Supplementary Information:

A framework to estimate and track remaining carbon budgets for stringent climate targets

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Supplementary Text 1: Extending beyond peak warming

The framework proposed in the main text is designed to transparently estimate the remaining carbon budget until peak warming. Extending the framework to also apply to remaining carbon budgets in line with returning to a specific level of global temperature increase after having temporarily exceeded it ($RB_{lim,postOS}$), referred to as an overshoot (OS, see also Threshold Return Budgets in Box 1 of the main text), would require several additional uncertainties to be assessed. This includes, the symmetry of TCRE under net positive ($TCRE$) and negative ($TCRE_{neg}$) fluxes of carbon (e.g. ref. 1), the non-linearity in Earth system response feedbacks and hysteresis[2] ($E_{ESfb,withOS}$), and the evolution of non-CO_2 warming until temperature is returned to the intended level of global warming[3-5], represented by SI Equation 1.

$$RB_{lim,postOS} = \left(T_{zeroCO_2} - T_{hist} - T_{nCO_2} - T_{ZEC}\right) \times TCRE^{-1} + \left(T_{lim,postOS} - T_{zeroCO_2} + T_{nCO_2} - T_{nCO_2,postOS} + T_{ZEC} - T_{ZEC,neg}\right) \times TCRE_{neg}{}^{-1} - E_{ESfb,withOS} \qquad \text{SI Eq. (1)}$$

In addition to the terms defined earlier, T_{zeroCO_2} here represents the human-induced temperature increase reached during the temporary overshoot, $T_{lim,postOS}$ the limit to which human-induced temperature increase is ultimately kept after overshoot, $T_{nCO_2,postOS}$ the non-CO_2 warming contribution at the time of returning total human-induced warming to the desired limit, and $T_{ZEC,neg}$ the zero emission commitment adjustment due to potential time lags in cooling as a result of net removal of CO_2 from the atmosphere. In general, the terms involved in defining the remaining carbon budget for limiting warming to a specific temperature threshold after an overshoot are less precisely defined as for the remaining carbon budget until net zero CO_2 emissions and hence peak warming. When looking at the bigger picture, uncertainties and sustainability concerns related to the technical achievement of CO_2 removal at a global scale are probably much larger at present.

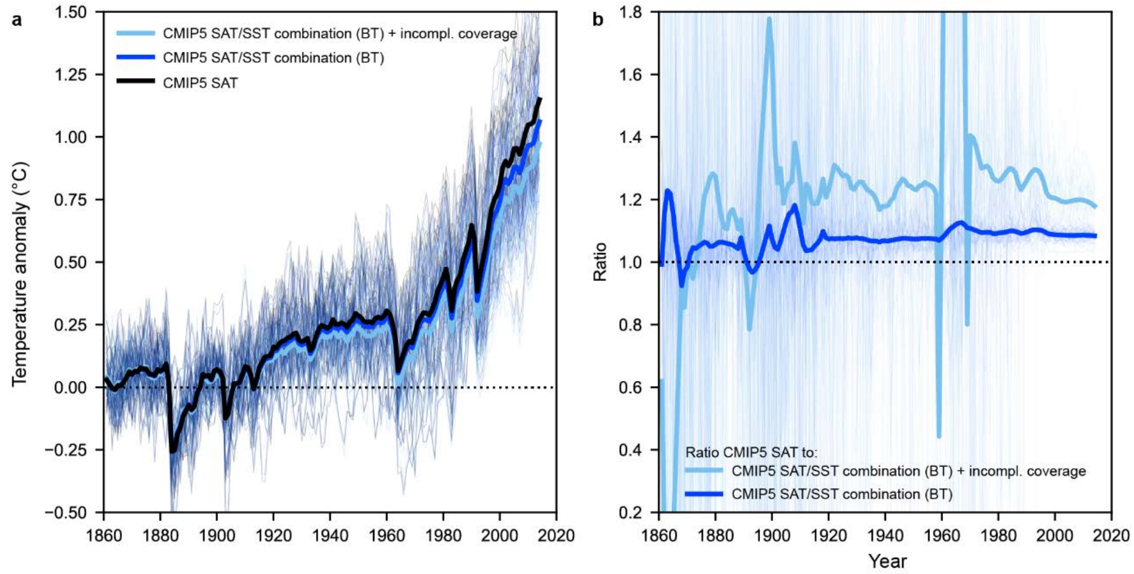
Supplementary Text 2: Issues surrounding definitions of T_{lim} and T_{hist}

