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# Cumulative carbon emissions budgets consistent with 1.5 °C global warming

**Katarzyna B. Tokarska[1,2*] and Nathan P. Gillett[3]**

[1] School of Earth and Ocean Sciences, University of Victoria, 3800 Finnerty Road, Victoria, British Columbia V8W 3V6, Canada.

[2] School of Geosciences, University of Edinburgh, Edinburgh EH9 3JW, UK.

[3] Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, University of Victoria, PO Box 1700, STN CSC, Victoria, British Columbia V8W 2Y2, Canada.

Contact: kasia.tokarska@ed.ac.uk

**The Paris Agreement[1] commits ratifying parties to pursuing efforts to limit the global temperature increase to 1.5 °C relative to pre-industrial levels. Carbon budgets[2-5] consistent with remaining below 1.5 °C warming reported in the IPCC Fifth Assessment Report (AR5)[2,6], are directly based on Earth System Model (CMIP5)[7] responses, which, on average, warm more than observations in response to historical $CO_2$ emissions and other forcings[8,11]. These models indicate a median remaining budget of 55 PgC (Ref. 9, base period 1870) left to emit from January 2016, the equivalent to approximately five years of emissions at the 2015 rate[12,13]. Here we calculate warming and carbon budgets relative to the last decade (2006-2015), which eliminates model-observation differences in climate-carbon response over the historical period[11], and increases the median remaining carbon budget to 208 PgC (33-66% range of 130-255 PgC) from January 2016 (with mean warming of 0.89 °C for 2006-2015 relative to 1861-1880[14-19]). There is little sensitivity to the observational dataset used to infer warming to date, and no significant dependence on the choice of emissions scenario. Thus, while limiting median projected global warming to below 1.5 °C is undoubtedly challenging[21-23], our results indicate it is not impossible as might be inferred from the IPCC AR5 carbon budgets[2,8].**

We make use of simulations from 16 comprehensive Earth system models (ESMs) from the Fifth Coupled Climate Model Intercomparison Project[7] (CMIP5; models listed in Supplementary Table S2). We use all available ensemble members for a total of 58 simulations of the response to historical and future concentration-driven scenarios: Representative Concentration Pathways 4.5 and 8.5, which reach radiative forcing levels of 4.5 W/m$^2$ and 8.5

W/m$^2$ by year 2100, respectively[24]. We do not use RCP 2.6 simulations in our analysis, to avoid bias towards models that warm more strongly, because some of the RCP 2.6 simulations do not reach 1.5 °C global warming by 2100. Moreover, we find that for each CMIP5 model with multiple ensemble members, there are no statistically significant differences between 1.5 °C carbon budgets calculated from the RCP 2.6 scenario and those calculated from the RCP 4.5 or RCP 8.5 scenarios (Supplementary Table S3). This result is consistent with mean cumulative emissions budgets in RCP 2.6, RCP 4.5, and RCP 8.5 being coincident with each other at 1.5 °C global warming[8] (Ref 8,10: TFE.8, Supplementary Figure S1). Ref. 11 reports a carbon budget to remain below 1.5 °C in 66% of CMIP5 ESMs which is 40 PgC higher when calculated from the RCP 2.6 than when calculated from RCP 8.5, which they ascribe to mitigation of non-$CO_2$ drivers in RCP 2.6. However, Ref. 11 use different sets of models to evaluate carbon budgets from RCP 2.6 and RCP 8.5 scenarios, and we suggest that either this, or internal variability, is the reason their carbon budgets differ for the different RCP scenarios.

Global mean temperature and diagnosed cumulative carbon emissions simulated in response to both scenarios (RCP 4.5 and 8.5) are shown in Figure 1. The simulations first reach 1.5 °C global warming, relative to an 1861-1880 base period, between years 2005 and 2054 (Figure 1a). For comparison, observed warming of 0.89 °C for the past decade (2006-2015) relative to 1861-1880, based on a mean of five of the most recent observational data sets[14-19] (see *Methods*), is indicated by dotted lines (Figure 1a). Total diagnosed cumulative carbon emissions are a sum of total cumulative diagnosed fossil fuel emissions (Figure 1b) and cumulative land-use change emissions (see *Methods*).

