Transient Climate Response to cumulative Emissions (TCRE) of CO2 only (no other GHGs)

The total amount of anthropogenic *CO2* released in the atmosphere since pre-industrial (often termed cumulative carbon emission, although it applies *only to CO2* emissions) is a good indicator of the atmospheric CO2 concentration and hence of the global warming response. The ratio of GMST [Global Mean Surface Temperature] change to total cumulative anthropogenic CO2 emissions is relatively constant over time and independent of the scenario.

This near-linear relationship between *total CO2 emissions* and global temperature change makes it possible to define a new quantity, the transient climate response to cumulative carbon emission (TCRE), as the transient GMST change for a given amount of *cumulated anthropogenic CO2 emissions*, usually 1000 GtC (TFE.8, Figure 1).

TCRE is model dependent, as it is a function of the cumulative CO2 airborne fraction and the transient climate response, both quantities varying significantly across models.

Taking into account the available information from multiple lines of evidence (observations, models and process understanding), the near linear relationship between cumulative CO2 emissions and peak global mean temperature is well established in the literature and robust for cumulative total CO2 emissions up to about 2000 GtC. It is consistent with the relationship inferred from past cumulative CO2 emissions and observed warming, is supported by process understanding of the carbon cycle and global energy balance, and emerges as a robust result from the entire hierarchy of models.

Expert judgment based on the available evidence suggests that TCRE is likely between 0.8°C and 2.5°C per 1000 GtC, for cumulative emissions less than about 2000 GtC until the time at which temperature peaks (TFE.8, Figure 1a). {6.4.3, 12.5.4; Box 12.2}

CO2-induced warming is projected to remain approximately constant for many centuries following a complete cessation of emissions. A large fraction of climate change is thus irreversible on a human time scale, except if net anthropogenic CO2 emissions were strongly negative over a sustained period.

Based on the assessment of TCRE

- (assuming a normal distribution with a **±1 standard deviation range of 0.8 to 2.5°C per 1000 GtC**),
- limiting the warming caused by anthropogenic CO2 emissions alone (i.e., ignoring other radiative forcings) to **less than 2°C** since the period 1861–1880
- with a probability of **>33%, >50% and >66%**, total CO2 emissions from all anthropogenic sources would need to be below a cumulative budget of about **1570 GtC, 1210 GtC and 1000 GtC since 1870**, respectively.
- An amount of **515 [445 to 585] GtC was emitted between 1870 and 2011** (TFE.8, Figure 1a,b).

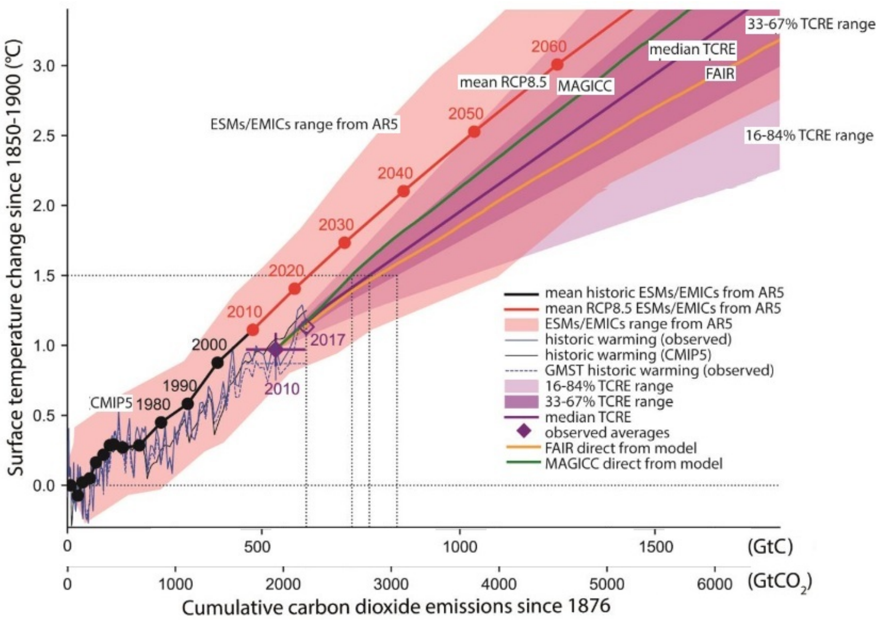
Source: pages 102 - 104, Thematic Focus Elements TFE.8 "Climate Targets and Stabilizaion", Technical Summary, CLIMATE CHANGE 2013, The Physical Science Basis, IPCC (WGI_AR5_all_final.pdf)

IPCC SR15
Special Report
Global Warming of 1.5 ºC

An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

.

Chapter 2: *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development*
Chapter 1 is locally here
page 105



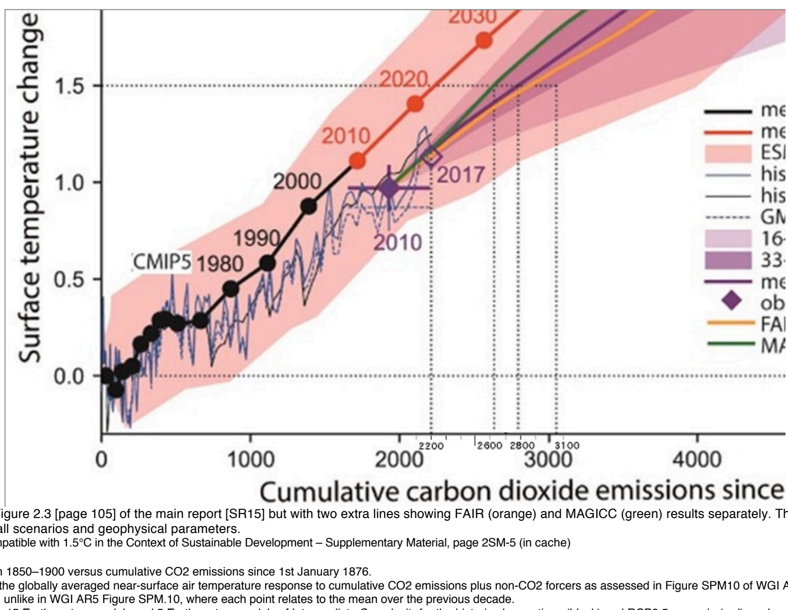


Figure 2.SM.3: This figure follows Figure 2.3 [page 105] of the main report [SR15] but with two extra lines showing FAIR (orange) and MAGICC (green) results separately. These additional lines show the full model response averaged across all scenarios and geophysical parameters.
Source: 2.SM Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development – Supplementary Material, page 2SM-5 (in cache)

Figure 2.3 | Temperature changes from 1850–1900 versus cumulative CO2 emissions since 1st January 1876.