The 1850–1900 period is often used as a proxy for preindustrial levels, because it benefits from the availability of historical observational temperature records, stretching back to the beginning of that period[6]. The period has also been used by the IPCC in the reports that fed into the international climate policy process over the 2013–2015 period, leading up to the Paris Agreement[7,8]. Using the 1850–1900 period also has drawbacks. For example, the period includes a large volcanic eruption, the 1883 eruption of Mount Krakatoa in Indonesia, and this eruption is estimated to have lowered the average temperature in that period[9,10]. Furthermore, earlier time periods, like the mid-1700s, have been suggested as better proxies for preindustrial conditions[11-13]. While true from a historical point of view, data limitations make estimating temperature rise since time periods before the early 19th century more challenging[11-13].

The next aspect determining the remaining allowable warming is the choice of metric by which global average temperature change is estimated. An important difference exists in how global average temperature is defined in studies analysing climate model simulations and in observational products. Climate model output is often expressed as the globally area-averaged change in surface air temperature (SAT) to estimate global average temperature increase; that is, the temperature at about 1.5m above the Earth's surface. Observational products, however, have to rely on the set of actual measurements available. They hence use a combination of SATs (as measured in a typical weather station) over land and sea-ice regions, and sea surface temperatures (SSTs, the temperature in the ocean's top layer as measured by ships) over open ocean[6]. SSTs generally warm slightly slower than SATs. Moreover, observations are not covering the globe homogeneously, and are notably absent in areas near the poles. Different observational products deal differently with this incomplete coverage[14,15]. Recent studies[16,17] estimate that the combined effect of using a mix of SSTs and SATs, and the limited observational coverage can result in an estimate of global average temperature rise to date that is more than 10% lower than if estimated from SATs covering the entire globe (Supplementary Figure 1).

Supplementary Text 3: reporting check-list of factors affecting remaining carbon budget estimates

- ☐ Type of budget estimated, or new definition of remaining carbon budget (see Box 1, including whether the estimate is for CO_2 only or takes into account all forcers)
- ☐ Estimate of historical warming to date as used by remaining carbon budget estimate (implicitly or explicitly)
- ☐ Value or distribution of TCRE used in the estimate (implicitly or explicitly)
- ☐ Surface temperature measure used (we recommend using globally averaged surface air temperatures – see main text and Supplementary Text 2)
- ☐ Starting date for remaining carbon budget estimate
- ☐ How underrepresented Earth-system feedbacks are included in the estimate (in TCRE or otherwise)
- ☐ Estimate of non-CO_2 contribution to future warming, including assumptions surrounding forcings and climate response
- ☐ Method or tool that was used to derive estimate (EMIC, ESM, observations, analytical framework, …)



Supplementary Figure 1 | Time evolution and ratio between various global average temperature metrics. **a**, evolution of global average temperature over time based on the historical simulations of the fifth phase of the coupled model intercomparison project[18] (CMIP5). Thin lines show single model projections, thick lines the multi-model mean. Three temperature metrics are shown relative to the 1861-1900 period: global coverage of surface air temperatures (SAT), a blended metric (BT) combining SAT over land and sea surface temperatures over water (SAT/SST combination), and a metric using the same temperature fields but assuming the same incomplete coverage as observational measurements[6]. Data from ref. [19]; **b**, ratio between global SAT temperature and temperatures estimated with the two other metrics shown in panel **a.** Ratios in panel **b** are calculated from time series smoothed with an 11-year 3rd order Savitzky-Golay smoothing filter[20] applied to the multi-model mean time series.