To robustly compare simulated warming as a function of cumulative emissions with observations, simulated temperature in each CMIP5 simulation used to compute cumulative fossil fuel emissions in Figure 2 (horizontal axis), was masked by observational coverage, and a running decadal mean was calculated. This was compared with the observed warming in the most recent decade (2006-2015) from three observational datasets[14-17], in order to determine the last year before which simulated decadal mean warming first exceeded this observed warming for each simulation and observational dataset. That year was then used to calculate cumulative fossil fuel emissions at the present level of warming, as simulated by each model, which were compared with reported total amount of fossil-fuel emissions of 360.8 PgC ±20 PgC ($\pm 1\sigma$; Ref 13; *Methods*), for the period 1870-2010, since the end of 2010 is at the centre of the decade

2006-2015 (Figure 2, horizontal axis). Fossil fuel emissions can be directly diagnosed from the models, and have lower observational uncertainties than total cumulative emissions (that include more uncertain estimates of observed land use change emissions[12], see *Methods*).

On average cumulative emissions at the present level of warming in the CMIP5 models are lower than actual emissions (Figure 2). Figure 2 also shows that there is only a weak correlation ($r = 0.37$, for all markers) between the model cumulative fossil-fuel emissions at present warming (*Methods*) (Figure 2, horizontal axis) and the cumulative total carbon emissions consistent with limiting warming to less than 1.5 °C (Figure 2, vertical axis). The fact that this correlation is relatively low likely relates to differing responses to non-$CO_2$ forcings between models[20], since the relative contributions of these forcings, particularly aerosols, differ strongly at present warming and at 1.5 °C warming above the pre-industrial level. Nonetheless, since there is a weak correlation between these quantities, we might expect that if models underestimate warming as a function of emissions over the historical period they will also do so in future, based on physical grounds. Hence, we investigate whether by comparing the simulated cumulative fossil-fuel carbon emissions at present warming (Figure 2, horizontal axis) with the reported cumulative fossil-fuel carbon emissions at present warming (Figure 2, dashed lines), 1.5 °C carbon budgets might be observationally constrained, by screening out models that are inconsistent with observations. We apply a consistency test (*Methods*), which accounts for uncertainties related to the internal variability, uncertainties in the observed estimate of cumulative carbon emissions and observational uncertainties in temperature (*Methods*). To assess robustness, we apply the result using temperatures and cumulative emissions averaged over three periods (*Methods*).

Sixteen models were screened with a consistency test (*Methods*), with models screening in if the test yields a $p$-value larger than 0.1. The test was carried out for three different base periods: 1995-2006, 2002-2011, and 2006-2015, with 14,12 and 8 models screening in, respectively for each period (*Methods;* Figure 2; Supplementary Table S2; Supplementary Figure S2). Carbon budgets consistent with staying below 1.5 °C warming were calculated based on all model responses (Figure 3; ALL models), and based only on the models that are consistent with observations over the three periods considered (Figure 3; OC models). In each case, all available ensemble members were used, with ensemble members weighted in such a way that each model had equal weight, in order to avoid a bias towards models with larger ensembles[25] (*Methods*

Eq.1.1 and Eq.1.2). The right-hand edges of the bars in Figure 3 represent percentiles of the resulting distributions. The unconstrained carbon budgets for 1.5 °C warming (Figure 3, ALL models) closely resemble the values reported by the IPCC AR5 (Ref. 8,10: TFE.8, Figure 1), with small differences arising from our consideration of multiple ensemble members, inclusion of RCP 4.5 results, and the slightly different sets of models used. The 10th percentile of the unconstrained budgets had already been exceeded in 2015 (Figure 3, ALL models, 1861-1880 baseline), suggesting a greater than 10% chance that emissions to date should have already caused 1.5 °C warming. The median remaining carbon budget in year 2015, consistent with staying below 1.5 °C peak warming, is 74.5 PgC, based on unconstrained responses of all models considered here. Applying observational constraints to emission budgets relative to 1860-1881 does not substantially change this budget, with an increase in the median budget relative to 1860-1881 of 8 PgC using observations over the period 2006-2015 and a decrease in the median budget of 13 PgC using observations over periods 2002-2011 or 1995-2006 (Figure 3, top three bars).