- Solid lines with dots reproduce the globally averaged near-surface air temperature response to cumulative CO2 emissions plus non-CO2 forcers as assessed in Figure SPM10 of WGI AR5, except that points marked with years relate to a particular year, unlike in WGI AR5 Figure SPM.10, where each point relates to the mean over the previous decade.
- The AR5 data was derived from *15 Earth system models and 5 Earth system models of Intermediate Complexity* for the historic observations (black) and RCP8.5 scenario (red), and

- the red shaded plume shows the range across the[se] models as presented in the AR5.
- The purple shaded plume and the line are indicative of the temperature response to cumulative CO2 emissions and non-CO2 warming adopted in this report.
- The non-CO2 warming contribution is averaged from the MAGICC and FAIR models, and the purple shaded range assumes the AR5 WGI TCRE distribution (Supplementary Material 2.SM.1.1.2).
- The *2010* observation of surface temperature change (0.97°C based on 2006–2015 mean compared to 1850–1900, Chapter 1, Section 1.2.1) and cumulative carbon dioxide emissions from 1876 to the end of 2010 of 1,930 GtCO2 (Le Quéré et al., 2018) is shown as a filled purple diamond.
- The value for *2017* based on the latest cumulative carbon emissions up to the end of 2017 of 2,220 GtCO2 (Version 1.3 accessed 22 May 2018) and a surface temperature anomaly of 1.1°C based on an assumed temperature increase of 0.2°C per decade is shown as a hollow purple diamond.
- The thin blue line shows annual observations, with CO2 emissions from Le Quéré et al. (2018) and estimated globally averaged near-surface temperature from scaling the incomplete coverage and blended HadCRUT4 dataset in Chapter 1.
- The thin blue line shows the CMIP5 multimodel mean estimate with CO2 emissions also from (Le Quéré et al., 2018). The thin black line shows the GMST historic temperature trends from Chapter 1, which give lower temperature changes up to 2006–2015 of 0.87°C and would lead to a larger remaining carbon budget.
- The dotted black lines illustrate the remaining carbon budget estimates for 1.5°C given in Table 2.2.
- Note these remaining budgets exclude possible Earth system feedbacks that could reduce the budget, such as CO2 and CH4 release from permafrost thawing and tropical wetlands (see Section 2.2.2.2).

Source: SR15, page 105

Estimating carbon budgets compatible with 1.5°C, 1.75°C or 2°C,
remaining on January 1, 2018

15 Earth System Models (CMIP5 ESMs),
5 Earth system Models of Intermediate Complexity (CMIP5 EMICs)
and -a simplification of ESMs and EMICs-
Transient Climate Response to cumulative CO2 Emissions (TCRE)
TCRE is assumed to be normally distributed with a standard deviation range of less than or equal 0.8 to 2.5 Celsius/TtC
to update to later years, shift abscissa origin by 0.04 TtCO2/year to the right

TCRE range (mu - sigma to mu + sigma): 0.28 to 0.82 Celsius / TtCO2

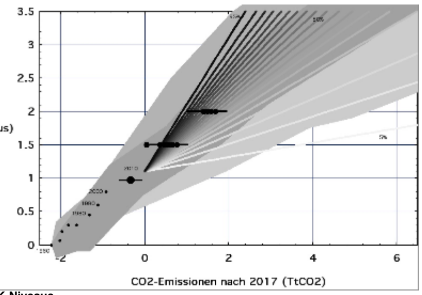


Fig. 2.3 TCRE & PIK-Niveaus
- Plumes (range of ESMs & EMICs), TCRE fan, historical data (small dots and large dot with uncertainties represented as bars at 2010)
    - from IPCC SR15 Special Report "Global Warming of 1.5", Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development, Fig. 2.3, page 105
    - TCRE is assumed to be a normal distribution with
        - a median at 2.0 Celsius/TtC (0.55 Celsius/TtCO2) and
        - a standard deviation of 0.99°C/TtC (0.27 Celsius/TtCO2)
- large dots with overlapping horizontal bars at 1.5 Celsius and 2.0 Celsius are
    - estimates (and their variations) of carbon budgets remaining after 31 December 2017 for limiting global warming to 1.5 °C and to 2 °C relative to preindustrial levels: Fig. 2 of Rogelj et al., 2019

TCRE range (mu - sigma to mu + sigma): 0.28 to 0.82 Celsius / TtCO2

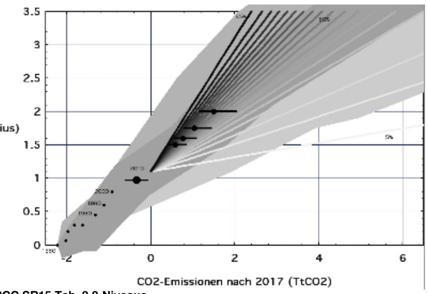
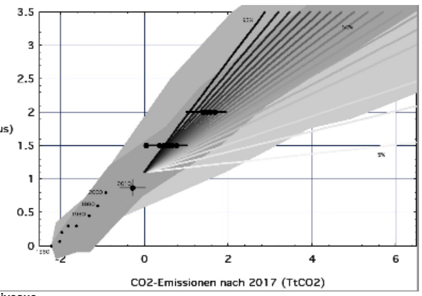