Supplementary Table 1 | Interpretation of literature estimates in the context of the remaining carbon budget framework. Mapping of assumptions made by a selection of studies in their approaches to estimate remaining carbon budgets in line with stringent mitigation targets onto the various terms defining the remaining carbon budget framework proposed in this paper. SAT: global average near-surface air temperatures; BT: blended temperature metric using a mix of SAT over land and sea-ice regions and sea-surface temperatures (SST) over open ocean; ESM: Earth system model; EMIC: Earth system model of intermediate complexity; RCP: representative concentration pathway; AR5: Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC); SR15: IPCC Special Report on Global Warming of 1.5°C; CMIP5: Phase 5 of the coupled model intercomparison project. Estimates are listed in the same order as shown in Figure 3 in the main paper.

		Historical human-induced warming	**Future non-CO_2 contribution to global temperature rise**	**Zero emissions commitment**	**Transient climate response to cumulative emissions of CO_2**	**Unrepresented Earth system feedbacks**	**Temperature limit metric**
#	**Symbol**	T_{hist}	T_{nCO_2}	T_{ZEC}	$TCRE$	E_{ESfb}	T_{lim}
1	**IPCC SR1.5 (2018)[5]**	0.97°C in SAT until 2015 relative to 1850-1900	Explicitly estimated from pathways reaching net zero CO_2 emissions[3-5]	Assumed to be negligibly small	Assessed IPCC uncertainty range of 0.8-2.5°C/1000PgC, with a normal distribution	Not explicitly taken into account	SAT
2	**IPCC SR1.5 (2018)[5]**	0.97°C in SAT until 2015 relative to 1850-1900	Explicitly estimated from pathways reaching net zero CO_2 emissions[3-5]	Assumed to be negligibly small	Assessed IPCC uncertainty range of 0.8-2.5°C/1000PgC, with a normal uncertainty distribution	Assessed to reduce carbon budgets by 100 $GtCO_2$ until 2100, and more thereafter	SAT
3	**IPCC SR1.5 (2018)[5]**	0.87°C in BT until 2015 relative to 1850-1900	Explicitly estimated from pathways reaching net zero CO_2 emissions[3-5]	Assumed to be negligibly small	Assessed IPCC uncertainty range of 0.8-2.5°C/1000PgC, with a normal uncertainty distribution	Not explicitly taken into account	BT for historical warming and SAT for projections
4	**IPCC SR1.5 (2018)[5]**	0.87°C in BT until 2015 relative to 1850-1900	Explicitly estimated from pathways reaching net zero CO_2 emissions[3-5]	Assumed to be negligibly small	Assessed IPCC uncertainty range of 0.8-2.5°C/1000PgC, with a normal uncertainty distribution	Assessed to reduce remaining carbon budgets by 100 $GtCO_2$ until 2100, and more thereafter	BT for historical warming and SAT for projections
5	**Tokarska and Gillett (2018)[21]**	0.89 °C in BT for 2006-2015 relative to the 1861-1880 period	Implicit, based on modelled warming by 16 ESMs for RCP4.5 and RCP8.5[13,22]	Implicitly assumed to be zero	Implicit distribution from 16 ESMs, some with multiple ensemble members, in some case constrained by historical CO_2 estimates	Discussed, but not explicitly taken into account	BT for historical warming and SAT for projections
6	**Friedlingstein et al. (2014)[23]**	0.61°C in BT for 1986-2005 relative to 1850-1900 period	Explicitly estimated from integrated pathways at time of exceeding 1.5°C of warming in weak mitigation scenarios[24]	Assumed to be zero	Implicit from observationally constrained scenario setup consistent with AR5 climate sensitivity assessment	Not explicitly taken into account	BT for historical warming and SAT for projections
7	**Millar et al (2017)[25]**	About 0.9°C in BT from the mid-nineteenth century to the present decade	Implicit, based on modelled warming by 15 ESMs and 5 EMICs for RCP8.5[13,22]	Implicitly assumed to be zero	Implicit distribution from 15 ESMs and 5 EMICs	Not explicitly taken into account	BT for historical warming and SAT for projections
8	**Goodwin et al (2018)[26]**	90% within +- 0.05°C range of BT from observed HadCRUT4[6] 2007-2016 rel. to 1850-1900	Implicit, based on arbitrary distribution of non-CO_2 forcing across the four RCPs at time of crossing 1.5°C[13]	Implicitly assumed to be zero	Implicit distribution based on explicit uncertainty assessment of nine earth system properties	Not explicitly taken into account	BT due to observational constraints of earth system properties based on BT
9	**IPCC AR5 (2014)[27]**	1.1°C by 2011 in SAT, based implicitly on projections in 15 ESMs and 5 EMICs.	Implicit, based on modelled warming in RCP8.5[13,22]	Assumed to be zero	Implicit distribution from 15 ESMs and 5 EMICs	Not explicitly taken into account	SAT

