46	1.80	1.97	2.14	2.31	2.48	2.65	2.82	2.99	3.16	3.33	3.50	3.67	3.84	4.02	4.19
0.5	1.55	1.90	2.07	2.25	2.42	2.59	2.77	2.94	3.11	3.29	3.46	3.63	3.81	3.98	4.16	4.33
0.6	1.64	2.00	2.18	2.35	2.53	2.71	2.88	3.06	3.24	3.41	3.59	3.77	3.94	4.12	4.30	4.47
0.7	1.74	2.10	2.28	2.46	2.64	2.82	3.00	3.18	3.36	3.54	3.72	3.90	4.08	4.26	4.44	4.62
0.8	1.84	2.20	2.39	2.57	2.75	2.94	3.12	3.31	3.49	3.67	3.86	4.04	4.22	4.41	4.59	4.77
0.9	1.94	2.31	2.50	2.68	2.87	3.06	3.25	3.43	3.62	3.81	3.99	4.18	4.37	4.55	4.74	4.93
1.0	2.04	2.42	2.61	2.80	2.99	3.18	3.37	3.56	3.75	3.94	4.13	4.32	4.51	4.70	4.90	5.09
1.1	2.14	2.53	2.72	2.92	3.11	3.30	3.50	3.69	3.89	4.08	4.28	4.47	4.66	4.86	5.05	5.25
1.2	2.24	2.64	2.84	3.03	3.23	3.43	3.63	3.83	4.02	4.22	4.42	4.62	4.82	5.01	5.21	5.41
1.3	2.35	2.75	2.95	3.16	3.36	3.56	3.76	3.96	4.16	4.37	4.57	4.77	4.97	5.17	5.37	5.58
1.4	2.46	2.87	3.07	3.28	3.49	3.69	3.90	4.10	4.31	4.51	4.72	4.92	5.13	5.33	5.54	5.74
	Equilibrium Temperature															

		Climate Sensitivity	4.0														
		CO2 Emissions															
		100	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900
Non-CO2 RF	0.0	1.31	1.68	1.86	2.05	2.24	2.42	2.61	2.79	2.98	3.17	3.35	3.54	3.72	3.91	4.10	4.28
	0.1	1.41	1.78	1.97	2.16	2.35	2.54	2.73	2.92	3.11	3.30	3.49	3.68	3.87	4.06	4.25	4.44
	0.2	1.51	1.89	2.09	2.28	2.47	2.67	2.86	3.05	3.25	3.44	3.63	3.82	4.02	4.21	4.40	4.60
	0.3	1.61	2.00	2.20	2.40	2.59	2.79	2.99	3.19	3.38	3.58	3.78	3.97	4.17	4.37	4.56	4.76
	0.4	1.72	2.12	2.32	2.52	2.72	2.92	3.12	3.32	3.52	3.72	3.92	4.12	4.32	4.52	4.72	4.92
	0.5	1.82	2.23	2.44	2.64	2.85	3.05	3.25	3.46	3.66	3.87	4.07	4.28	4.48	4.68	4.89	5.09
	0.6	1.93	2.35	2.56	2.77	2.98	3.18	3.39	3.60	3.81	4.02	4.22	4.43	4.64	4.85	5.06	5.26
	0.7	2.05	2.47	2.68	2.89	3.11	3.32	3.53	3.74	3.95	4.17	4.38	4.59	4.80	5.02	5.23	5.44
	0.8	2.16	2.59	2.81	3.02	3.24	3.46	3.67	3.89	4.11	4.32	4.54	4.75	4.97	5.19	5.40	5.62
	0.9	2.28	2.72	2.94	3.16	3.38	3.60	3.82	4.04	4.26	4.48	4.70	4.92	5.14	5.36	5.58	5.80
	1.0	2.40	2.84	3.07	3.29	3.52	3.74	3.97	4.19	4.41	4.64	4.86	5.09	5.31	5.53	5.76	5.98
	1.1	2.52	2.97	3.20	3.43	3.66	3.89	4.12	4.34	4.57	4.80	5.03	5.26	5.49	5.71	5.94	6.17
	1.2	2.64	3.10	3.34	3.57	3.80	4.04	4.27	4.50	4.73	4.97	5.20	5.43	5.67	5.90	6.13	6.36
	1.3	2.76	3.24	3.48	3.71	3.95	4.19	4.42	4.66	4.90	5.14	5.37	5.61	5.85	6.08	6.32	6.56
	1.4	2.89	3.38	3.62	3.86	4.10	4.34	4.58	4.83	5.07	5.31	5.55	5.79	6.03	6.28	6.52	6.76
		Equilibrium Temperature															