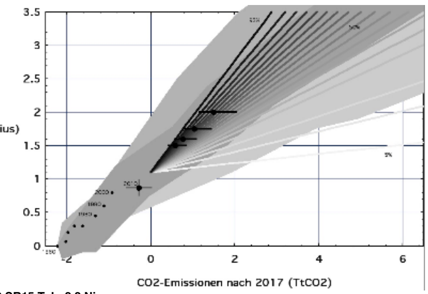
Fig. 2.3 TCRE & IPCC SR15 Tab. 2.2-Niveaus
- Plumes (range of ESMs & EMICs), TCRE fan, historical data (small dots and large dot with uncertainties represented as bars at 2010)
    - from IPCC SR15 Special Report "Global Warming of 1.5", Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development, Fig. 2.3, page 105
    - TCRE is assumed to be a normal distribution with
        - a median at 2.0 Celsius/TtC (0.55 Celsius/TtCO2) and
        - a standard deviation of 0.99°C/TtC (0.27 Celsius/TtCO2)
- large dots with overlapping horizontal bars at 1.5 Celsius, 1.75 Celsius and 2.0 Celsius are
    - assessed carbon budgets (and their uncertainties) remaining after 31 December 2017, IPCC SR15 Special Report "Global Warming of 1.5", Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development: Table 2.2, page 108

TCRE range (mu - sigma to mu + sigma): 0.2 to 0.7 Celsius / TtCO2



WGI TCRE & PIK-Niveaus
- Plumes (range of ESMs & EMICs), TCRE fan, historical data (small dots and large dot with uncertainties represented as bars at 2010)
    - from IPCC SR15 Special Report "Global Warming of 1.5", Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development, Fig. 2.3, page 105
- TCRE is assumed to be a normal distribution after "Climate Change 2013: The Physical Science Basis", Working Group I, Assessment Report 5, Technical Summary, TFE.8, pages 102 - 104 with
    - a median at 1.65 Celsius/TtC (0.45 Celsius/TtCO2) and
    - a standard deviation of 0.85 Celsius/TtC (0.23 Celsius/TtCO2)
- large dots with overlapping horizontal bars at 1.5 Celsius and 2.0 Celsius are
    - estimates (and their variations) of carbon budgets remaining after 31 December 2017 for limiting global warming to 1.5 °C and to 2 °C relative to preindustrial levels: Fig. 2 of Rogelj et al., 2019

TCRE range (mu - sigma to mu + sigma): 0.2 to 0.7 Celsius / TtCO2



WGI TCRE & IPCC SR15 Tab. 2.2 Niveaus
- Plumes (range of ESMs & EMICs), TCRE fan, historical data (small dots and large dot with uncertainties represented as bars at 2010)
    - from IPCC SR15 Special Report "Global Warming of 1.5", Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development, Fig. 2.3, page 105
- TCRE is assumed to be a normal distribution after "Climate Change 2013: The Physical Science Basis", Working Group I, Assessment Report 5, Technical Summary, TFE.8, pages 102 - 104 with
    - a median at 1.65 Celsius/TtC (0.45 Celsius/TtCO2) and
    - a standard deviation of 0.85 Celsius/TtC (0.23 Celsius/TtCO2)
- large dots with overlapping horizontal bars at 1.5 Celsius, 1.75 Celsius and 2.0 Celsius are
    - assessed carbon budgets (and their uncertainties) remaining after 31 December 2017, IPCC SR15 Special Report "Global Warming of 1.5", Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development: Table 2.2, page 108

Table 2.2 I 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	Budgets on the left are reduced by about −100 on centennial time scales					
0.4		530	350	230						
0.5		770	530	380						
0.53	~1.5°C	**840**	**580**	**420**		±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						

page 96 of SR15, Chapter 2
Cumulative CO2 emissions are kept within a budget by reducing global annual CO2 emissions to net zero.

This assessment suggests a remaining budget of about 420 GtCO2 for a two-thirds chance of limiting warming to 1.5°C, and of about 580 GtCO2 for an even chance (medium confidence).

The remaining carbon budget is defined here as cumulative CO2 emissions from the start of 2018 until the time of net zero global emissions for global warming defined as a change in global near-surface air temperatures.

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.

These estimates come with an additional geophysical uncertainty of at least ±400 GtCO2, related to non-CO2 response and TCRE distribution.

Uncertainties in the level of historic warming contribute ±250 GtCO2.

In addition, these estimates can vary by ±250 GtCO2 depending on non-CO2 mitigation strategies as found in available pathways. {2.2.2, 2.6.1}

*(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 CO2 emissions since the middle of the 1850–1900 historical base period (mid-1875) are estimated at 1940 GtCO2 (1640–2240 GtCO2, one standard deviation range) until end 2010. Since 1 January 2011, an additional 290 GtCO2 (270–310 GtCO2, 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 GtC (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker et al., 2013). Values are rounded to the nearest 10 GtCO2. [TCRE in "Estimating and Tracking the Remaining Carbon Budget ..." in units °C/GtCO2
*(4) Focussing on the impact of various key uncertainties on median budgets for 0.53°C of additional warming.
*(5) Earth system feedbacks include CO2 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-CO2 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.
Quelle: Table 2.2 of **IPCC SR15, Chapter 2, page 108**

The uncertainties presented in Table 2.2 cannot be formally combined, but current understanding of the assessed geophysical uncertainties suggests

- at least a ±50% possible variation for remaining carbon budgets for 1.5°C-consistent pathways.
- By the end of 2017, anthropogenic CO2 emissions since the pre-industrial period are estimated to have amounted to approximately 2200 ±320 GtCO2 (medium confidence) (Le Quéré et al., 2018).
- When put in the context of year-2017 CO2 emissions (about 42 GtCO2 yr-1, ±3 GtCO2 yr-1, high confidence) (Le Quéré et al., 2018),
  - a remaining carbon budget of 580 GtCO2 (420 GtCO2) suggests meeting net zero global CO2 emissions in about 30 years (20 years) following a linear decline starting from 2018 (rounded to the nearest five years), with a variation of ±15–20 years due to the geophysical uncertainties mentioned above (high confidence).