		Historical human-induced warming	**Future non-CO_2 contribution to global temperature rise**	**Zero emissions commitment**	**Transient climate response to cumulative emissions of CO_2**	**Unrepresented Earth system feedbacks**	**Temperature limit metric**
#	**Symbol**	T_{hist}	T_{nCO_2}	T_{ZEC}	$TCRE$	E_{ESfb}	T_{lim}
10	**Mengis et al (2018)[28]**	Estimates start from preindustrial levels	Explicit, based on modelled warming from RCP2.6 non-CO_2 greenhouse gas and spatial aerosol emissions	Implicitly by diagnosing emissions for stabilizing global warming at 1.5°C	Implicit from observationally constrained perturbed parameter ensemble with variations in land and ocean carbon uptake	Not explicitly taken into account	Consistent with BT for historical warming
--	**Mengis et al (2018)[28] (not shown)**	Estimates start from preindustrial levels	Explicit, based on modelled warming from RCP2.6 non-CO2 greenhouse gas and spatial aerosol emissions until 2200	Implicitly by diagnosing emissions for stabilizing global warming at 1.5°C	Implicit from observationally constrained perturbed parameter ensemble with variations in land and ocean carbon uptake	Not explicitly taken into account	Consistent with BT for historical warming
11	**Matthews et al (2018)[29]**	Estimates start from preindustrial levels	Implicit: ratio of non-CO_2 to CO_2 forcing assumed to remain constant, with potential changes highlighted	Assumed to be negligibly small	Inferred from total warming in CMIP5 models (1.86°C/1000PgC)	Not explicitly taken into account	SAT
12	**Matthews et al (2018)[29]**	Estimates start from preindustrial levels	Implicit ratio of non-CO_2 to CO_2 forcing assumed to remain constant, with potential changes highlighted	Assumed to be negligibly small	Inferred from observations (1.78°C/1000PgC)	Not explicitly taken into account	BT
13	**Gasser et al (2018)[30]**	Estimates start from preindustrial, with warming based implicitly on CMIP5 models due to tuning	Implicit, based on modelled warming across the four RCPs	Assumed to be zero	No distribution assumed, but variation due to four permafrost emulations	Permafrost explicitly not accounted by switching off permafrost modules	Not explicitly reported. Assumed to be SAT due to tuning to a selection of CMIP5 models
14	**Gasser et al (2018)[30]**	Estimates start from preindustrial, with warming based implicitly on CMIP5 models due to tuning	Implicit, based on modelled warming across the four RCPs	Assumed to be zero	No distribution assumed, but variation due to four permafrost emulations	Permafrost explicitly accounted for by emulation of four permafrost models	Not explicitly reported. Assumed to be SAT due to tuning to a selection of CMIP5 models
15	**IPCC AR5 (2014)[27]**	0.61°C in BT for 1986-2005 relative to 1850-1900 period	Explicitly estimated from integrated pathways at their time of peak warming[24]	Assumed to be zero	Implicit from observationally constrained setup consistent with AR5 climate sensitivity assessment	Not explicitly taken into account	BT for historical warming and SAT for projections, but imprecise target T level
16	**Rogelj et al (2018)[31]**	0.61°C in BT for 1986-2005 relative to 1850-1900 period	Explicitly estimated from pathways at their time of reaching 1.9 W/m^2 of total anthropogenic radiative forcing	Implicitly assumed to be zero	Implicit from observationally constrained scenario setup consistent with AR5 climate sensitivity assessment	Not explicitly taken into account	varying levels of warming consistent with 1.9 W/m2 forcing in 2100, BT for historical warming and SAT for projections