While applying observational constraints to CMIP5 models does not substantially change emissions budgets calculated relative to 1861-1880, changing the base period to the recent decade (2006-2015) (Figure 3; ALL models) substantially increases the median carbon budget relative to 2015 from 74.5 PgC to 208 PgC remaining, and reduces the 10-90% uncertainty range width by 64 PgC (from 367 PgC to 303 PgC), due to elimination of uncertainties related to historical carbon emissions[11]. Comparing these results with the carbon budgets reported in the IPCC AR5 (Supplementary Table S1)[2,6], the remaining carbon budgets reported in this study are nearly four times as large as the IPCC AR5 remaining carbon budget estimate in 2015 of 55 PgC (based on Ref 9: see Supplementary Table S1).

The increase in the median remaining 1.5 °C carbon budget varies between 174 PgC and 226 PgC depending on which of five recent observational datasets is used to determine the level of present warming, but in all cases this is a substantial increase compared to the IPCC AR5 budget (Figure 4). The increase in the median remaining carbon budget resulting from changing the base period to a more recent one is also explored for other base periods (1989-1998, 1995-2006, 2002-2011 and 2012-2015; Supplementary Figure S3). As might be expected, changing the base period to a less recent one (e.g. 1989-1998; Supplementary Figure S3) results in a smaller increase in the remaining median carbon budget.

The carbon budgets reported here are threshold exceedance budgets (TEB)[6], since they are based on emissions budgets calculated just before temperatures first exceed 1.5 °C in RCP scenario simulations. The levels of non-$CO_2$ forcings at this point of exceedance may not be representative of levels at stabilisation in a scenario that limits warming to 1.5 °C. As shown in Ref. 6, non-$CO_2$ radiative forcing at the time of crossing 2.0 °C for RCP 4.5 and RCP 8.5 is at the higher end of the distribution of such forcing over a broader range of scenarios, so the contributions from non-$CO_2$ forcings may be on the higher end of warming estimates at the time of crossing 1.5 °C as well. An alternative approach is to calculate threshold avoidance budgets (TAB) [6], from simulations forced with lower emissions scenarios. However, such simulations are not available for the set of comprehensive Earth System Models considered here. The committed warming after cessation of emissions in TEB scenarios is likely to be small for low warming climate targets such as 1.5 °C or 2.0 °C (Ref.26), due to the additional warming from declining ocean heat uptake being compensated by a decline in atmospheric $CO_2$ concentration (and hence, a decline in $CO_2$ radiative forcing) due to ongoing carbon uptake, especially by the ocean, when emissions cease in low-concentration scenarios[26]. Based on Ref. 26, accounting for a maximum committed warming up to 0.1 °C by the end of the century (for a scenario where the atmospheric $CO_2$ concentration reaches double of the pre-industrial values)[26] would reduce the carbon emission budget by a maximum of approximately 17%.

CMIP5 models considered here do not include permafrost carbon feedbacks that could lead to additional warming[27], estimated to range from 0.13 to 0.27 °C by year 2100, primarily based on RCP 8.5 scenario[28], and hence reduce carbon budgets[29]. However, these feedbacks become more important at higher levels of warming[2,30], and we would not expect them to have a substantial impact on our results for the 1.5 °C carbon budgets. Also, it is important to recognise ambiguities in defining the Paris Agreement 1.5 °C target, as the choice of pre-industrial baseline introduces uncertainties of 0.1-0.2 °C if the 1.5 °C warming is calculated from earlier periods[31] than the standard IPCC baseline (1861-1880), which is our focus here.