Quelle: page 107, **IPCC SR15, Chapter 2**

Joeri Rogelj, Piers M. Forster, Elmar Kriegler, Christopher J. Smith & Roland Séférian,

Estimating and tracking the remaining carbon budget for stringent climate targets

Nature volume 571, pages 335–342 (2019), published: 17 July 2019
"PIK 2019"

Transient climate response to cumulative emissions (TCRE)
Arguably the most central term to estimating the remaining carbon budget is the TCRE (in units of °C per gigatonne of carbon dioxide (Gt CO2). In essence, the remaining carbon budget is estimated by multiplying the remaining allowable warming with the inverse of the TCRE, where the magnitude of the remaining allowable warming is the result of various contributions shown in Fig. 1 and discussed below. The TCRE can be estimated from several lines of evidence, including

- the observational record [10,12,49–51],
- CO2-only simulations [10] and
- multi-gas simulations [12,31,49–53] with Earth system models of varying complexity.

In its latest assessment [54], the IPCC reported the TCRE to fall within the range of **0.2 – 0.7 °C per 1,000 GtCO2** (= **0.8°C - 2.5°C per 1000 GtC)** with a probability of at least 66%.

TCRE, and hence the linear proportionality of warming to cumulative emissions of CO2, has also been found to be robust up to about 7,300 Gt CO2 of cumulative emissions [54,55] and probably more [56]. This domain of application easily spans the range of carbon budgets consistent with warming limits of 1.5 °C and 2 °C.

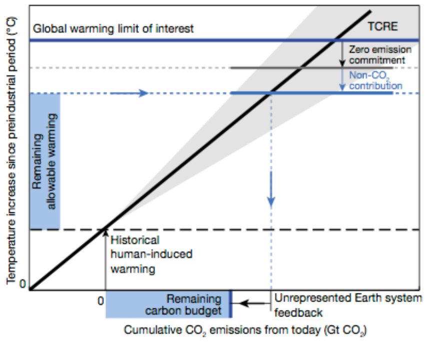


Figure 1
For description see column to the left

Box 2 of PIK 2019

The combination of all terms in the framework presented here, and subtracting 290 Gt CO2 for global CO2 emissions since 2011 [between 2011 and 1 Jan. 2018], results in a remaining carbon budget

[for a 1.5 C limit]
Blim of 480 Gt CO2 for a 50% probability of limiting global warming to 1.5 °C (and with a Blim of 740 and 320 Gt CO2 for 33% and 66% probabilities, respectively).

For a 2 °C limit,
Blim amounts to 1,400 Gt CO2 for a 50% probability (and 1,930 or 1,070 Gt CO2 for a 33% or 66% probability, respectively).

In the IPCC report48, reported numbers are 100 Gt CO2 larger because EEsfb is reported separately.

Fig. 1 | Schematic of factors contributing to the quantification of a remaining carbon budget.

Arrows and dashed lines are visual guides illustrating how the various factors combine to provide an estimate of the remaining carbon budget.

Besides estimating the remaining carbon budget Blim, the framework can also be applied to understand, decompose and discuss estimates of carbon budgets calculated by other methods.
(The relative sizes of the various contributions shown in this schematic are not to scale.)

$B_{lim} = (T_{lim} - T_{hist} - T_{nonCO2} - T_{ZEC})/TCRE - E_{Esfb}$

- global warming limit of interest (Tlim)
- the historical **human**-induced warming to date (Thist) - clearly separate from this the natural warming,
- the non-CO2 contribution to future temperature rise, consistent with global net-zero CO2 emissions or otherwise (TnonCO2),
- the zero-[CO2]-emissions commitment (TZEC),
    - [overshoot of warming T after end of CO2 emissions]
    - Instead of being accounted for as a separate term, the TZEC could also be integrated within the assessment of TCRE, although a dedicated methodological framework to do so is currently lacking [more on page 337].
- the TCRE, and
- an adjustment term (GtCO2) for sources of unrepresented Earth system feedback (EEsfb).
- The grey shading illustrates how uncertainty in TCRE propagates from the start point.

Thist
Thist is the amount of human-induced warming since preindustrial times until a more recent reference period, such as the 2006–2015 period.

The estimation of Thist is a central factor affecting the size of the remaining carbon budget, because it determines how far we currently are from policy-relevant temperature limits (1.5 °C or 2 °C). The assessment of Thist should adequately isolate the human-induced warming signal from the effects of natural forcing and variability [57,58].

The 1850–1900 period is often used as a proxy for pre-industrial levels because observational temperature records stretch back to the beginning of that period [60], and key scientific reports that fed into the Paris Agreement also used this proxy [1,59,61,62] (see Supplementary Text 2 for more details).

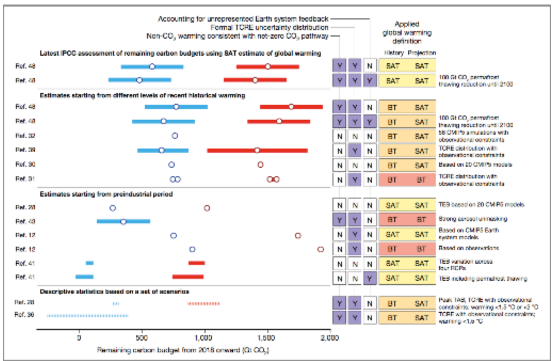
Other periods have been suggested [63–65], but ultimately the crux lies in that Thist and Tlim should always be expressed relative to the same pre-industrial reference period to avoid introducing erroneous changes to the remaining allowable warming and therewith the remaining carbon budget.

Besides defining an appropriate pre-industrial reference period, the choice of metric by which warming is estimated from that period is also important. Studies analysing climate model simulations or observational products can use different metrics to estimate global mean temperature change (see Supplementary Text 2). The impact of this metric choice has been highlighted recently with studies [34,59] showing that this choice can result
- in variations in the estimated global warming of the order of 10% (Supplementary Fig. 1), leading to
- [in] a potential variation in remaining carbon budget estimates of more than 400 GtCO2 [59].