Supplementary Table 2 | Comparison of literature estimates of remaining carbon budgets. Remaining carbon budgets reported for limiting warming to 1.5°C or 2°C with 50 and 66% probability. Note that in some cases, studies do not formally represent the uncertainty in TCRE and rather report a frequency distribution of models instead (see main text). Estimates are listed in the same order as shown in Figure 3 in the main paper and the same order as in Supplementary Table 1.

#	Source	Remaining carbon budget method	Reported values for 50% chance of limiting warming to 1.5°C (or best estimate)	Expressed relative to the start of 2018 in GtCO$_2$	Reported values for 50% chance of limiting warming to 2°C (or best estimate)	Expressed relative to the start of 2018 in GtCO$_2$
1	**IPCC SR1.5 (2018)[5] SAT**	TCRE-based	580 GtCO$_2$ from 2018 onwards	580	1500 GtCO$_2$ from 2018 onwards	1500
2	**IPCC SR1.5 (2018)[5] SAT with add. Earth system feedback**	TCRE-based	480 GtCO$_2$ from 2018 onwards	480	1400 GtCO$_2$ from 2018 onwards	1400
3	**IPCC SR1.5 (2018)[5] BT**	TCRE-based	770 GtCO$_2$ from 2018 onwards	770	1690 GtCO$_2$ from 2018 onwards	1690
4	**IPCC SR1.5 (2018)[5] BT with add. Earth system feedback**	TCRE-based	670 GtCO$_2$ from 2018 onwards	670	1590 GtCO$_2$ from 2018 onwards	1590
5	**Tokarska and Gillett (2018)[21]**	TEB	208 GtC from 2016	761	N/A	N/A
6	**Friedlingstein et al. (2014)[23]**	TEB	735 (545,950; range across scenarios) GtCO$_2$ from 2015 (own calculations based on same method)	653 (463,868)	1500 (1100,1900; range across scenarios) GtCO$_2$ from 2015	1418 (1018,1818)
7	**Millar et al (2017)[25]**	TEB	about 223 GtC from 2016 onward	735	about 416 GtC from 2016 onward	1441
8	**Goodwin et al (2018)[26]**	TEB	215 to 225 PgC from 2017 onwards	746 to 783	425 to 440 PgC from 2017 onwards	1515 to 1570
9	**IPCC AR5 (2013-2014)[27]**	TEB	550 GtCO$_2$ from 2011	265	1300 GtCO$_2$ from 2011	1015
10	**Mengis et al (2018)[28]**	Peak temperature (year 2055)	699 PgC (641 to 758 PgC; 95%) from preindustrial (570 PgC est. until 2015)	349 (137 to 565)	N/A	N/A
--	**Mengis et al (2018)[28] (not shown)**	Peak temperature sustained until 2200	625 PgC (565 to 622 PgC; 95%) from preindustrial (570 PgC est. until 2015)	201 (-18 to 190)	N/A	N/A
11	**Matthews et al (2018)[29]**	TCRE-based	2950 GtCO$_2$ since preindustrial (best estimate)	750	3940 GtCO$_2$ since preindustrial (best estimate)	1740
12	**Matthews et al (2018)[29]**	TCRE-based	3100 GtCO$_2$ since preindustrial (best estimate)	900	4125 GtCO$_2$ since preindustrial	1925
13	**Gasser et al (2018)[30]**	TEB	2290 to 2350 GtCO$_2$ from preindustrial (with 2240 GtCO$_2$ until 2017)	50 to 110	3110 to 3240 GtCO$_2$ from preindustrial (with 2240 GtCO$_2$ until 2017)	870 to 1000
14	**Gasser et al (2018)[30]**	TEB (with permafrost)	2210 to 2350 GtCO$_2$ from preindustrial	-30 to 110	2980 to 3230 GtCO$_2$ from preindustrial	740 to 990
15	**IPCC AR5 (2013-2014)[27]**	TAB (peak)	550 to 600 GtCO$_2$ from 2011	265 to 315	1150 to 1400 GtCO$_2$ from 2011	865 to 1115
16	**Rogelj et al (2018)[31] (value in next table shown in Fig. 3)**	Cum. CO$_2$ until 2100 (Threshold return budget)	N/A	N/A	N/A	N/A