To summarise, CMIP5 models on average simulate more warming as a function of cumulative carbon emissions than observed over the historical period. Since there is only a weak relationship between diagnosed cumulative emissions at present warming levels and at 1.5 °C, sub-setting models based on consistency with observed warming does not substantially change 1.5 °C emissions budgets. However, changing the anomaly base period to the recent decade[11]

(2006-2015) eliminates uncertainties in the climate-carbon response in the historical period, arising from discrepancies between observations and model representation of carbon cycle responses and resulting temperature changes. This change of the base period to a recent decade (2006-2015) increases the median 1.5 °C budget remaining in 2015 from 74.5 PgC (similar to the budget assessed by IPCC AR5 of 55 PgC remaining in 2015, Supplementary Table S1, Ref. 9) to 208 PgC (33-66% range of 130-255 PgC remaining in 2015; Supplementary Table S1). The median budget corresponds to around 20 years of emissions at the 2015 level of 10.6 PgC $yr^{-1}$ (Ref.12), and is similar to an estimate of 223 PgC reported by another recent study[11]. These budgets were not found to be very sensitive to the observational dataset used to infer present-day warming, and not dependent on the RCP scenario used. Despite the increase in the median unconstrained IPCC remaining carbon budget we find, we recognize that keeping the global mean temperature increase below 1.5 °C, in accord with the recent Paris Agreement[1] would require prompt and substantial reductions in greenhouse gas emissions on a global scale[21-23], with global emissions peaking in the next two decades[21], followed by negative emissions in the latter part of the 21st century[22,32], or reaching a global net-zero $CO_2$ emissions around 2045-2060, if emissions gradually decline to net-zero starting from year 2015 onwards[21]. Nonetheless, by demonstrating that the 1.5 °C carbon budget has not yet been exceeded, and by finding a substantially higher remaining budget than that shown by the IPCC AR5[8,9], our work indicates that limiting global mean warming to the 1.5 °C level, and hence limiting associated climate impacts[32], is more feasible than previously thought.

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## Methods

### Temperature and carbon budgets calculations

In the first part of the paper (the consistency test and Figure 2), for each CMIP5 model considered, the global mean temperature anomaly for each year was calculated from monthly mean anomalies separately for each of three datasets, using the same coverage and base period as the respective observational temperature data set (HadCRUT4, GISS or NOAA)[14-17]. For the observational data sets that start at year 1880, the temperature change between the periods 1880-1899 and 1861-1880 was calculated based on HadCRUT4 values and was added to the respective observational estimates of warming. An equivalent calculation using the same observational masking was performed for the simulated temperature data. A running decadal mean anomaly relative to the 1861-1880 period was calculated for the masked model data sets, to determine the year preceding the year in which a given model reaches the level of warming over the past decade (2006-2015), or over the other two periods considered (1995-2006 and 2002-2011), for each observational dataset separately. Similar analysis has been repeated for two other reference periods considered here, instead of the recent decade (Supplementary Figure S2). The temperature response at 1.5 °C warming was calculated from spatially complete model temperature output as an anomaly relative to 1861-1880, and with respect to the corresponding year in the pre-industrial control simulation, to remove the effects of any drift.

The IPCC estimate of cumulative fossil fuel emissions for the period 1870-2010 (ending in the middle of the decade 2006-2015) is based on the observational estimate of cumulative fossil fuel emissions[13] for the period 1870-2012 (380 ± 20 PgC), with the fossil fuel emission rate in the years 2011 and 2012 subtracted (9.5 ± 0.5 PgC $yr^{-1}$, and 9.7 ± 0.5 PgC $yr^{-1}$, respectively) to calculate the 1870-2010 estimate, where the uncertainties are reported as $\pm 1\sigma$.

Total cumulative fossil fuel carbon emissions (Figure 1b) were computed for models in which land-use change was implemented by summing time-integrated atmosphere-land carbon fluxes, atmosphere-ocean carbon fluxes and the atmospheric carbon anomaly relative to 1861-1880[2]. For the BCC-CSM-1-1-m and BCC-CSM-1-1 models in which land-use changes were not implemented, cumulative fossil fuel carbon emissions were computed by summing time-integrated atmosphere-land and atmosphere-ocean carbon fluxes with the atmospheric carbon anomaly and subtracting an estimate of cumulative land-use change emissions, as prescribed in the corresponding RCP scenario. In all CMIP5 models with interactive land use changes, total cumulative carbon emissions (Figure 1c) were computed by adding an estimate of cumulative land-use change emissions for the corresponding RCP scenario[24], to the fossil fuel cumulative carbon emissions shown in panel Figure 1b.