The IPCC has typically specified carbon budgets based on global area-averaged change in surface air temperature [48,66]. Other studies, however, have used different metrics and at times have even changed metrics between observations and projections (Supplementary Table 1, Fig. 2). This limits the comparability of these budget estimates [59]—a situation this new framework attempts to avoid.

EEsfb
... [F]eedback processes have typically been related to permafrost thawing [40–42,85] and the associated long-term release of CO2 and CH4. However, other Earth system feedback sources that can affect remaining carbon budgets have been identified [42], including
changes in vegetation CO2 uptake linked to nitrogen availability [86–88].

If unrepresented feedback results in a direct CO2 emission from an ecosystem, the translation to the EEsfb term is direct. However, because of the diverse nature of Earth system feedback [42], accounting for it through an adjustment in CO2 emissions is not always straightforward. For example, if a feedback system results in the release of other greenhouse gases or affects the Earth system through changes in surface albedo, clouds or fire regimes, for example, its contribution needs to be translated into an equivalent CO2 correction term (see refs 89,90 for example). Because most Earth system feedback is either sensitive to rising CO2 or to variations in climate parameters, it is expected that these contributions are scenario-dependent, nonlinear, and in some cases realized over longer timescales only [40,41,85,91–98]. This adds to the complexity of the translation into a CO2-equivalent correction term, and makes EEsfb an uncertain contribution. EEsfb could be estimated either for the time at which global net CO2 emissions become zero or until the end of the century or beyond, assuming anthropogenic CO2 emissions are kept at net-zero levels but feedback mechanisms continue to change over



Quelle: Seite 338 aus Joeri Rogelj, Piers M. Forster, Elmar Kriegler, Christopher J. Smith & Roland Séférian, Estimating and tracking the remaining carbon budget for stringent climate targets, Nature volume 571, pages 335–342 (2019), published: 17 July 2019
in cache: http://acamedia.info/sciences/sciliterature/globalw/reference/pik/Estimating_and_tracking_the_remaining_carbon_budget_fig2.png

Figure 2. **[In 2018] Remaining CO2-budget estimates** *Blim for T < 1.5 Celsius (blue) and T < 2 Celsius (red)*

Example of how to read Fig. 2
TCRE is assumed to be normally distributed [66] with a 1σ range of 0.2–0.7°C per 1,000 Gt CO2 [Box 2].

The combination of all terms in the next row, and subtracting 290 Gt CO2 for global CO2 emissions since 2011, results in a remaining carbon budget
- Blim [Tlim = 1.5 Celsius] = 480 GtCO2 for a 50% probability and with a
- Blim [Tlim = 1.5 Celsius] = 740 and 320 GtCO2 for 33% and 66% probabilities, respectively.

... [A]t present there are no studies dedicated to explicit analysis of the uncertainty distribution surrounding TCRE, resulting in limited evidence to support the choice of a particular formal distribution, be it
- normal,
- lognormal, or
- otherwise [10,31,54]

when estimating the remaining carbon budget

Figure 2 Comparison of recent remaining carbon budget (GtCO2) estimates for limiting global warming to 1.5 °C (blue) and to 2 °C (red) relative to pre-industrial levels, and overview of factors affecting their variation.

Estimates are shown for a 50% probability [circles] of limiting warming to the indicated temperature levels (additional estimates for a 66% probability [horizontal bars] are provided in Supplementary Table 2).

Several studies do not report formal probabilities, but report the frequency distribution across model simulations instead. The latter estimates are marked N in the 'Formal TCRE uncertainty distribution' column.

Estimates shown with dashed lines indicate carbon budget estimates with an imprecise level of implied global warming, for example, because they were reported for a radiative forcing target instead.

TEB means threshold exceedance budget [37];
TAB means threshold avoidance budget [37] (see Box 1).

Data are taken from
- the IPCC Special Report on Global Warming of 1.5 °C [48, 39] (with values for 1.5 °C based on our own calculations using the same method),
- the IPCC Fifth Assessment Report [28, 12, 30–32, 36, 41, 43].

The latest IPCC assessment of the remaining carbon budget [48] assumes 0.97 °C of historical warming until 2006–2015, whereas
other estimates assume either higher or lower warming for that period (Supplementary Table 1).

The background and values for all studies are provided in Supplementary Tables 1 and 2. The assumptions made for each study are coloured (right-hand side of figure) for ease of visual grouping:
- N = no; Y = yes; SAT = global near-surface air temperatures;
- BT = blended temperatures (surface air temperature over land and sea-ice regions combined with sea surface temperature over open ocean);
- RCP = Representative Concentration Pathway;
- CMIP5 = Phase 5 of the Coupled Model Intercomparison Project.

Table 1 | Key choices or uncertainties of terms affecting estimates of the remaining carbon budget

Term	Symbol	Key choices or uncertainties	Type	Level of understanding
Temperature limit	T_{lim}	Choice of temperature metrics used to express global warming, choice of preindustrial reference period, and consistency with global climate goals	Choice	Medium to high
Historical human-induced warming	T_{hist}	Choice of temperature metrics used to express global warming, choice of preindustrial reference period, and consistency with global climate goals	Choice	Medium to high
Historical human-induced warming	T_{hist}	Incomplete coverage in observational data sets, and methods to estimate human-induced component	Uncertainty	Medium to high
Non-CO_2 contribution to future global warming	T_{nonCO_2}	The level of different non-CO_2 emissions that are consistent with global net-zero CO_2 emissions, which depends on policy choices but also on uncertain success of their implementation	Choice and uncertainty	Medium
Non-CO_2 contribution to future global warming	T_{nonCO_2}	Climate response to non-CO_2 forcers, particularly in the level of aerosol recovery and temperature reduction from lower methane emissions	Uncertainty	Low to medium
Zero-emissions commitment	T_{ZEC}	Sign and magnitude of zero-emission commitment at decadal time scales for current and near-zero annual CO_2 emissions	Uncertainty	Low
Transient climate response to cumulative emissions of CO_2	TCRE	Distribution of TCRE uncertainty, linearity of TCRE for increasing and stabilizing cumulative CO_2 emissions, and impact of temperature metrics on TCRE estimate	Uncertainty	Low to medium
Transient climate response to cumulative emissions of CO_2	TCRE	When extended beyond peak warming (Supplementary Text 1), uncertainty about linearity, value and distribution of TCRE for decreasing cumulative CO_2 emissions	Uncertainty	Low
Unrepresented Earth system feedback mechanisms	E_{Esfb}	Timescale and magnitude of permafrost thawing and methane release from wetlands and their representation in Earth system models, as well as other potential types of feedback	Uncertainty	Very low

Each of the terms in equation (1) is listed. 'Level of understanding' indicates our assessment of the current level of understanding of the various uncertainty components.