Supplementary Table 2 – continued, for 66% probability

#	Source	Remaining carbon budget method	Reported values for 66% chance of limiting warming to 1.5°C	Expressed relative to the start of 2018 in $GtCO_2$	Reported values for 66% chance of limiting warming to 2°C	Expressed relative to the start of 2018 in $GtCO_2$
1	**IPCC SR1.5 (2018)[5] SAT**	TCRE-based	420 $GtCO_2$ from 2018 onwards	420	1170 $GtCO_2$ from 2018 onwards	1170
2	**IPCC SR1.5 (2018)[5] SAT with add. Earth system feedback**	TCRE-based	320 $GtCO_2$ from 2018 onwards	320	1070 $GtCO_2$ from 2018 onwards	1070
3	**IPCC SR1.5 (2018)[5] BT**	TCRE-based	570 $GtCO_2$ from 2018 onwards	570	1320 $GtCO_2$ from 2018 onwards	1320
4	**IPCC SR1.5 (2018)[5] BT with add. Earth system feedback**	TCRE-based	470 $GtCO_2$ from 2018 onwards	470	1220 $GtCO_2$ from 2018 onwards	1220
5	**Tokarska and Gillett (2018)[21]**	TEB	130 GtC from 2016	394	N/A	N/A
6	**Friedlingstein et al. (2014)[23]**	TEB	610 (425,820; range across scenarios) $GtCO_2$ from 2015 (own calculations based on same method)	528 (343,738)	1200 (900,1600; range across scenarios) $GtCO_2$ from 2015	1118 (818,1518)
7	**Millar et al (2017)[25]**	TEB	about 200 GtC from 2016 onward	650	about 395 GtC from 2016 onward	1364
8	**Goodwin et al (2018)[26]**	TEB	195 to 205 PgC from 2017 onwards	673 to 710	395 to 410 PgC from 2017 onwards	1405 to 1460
9	**IPCC AR5 (2013-2014)[27]**	TEB	400 $GtCO_2$ from 2011	115	1000 $GtCO_2$ from 2011	715
10	**Mengis et al (2018)[28]**	Peak temperature (year 2055)	N/A	N/A	N/A	N/A
--	**Mengis et al (2018)[28] (not shown)**	Peak temperature sustained until 2200	N/A	N/A	N/A	N/A
11	**Matthews et al (2018)[29]**	TCRE-based	N/A	N/A	N/A	N/A
12	**Matthews et al (2018)[29]**	TCRE-based	N/A	N/A	N/A	N/A
13	**Gasser et al (2018)[30]**	TEB	N/A	N/A	N/A	N/A
14	**Gasser et al (2018)[30]**	TEB (with permafrost)	N/A	N/A	N/A	N/A
15	**IPCC AR5 (2013-2014)[27]**	TAB (peak)	N/A	N/A	750 to 1400 $GtCO_2$ from 2011	465 to 1115
16	**Rogelj et al (2018)[31]**	Cum. CO_2 until 2100 (Threshold return budget)	-175 to 475 $GtCO_2$ from 2016 onward	-257 to 393	N/A	N/A

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