Carbon budgets shown in Figure 3 and Figure 4 are based on the spatially-complete model temperature output (as in Figure 1a), and model cumulative carbon emissions (Figure 1c). Carbon budgets calculated relative to the 2006-2015 base period (Figure 3 and Figure 4) were offset by the IPCC estimate of the cumulative carbon emissions up to end of 2010 (515 PgC), which is the middle year of that decade. Cumulative carbon emissions remaining from January 2016 were then calculated by subtracting the amount of carbon emitted between end of 2010 and end of 2015, based on reported values[12,13] (see also Supplementary Table S1). An amount of 555 PgC has been emitted for the period 1870-2015, based on reported values (Ref. 12).

The observed warming for the recent decade (2006-2015), relative to 1861-1880, is 0.886 °C , based on the mean from most recent versions of five observational data sets is: 0.833 °C (HadCRUT4), 0.915 °C (Cowtan and Way, denoted as CW, taking into account possible biases in HadCRUT4 dataset[18]), 0.889 °C (GISS), 0.830 °C (NOAA), and 0.964 °C (Berkley Earth dataset[19], denoted at BE). The mean warming (0.886 °C) was then used to calculate carbon budgets for the remaining warming until 1.5 °C is reached, as shown in Figure 3 (most bottom bar), Figure 4 (five bottom bars), and Supplementary Figure S3.

**Carbon budgets cumulative frequency distributions**

Cumulative frequency distributions of emissions budgets shown in Figure 3 and Figure 4 were calculated in the following way. If the $E_l$ are the cumulative emissions budgets simulated in individual ensemble members of all models considered sorted in ascending order, then the cumulative frequency distribution is defined as:

$$C(E) = \sum_{l=1}^{l=L} w_l \tag{1.1}$$

where:

$$w_l = \frac{1}{I\,N_l} \tag{1.2}$$

and $L$ is chosen such that $E_L < E < E_{L+1}$, $I$ is the number of models considered, and $N_l$ is the size of the ensemble from which the $l^{th}$ simulation is drawn. This approach uses all available ensemble members, but gives equal weight to each model[25]. If only one ensemble member is used from each model it is identical to the approach used to generate a similar figure in the IPCC assessment (Ref. 8,10: TFE.8, Figure 1).

**Consistency Test: model screening based on observational constraints**

To observationally-constrain the model responses, we screened models for consistency with observations of fossil fuel emissions at observed warming (Figure 2, Figure 3). The consistency test accounted for uncertainties associated with observational uncertainty in temperature, observational uncertainty in cumulative fossil fuel emissions, and internal variability in the observations and models. For the $i^{th}$ model, $j^{th}$ observational temperature dataset and $k^{th}$ ensemble member, the cumulative fossil fuel carbon budget at the present warming $\left(F_{T\_obs}\right)_{ijk}$(Figure 2) was estimated from a combination of a historical and RCP 4.5 simulations, since RCP 4.5 was the scenario with the most ensemble members. For models with multiple ensemble members, we found that carbon budgets consistent both with present day warming and with 1.5 °C warming are not significantly different when calculated from the RCP 2.6 and RCP 4.5, or RCP 2.6 and RCP 8.5 scenarios, using two-sample t-tests. Carbon budgets calculated from a smaller sample of models that had data available for all three RCP scenarios, and reach 1.5 °C warming, do not show significant differences when compared to results based on RCP 4.5 and RCP 8.5 only. However, since a larger sample of 16 models had data available for RCP 4.5 and 8.5, we use those scenarios in our main analysis. Since some models only had a single ensemble member available and others had only small ensembles, we made the simplifying assumption that internal variability in $F_{T\_obs}$ was equal in all models and in observations. This internal variability reflects internal variability in temperature, and to a lesser extent internal variability in the carbon cycle. To estimate the variance associated with internal variability, we calculated the sample variance in $F_{T\_obs}$ across all ensemble members for the $i^{th}$ model using the $j^{th}$ observational dataset, $\sigma_{I\,ij}^2$. The model mean variance associated with internal variability $\sigma_I^2$ was then estimated by:

$$\sigma_I^2 = \overline{\left(\frac{N_i}{N_i - 1}\sigma_{I\,ij}^2\right)} \tag{1.3}$$

where $N_i$ is the ensemble size for the $i^{th}$ model. The overbar indicates an average across the models and across the three observational data sets (HadCRUT4, NOAA, GISS). The factor $N_i/(N_i\text{-}1)$ is included to account for the fact that $\sigma_{I\,ij}^2$ is the sample variance calculated relative to the sample mean, not the true population mean.