Thist
Thist is the amount of human-induced warming since preindustrial times until a more recent reference period, such as the 2006–2015 period.

The estimation of Thist is a central factor affecting the size of the remaining carbon budget, because it determines how far we currently are from policy-relevant temperature limits (1.5 °C or 2 °C). The assessment of Thist should adequately isolate the human-induced warming signal from the effects of natural forcing and variability [57,58].

The *1850–1900 period* is often used as a proxy for pre-industrial levels because observational temperature records stretch back to the beginning of that period [60], and key scientific reports that fed into the Paris Agreement also used this proxy [1,59,61,62] (see Supplementary Text 2 for more details).

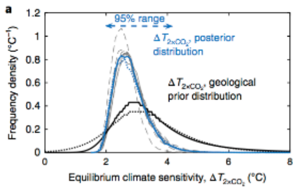
Other periods have been suggested [63–65], but ultimately the crux lies in that Thist and Tlim should always be expressed relative to the same pre-industrial reference period to avoid introducing erroneous changes to the remaining allowable warming and therewith the remaining carbon budget.

Besides defining an appropriate pre-industrial reference period, the choice of *metric* by which warming is estimated from that period is also important. Studies analysing climate model simulations or observational products can use different metrics to estimate global mean temperature change (see Supplementary Text 2). The impact of this metric choice has been highlighted recently with studies [34,59] showing that this choice can result

- in variations in the estimated global warming of the order of 10% (Supplementary Fig. 1), leading to
- [in] a potential variation in remaining carbon budget estimates of more than 400 GtCO2 [59].

The IPCC has typically specified carbon budgets based on global area-averaged change in surface air tem- perature [48,66]. Other studies, however, have used different metrics and at times have even changed metrics between observations and projections (Supplementary Table 1, Fig. 2). This limits the comparability of these budget estimates [59]—a situation this new framework attempts to avoid.

Philip Goodwin, Anna Katavouta, Vassil M. Roussenov, Gavin L. Foster, Eelco J. Rohling and Richard G. Williams
Pathways to 1.5 °C and 2 °C warming based on observational and geological constraints
NATURE GEOSCIENCE | VOL 11 | FEBRUARY 2018 | 102–107



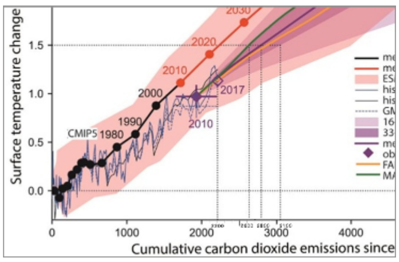
click here to enlarge
Assume that the above distribution is the one for TCRE. Assume
(*) global warming T = Blim TCRE
(*) TCRE is normally distributed,
(*) you have 100 people, each of them standing for a random TCRE value.

Then there would be
(*) 16 people telling that TCRE was larger than the mean + sigma
(*) 16 people telling that TCRE was smaller than the mean - sigma.

Therefore 16 out of 100 people would say
(*) Blim[TCREmean + sigma] = 2500 GtCO2 is already too large for T staying below Tlim = 1.5 C
(*) Blim[TCREmean - sigma] could be larger than 3500 GtCO2 for T staying below Tlim = 1.5 C

Fig. 3 | Model ensemble parameter distributions for equilibrium climate sensitivity. Input distributions in the initial 108 efficient Earth system model simulations (black) and the final distribution in the 104 observation-consistent simulations for RCP8.5 (blue).

The different distributions are included for the
- alternative geological reconstruction input distribution (black dotted line) and
- resulting alternative observationally constrained ensemble (blue dotted line) and
  - the observation-constrained ensembles for the other RCP scenarios (grey solid lines) and the
- perturbation experiments for RCP8.5 (grey dashed lines) (Supplementary Table 5).



TCRE range -sigma < TCRE < sigma is the wider range plume emerging from blue diamond at 2010, marked "16 - 84% TCRE range" in Fig 2.SM.3

Definition
TCRE [TCRE: mu - sigma to mu + sigma]
0.2 to 0.7 °C per 1,000 GtCO2 (= **0.8°C - 2.5°C per 1000 GtC)** (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker et al., 2013, i.e. IPCC WGI, Tech. Summary):
"A related quantity is the transient climate response to cumulative carbon emissions (TCRE). It quantifies the transient response of the climate system to cumulative carbon emissions (see Section E.8). TCRE is defined as the global mean surface temperature change per 1000 GtC emitted to the atmosphere. TCRE is likely in the range of 0.8°C to 2.5°C per 1000 GtC and applies for cumulative emissions up to about 2000 GtC until the time temperatures peak (see Figure SPM.10). {12.5, Box 12.2}

Based on the assessment of TCRE (assuming a normal distribution with a ±1 standard deviation range of 0.8 to 2.5°C per 1000 GtC), limiting the warming caused by anthropogenic CO2 emissions alone (i.e., ignoring other radiative forcings) to less than 2°C since the period 1861–1880 with a probability of >33%, >50% and >66%, total CO2 emissions from all anthropogenic sources would need to be below a cumulative budget of about 1570 GtC, 1210 GtC and 1000 GtC since 1870, respectively. An amount of 515 [445 to 585] GtC was emitted between 1870 and 2011 (TFE.8, Figure 1a,b).
(Source: page 103 of CLIMATE CHANGE 2013 - The Physical Science Basis, 2013, WGI_AR5_all_final
see Mathematica calculation "remaining_C_budget_for_TCRE.ma"
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pages 104 ff of IPCC SR15, Chapter 2
2.2.2The Remaining 1.5°C Carbon Budget [from 1 Jan. 2018]