Note that for CS=3, NonCO2RF=0.8, CO2 emissions of 525 GTC result in an equilibrium temperature of about 3°C and for CS=3.4, NonCO2RF=0.8, CO2 emissions of 420 GTC result in an equilibrium temperature of about 3°C. Since natural emissions are apt to be at least 100 GTC[1,2] (for a temperature increase less than 2°C), it seems logical to assume that a climate sensitivity of 3 where natural emissions are included is equivalent to a climate sensitivity of 3.5 where natural emissions are not included (and the "equivalence" is apt to be wider for higher temperatures)

1 From **What Lies Beneath** (download PDF from https://www.breakthroughonline.org.au/) (Page 24)

A carbon budget is an estimate of the total future human-caused greenhouse gas emissions, in tons of carbon, CO_2 or CO_2 equivalent, that would be consistent with limiting warming to a specified figure, such as 1.5°C or 2°C, with a given risk of exceeding the target, such as a 50%, 33% or 10% chance.

The discussion of carbon budgets is frequently opaque. Often, it is difficult to ascertain whether the assumptions are realistic, for example whether a budget includes non-CO_2 forcings such as methane and nitrous oxide. Too often, the risk of failure is not clearly spelt out, especially the fat-tail risks. Contrary to the tone of the IPCC reports, the evidence shows we have no carbon budget for 2°C for a sensible risk-management, low-probability (of a 10%, or one-in-ten) chance of exceeding that target. The IPCC reports fail to say there is no carbon budget if 2°C is considered a cap (an upper boundary not to be exceeded) as per the *Copenhagen Accord*, rather than a target (an aspiration which can be significantly exceeded). The IPCC reports fail to say that once projected emissions from future food production and deforestation are taken into account, there is no carbon budget for fossil-fuel emissions for a 2°C target.[71]

Carbon budgets are routinely proposed that have a substantial and unacceptable risk of exceeding specified targets and hence entail large and unmanageable risks of failure.

Research published in December 2017 compared “raw” climate models (used by the IPCC) with models that are “observationally informed” and best capture current conditions. The latter produce 15% more warming by 2100 than the IPCC suggests, thus reducing the carbon budget by around 15% for the 2°C target. Hence, as one example, the actual warming for the RCP4.5 emissions path is in reality likely to be higher, similar to that projected by raw models for RCP6.0.[72] (RCPs are representative concentration pathways of greenhouse gas emission trajectories. RCP2.6 is the