The observational uncertainty variance for the reported cumulative fossil fuel carbon emissions $\sigma_F^2$ (400 [PgC]$^2$) for the period 1870-2010 was calculated from Ref.13 based on the $\pm 1\sigma$ uncertainty range. The uncertainty in the observed temperature measurements was accounted for in the term $\sigma_T^2$ (317 PgC$^2$) (*Methods* Eq. 1.4), and is smaller than the uncertainties in the reported cumulative fossil fuel emissions $\sigma_F^2$ (400 PgC$^2$) or the uncertainty associated with internal variability $\sigma_I^2$ (524 PgC$^2$) (*Methods* Eq. 1.3).

The variance in $F_{T\_obs}$ associated with observational uncertainty in temperature was estimated from the spread in emissions budgets calculated with the three different temperature data sets. $\sigma_T^2$ was calculated according to Eq. 1.4, where $J$ is the number of observational temperature data sets ($J$=3) and $\sigma_{T\,ik}^2$ is the sample variance in cumulative emissions budgets across the three different observational datasets for the $i^{th}$ model and $k^{th}$ ensemble member, and the overbar represents an average across models and ensemble members.

$$\sigma_T^2 = \left(\frac{J}{J-1}\right)\overline{\sigma_{T\,ik}^2} \qquad (1.4)$$

For the $i^{\text{th}}$ model we can define the difference $D$:

$$D_i = \overline{\left(F_{T\_obs}\right)_{ijk}} - F_{Obs} \qquad (1.5)$$

where the overbar indicates an average over ensemble members, $k$, and observational temperature datasets, $j$, and $F_{Obs}$= 360.8 PgC $\pm$ 20 PgC (Ref.13). We then divide $D_i$ by an estimate of its standard deviation under the null hypothesis that the simulated and reported cumulative fossil fuel emissions budgets are drawn from the same distribution:

$$x_i = \frac{D_i}{\sqrt{\sigma_F^2 + \sigma_I^2\left(1 + \frac{1}{N_i}\right) + \sigma_T^2}} \qquad (1.6)$$

where the term $(1 + \frac{1}{N_i})$ is included to account for internal variability in both the observations and the model. We find that $\sigma_F^2$=400 [PgC]$^2$, $\sigma_I^2$=524 [PgC]$^2$, and $\sigma_T^2$=317 [PgC]$^2$, indicating that internal variability is the largest contributor to the standard deviation in $D_i$. Making the simplifying assumption that $x_i$ is normally distributed under the null hypothesis, we calculate the p-value corresponding to $x_i$ for a normal distribution (two-tailed test at a significance level of 0.1), and asses that the model is consistent with the observations if $p(x_i) > 0.1$ (Supplementary Table S2). The results do not change substantially when the significance level of the consistency test is changed from 0.1 to 0.05 or 0.2, as most of the models either pass or fail the test at all these three significance levels.

## Data availability

Observed temperature HadCRUT4 dataset is available online at http://www.metoffice.gov.uk/hadobs/index.html, Cowtan and Way reanalysis is available at http://www-users.york.ac.uk/~kdc3/papers/coverage2013/series.html. GISTEMP and NOAA Global Surface Temperature (NOAAGlobalTemp) are available online at http://www.esrl.noaa.gov/psd/. Global temperature datasets are available at: https://climatedataguide.ucar.edu/climate-data/global-temperature-data-sets-overview-comparison-table. CMIP5 model data is available on the Earth System Grid Portal at https://esgf-node.llnl.gov/projects/esgf-llnl/ .

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## Author contributions

N.P.G. designed the study. K.B.T. collected and analysed data. K.B.T. and N.P.G. interpreted the data and wrote the manuscript.