Table 2.2 and Figure 2.3 show the assessed remaining carbon budgets and key uncertainties for a set of additional warming levels **relative to the 2006–2015** period (see Supplementary Material 2.SM.1.1.2 for details). With an assessed historical warming of 0.87°C ± 0.12°C from 1850–1900 to 2006–2015 (Chapter 1, Section 1.2.1), 0.63°C of additional warming would be approximately consistent with a global mean temperature increase of 1.5°C relative to pre-industrial levels. For this level of additional warming, remaining carbon budgets have been estimated (Table 2.2, Supplementary Material 2.SM.1.1.2).

The remaining carbon budget calculation presented in the Table 2.2 and illustrated in Figure 2.3 does not consider additional Earth system feedbacks such as permafrost thawing. These are uncertain but estimated to reduce the remaining carbon budget by an order of magnitude of about *100 GtCO2 and more thereafter.* Accounting for such feedbacks would make the carbon budget more applicable for 2100 temperature targets, but would also increase uncertainty (Table 2.2 and see below).

Table 2.2 and Figure 2.3 show the assessed remaining carbon budgets and key uncertainties for a set of additional warming levels relative to the 2006–2015 period (see Supplementary Material 2.SM.1.1.2 for details). With an assessed historical warming of 0.87°C ± 0.12°C from 1850–1900 to 2006–2015 (Chapter 1, Section 1.2.1), 0.63°C of additional warming would be approximately consistent with a *global mean temperature increase of 1.5°C relative to pre-industrial levels.* For this level of additional warming, remaining carbon budgets have been estimated (Table 2.2, Supplementary Material 2.SM.1.1.2).

Excluding such feedbacks, the assessed range for the remaining carbon budget is estimated to be
- 840 GtCO2 [230 GtC] for the 33rd TCRE percentile,
- 580 GtCO2 [160 GtC] median TCRE, and
- 420 GtCO2 [110 GtC] for the 67th TCRE percentile

with a median non-CO2 warming contribution and **starting from 1 January 2018 onward**.

An amount of
- 445 [1630 GtCO2] for the 33rd TCRE percentile,
- 515 [1890 GtCO2] median
- 585 GtC [2200 GtCO2] for the 67th TCRE percentile

was emitted between 1870 and 2011 (TFE.8, Figure 1a,b). (Source: page 103 of CLIMATE CHANGE 2013 - The Physical Science Basis, 2013, WGI_AR5_all_final

C. le Quere et al.,
Global Carbon Budget 2016
Earth Syst. Sci. Data, 8, 605–649, 2016
www.earth-syst-sci-data.net/8/605/2016/
doi:10.5194/essd-8-605-2016
https://www.earth-syst-sci-data.net/8/605/2016/essd-8-605-2016.pdf
see also
C. le Quere et al. Global Carbon Budget 2018

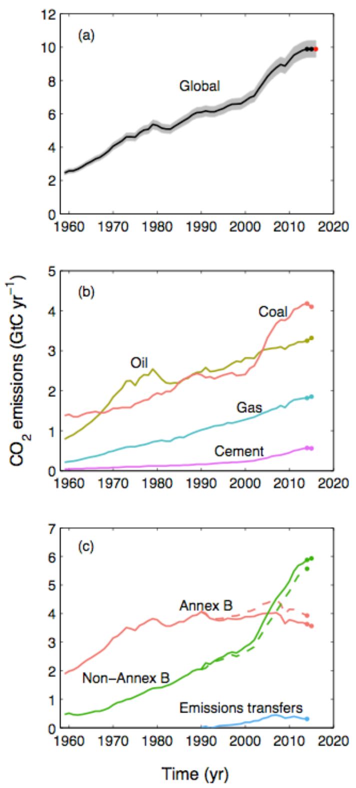

Figure 5. CO2 emissions from fossil fuels and industry for(a) the globe, including an uncertainty of ±5% (grey shading), the emissions extrapolated using BP energystatistics (blackdots), and the emissions projection for year 2016 based on GDP projection (red dot).
Source: Figure 5 (page 627) of C. Le Quéré et al., Global Carbon Budget 2016, Earth Syst. Sci. Data, 8, 605–649, 2016
https://www.earth-syst-sci-data.net/8/605/2016/essd-8-605-2016.pdf
www.earth-syst-sci-data.net/8/605/2016/
doi:10.5194/essd-8-605-2016

rough estimate used in Mathematica Notebook TCRE_C_budgets.ma:
CO_2 emissions 2010 - 2020 = 36.7 $GtCO_2$/a

CO_2 emissions 2010 - 2017: 8 a * 36.7 $GtCO_2$/a = 294 $GtCO_2$

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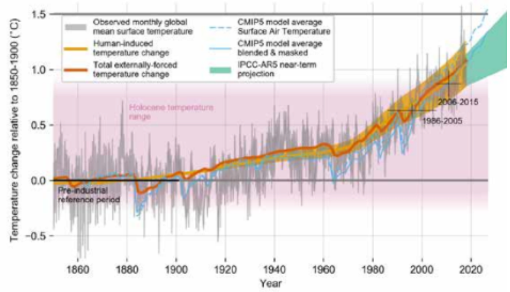
pages 104 ff of IPCC SR15, Chapter 2

2.2.2 The Remaining 1.5°C Carbon Budget [from 1 Jan. 2018]



Quelle: IPCC SR15, Chapter 1, Page 57

Figure 1.2 I Evolution of global mean surface temperature (GMST) over the period of instrumental observations.
Grey shaded line shows monthly mean GMST in the HadCRUT4, NOAAGlobalTemp, GISTEMP and Cowtan-Way datasets, expressed as departures from 1850–1900, with varying grey line thickness indicating inter-dataset range. All observational datasets shown represent GMST as a weighted average of near surface air temperature over land and sea surface temperature over oceans.