	lowest and RCP8.5 is the highest.) This is consistent with findings five years earlier that climate model projections which show a greater rise in global temperature are likely to prove more accurate than those showing a lesser rise.[73] As well, the IPCC uses a definition of global mean surface temperature that underestimates the amount of warming over the pre-industrial level. When estimates for the effect of calculating (1) warming for total global coverage rather than for the coverage for which observations are available, (2) warming using surface air temperature measurements (SATs) over the entire globe instead of the observational blend of sea surface temperatures (SSTs) and SATs, and (3) warming from a pre-industrial, instead of a late-nineteenth century baseline, are taken into account, the underestimation is around 0.3°C. This results in a significant overestimation of allowable emissions.[74] For example, for stabilization at 2°C, allowable emissions decrease by as much as 40% when earlier than nineteenth-century climates are considered as a baseline.[75] There are also problems with carbon budgets which incorporate "overshoot" scenarios, in which warming exceeds the target before being cooled by carbon drawdown. Pam Pearson, Director of the International Cryosphere Climate Initiative, says that most cryosphere thresholds are determined by peak temperature, and the length of time spent at that peak, warning that "later, decreasing temperatures after the peak are largely irrelevant, especially with higher temperatures and longer duration peaks". Thus "overshoot scenarios", which are now becoming the norm in policymaking circles, hold much greater risks.[76]
2	NAS post 2015 Budget = 236 GTC — https://science2017.globalchange.gov/downloads/CSSR_Ch14_Mitigation.pdf IPCC post 2015 Budget = 220 GTC — https://docs.google.com/spreadsheets/d/1odltJu_rxabdVXv_pACMBNIRiFSkc_HqJn-V8z0av2w/edit#gid=731498129
	• Recently it has been demonstrated the models that best capture current conditions have a mean value of 3.7°C compared to 3.1°C by the raw model projections[3] (See http://ccdatacenter.org/documents/ClimateSensitivityExpectations.pdf for footnotes for the above)
3	Permafrost and wetland emissions could cut 1.5C carbon budget 'by five years' That means accounting for the impacts of permafrost and wetlands takes around five years off the 1.5C budget. And, as the table below shows, the budgets for the 1.5C overshoot and 2C scenarios are similarly reduced.

	Control		**Feedbacks included**	
	Tonne of CO2	Years of emissions	Tonne of CO2	Years of emissions
1.5C	720-929bn	20-25	533-753bn	14-20
1.5C overshoot	723-947bn	20-26	522-771bn	14-21
2C	1592-1974bn	43-54	1372-1776bn	37-48

Table shows remaining carbon budget (from 2018 to 2100) for three temperature pathways for the "control" (left) and "feedbacks included" (right) scenarios. Carbon budgets are shown as tonnes of CO2 and as total years of emissions (based on 2017 global emissions). Table adapted from Comyn-Platt et al. (2018)

Note: Including feedbacks for permafrost and wetlands decreases the budgets by about 200 GTCO2. Since there are other feedbacks (peat, soils, surface waters, etc., the total contribution from natural feedbacks is likely closer to 300-400 GTCO2 (perhaps 100 GTC??).

https://www.carbonbrief.org/permafrost-wetland-emissions-could-cut-1-5c-carbon-budget-five-years

4 **Study reveals what natural greenhouse emissions from wetlands and permafrosts mean for Paris Agreement targets**

July 9, 2018 by Simon Williams, Centre for Ecology & Hydrology

Global fossil fuel emissions would have to be reduced by as much as 20% more than previous estimates to achieve the Paris Agreement targets, because of natural greenhouse gas emissions from wetlands and permafrost, new research has found.

The additional reductions are equivalent to 5-6 years of carbon emissions from human activities at current rates, according to a new paper led by the UK's Centre for Ecology & Hydrology.

The 2015 Paris Climate Agreement aims to keep "the global average temperature increase to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels".

The research, published in the journal Nature Geoscience today (July 9, 2018) uses a novel form of climate model where a specified temperature target is used to calculate the compatible fossil fuel emissions.

The model simulations estimate the natural wetland and permafrost response to climate change, including their greenhouse gas emissions, and the implications for human fossil-fuel emissions.

Co-author Dr. Sarah Chadburn, of the University of Leeds, said: "We found that permafrost and methane emissions get more and more important as we consider lower global warming targets.

"These feedbacks could make it much harder to achieve the target, and our results reinforce the urgency in reducing fossil fuel burning."

Co-author Prof Chris Huntingford, of the Centre for Ecology & Hydrology, said: "We were surprised at how large these permafrost and wetland feedbacks can be for the low warming target of just 1.5°C."

https://phys.org/news/2018-07-reveals-natural-greenhouse-emissions-wetlands.html