Human- induced (yellow) and total (human- and naturally-forced, orange) contributions to these GMST changes are shown calculated following Otto et al. (2015) and Haustein et al. (2017). Fractional uncertainty in the level of human-induced warming in 2017 is set equal to ±20% based on multiple lines of evidence.

Thin blue lines show the modelled global mean surface air temperature (dashed) and blended surface air and sea surface temperature accounting for observational coverage (solid) from the CMIP5 historical ensemble average extended with RCP8.5 forcing (Cowtan et al., 2015; Richardson et al., 2018).

The pink shading indicates a range for temperature fluctuations over the Holocene (Marcott et al., 2013).

Light green plume shows the AR5 prediction for average GMST over 2016–2035 (Kirtman et al., 2013). See Supplementary Material 1.SM for further details.

Table 1.1 | Observed increase in global average surface temperature in various datasets.
Numbers in square brackets correspond to 5–95% uncertainty ranges from individual datasets, encompassing known sources of observational uncertainty only.

Diagnostic / dataset	1850–1900 to (1) 2006–2015	1850–1900 to (2) 1986–2005	1986–2005 to (3) 2006–2015	1850–1900 to (4) 1981–2010	1850–1900 to (5) 1998–2017	Trend (6) 1880–2012	Trend (6) 1880–2015
HadCRUT4.6	0.84 [0.79–0.89]	0.60 [0.57–0.66]	0.22 [0.21–0.23]	0.62 [0.58–0.67]	0.83 [0.78–0.88]	0.83 [0.77–0.90]	0.88 [0.83–0.95]
NOAAGlobalTemp (7)	0.86	0.62	0.22	0.63	0.85	0.85	0.91
GISTEMP (7)	0.89	0.65	0.23	0.66	0.88	0.89	0.94
Cowtan-Way	0.91 [0.85–0.99]	0.65 [0.60–0.72]	0.26 [0.25–0.27]	0.65 [0.60–0.72]	0.88 [0.82–0.96]	0.88 [0.79–0.98]	0.93 [0.85–1.03]
Average (8)	**0.87**	0.63	0.23	0.64	0.86	0.86	0.92
Berkeley (9)	0.98	0.73	0.25	0.73	0.97	0.97	1.02
JMA (9)	0.82	0.59	0.17	0.60	0.81	0.82	0.87
ERA-Interim	N/A	N/A	0.26	N/A	N/A	N/A	N/A
JRA-55	N/A	N/A	0.23	N/A	N/A	N/A	N/A
CMIP5 global SAT (10)	0.99 [0.65–1.37]	0.62 [0.38–0.94]	0.38 [0.24–0.62]	0.62 [0.34–0.93]	0.89 [0.62–1.29]	0.81 [0.58–1.31]	0.86 [0.63–1.39]
CMIP5 SAT/SST blend-masked	0.86 [0.54–1.18]	0.50 [0.31–0.79]	0.34 [0.19–0.54]	0.48 [0.26–0.79]	0.75 [0.52–1.11]	0.68 [0.45–1.08]	0.74 [0.51–1.14]

The global warming from the pre-industrial period until the 2006–2015 reference period is estimated to amount to **0.97°C** *with an uncertainty range of about ±0.1°C* (see Chapter 1, Section 1.2.1).

When estimating global warming until the 2006–2015 reference period as a blend of near-surface air temperature over land and sea-ice regions, and sea-surface temperature over open ocean, by averaging the four global mean surface temperature time series listed in Chapter 1 Section 1.2.1, the global warming would amount to **0.87°C** ±0.1°C.
Quelle dieses Textes: IPCC SR15, Chapter 2, page 106

Consistent with the approach used in the IPCC Fifth Assessment Report (IPCC, 2013b), the latter estimates use *global near-surface air temperatures both over the ocean and over land* to estimate global surface temperature change since pre- industrial.

The global warming from the pre-industrial period until the 2006–2015 reference period is estimated to amount to *0.97°C with an uncertainty range of about ±0.1°C* (see Chapter 1, Section 1.2.1).

Three methodological improvements lead to these estimates of the remaining carbon budget being about 300 $GtCO_2$ larger than those reported in Table 2.2 of the IPCC AR5 SYR (IPCC, 2014a) (medium confidence).

The AR5 used 15 Earth System Models (ESM) and 5 Earth-system Models of Intermediate Complexity (EMIC) to derive an estimate of the remaining carbon budget. Their approach hence made implicit assumptions about

- the level of warming to date,
- the future contribution of non-CO_2 emissions, and
- the temperature response to CO_2 (TCRE).

In this report, each of these aspects are considered explicitly.

When estimating *global warming until the 2006–2015* reference period as *a blend of near-surface air temperature over land and sea-ice regions, and sea-surface temperature over open ocean*, by averaging the four global mean surface temperature time series listed in Chapter 1 Section 1.2.1, the global warming would amount to *0.87°C ±0.1°C.*

Using the latter estimate of historical warming and projecting global warming using global near-surface air temperatures from model projections leads to remaining carbon budgets for limiting global warming to 1.5°C of
1080, 770, and 570 $GtCO_2$ for the
33rd, 50th, and 67th percentile of TCRE, respectively.

Note that future research and ongoing observations over the next years will provide a better indication as to how the 2006–2015 base period compares with the long-term trends and might affect the budget estimates. Similarly, improved understanding in Earth system feedbacks would result in a better quantification of their impacts on remaining carbon budgets for 1.5°C and 2°C.

Matthews, HD, Landry, J-S, Partanen, A-I et al.
Estimating Carbon Budgets for Ambitious Climate Targets
Current Climate Change Reports, 3 (1). pp. 69-77 (2017)
ISSN 2198-6061
https://doi.org/10.1007/s40641-017-0055-0

Valuing Climate Damages
National Academies Press, 2017
Chapter 4: Climate