## Additional information

Correspondence and requests for materials should be addressed to K.B.T.

## Competing financial interests

The authors declare no competing financial interests.

# Figures

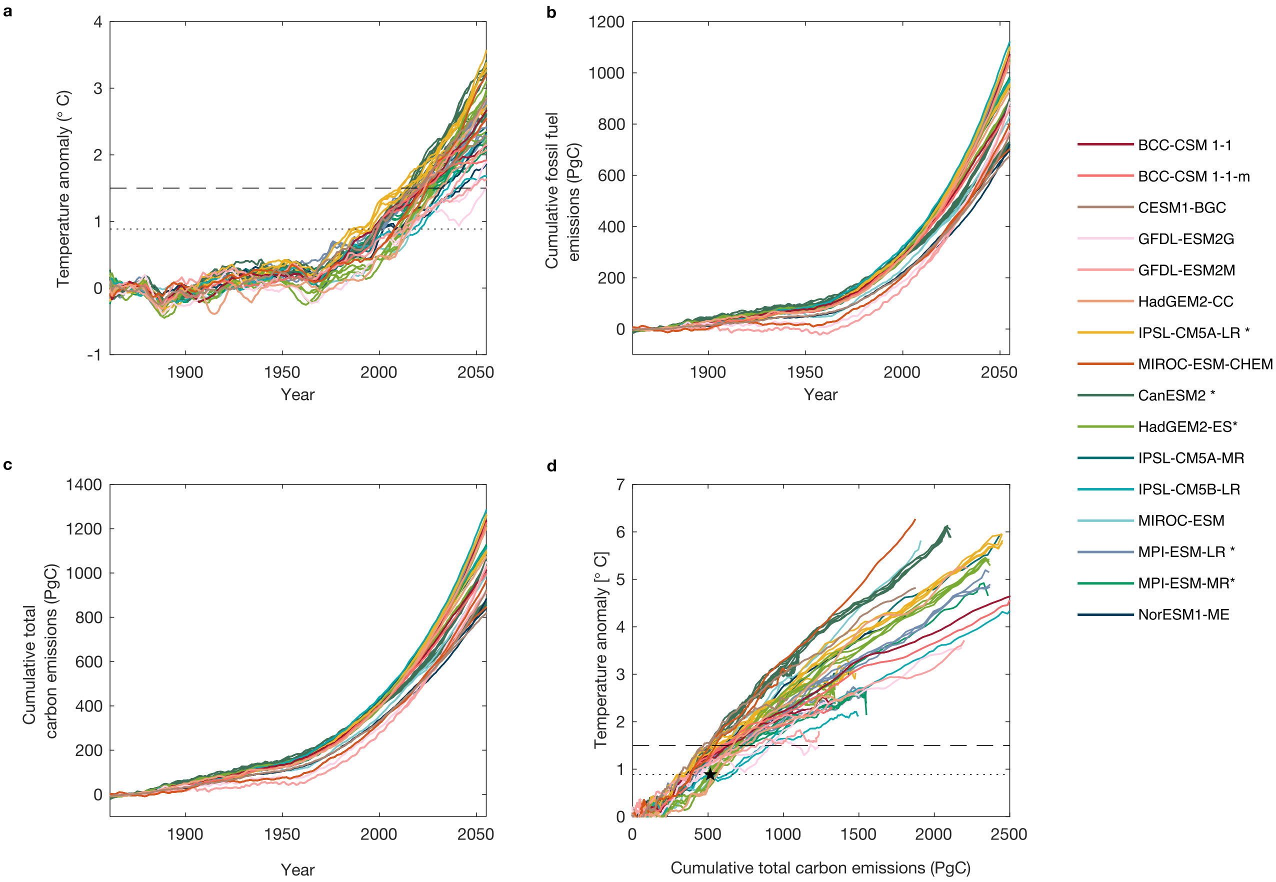


**Figure 1. Time series of global mean temperature and cumulative carbon emissions for RCP 4.5 and RCP 8.5 scenarios**. Panel (**a**) global mean temperature anomaly (decadal mean); (**b**) cumulative fossil fuel emissions; (**c**) cumulative total carbon emissions; (**d**) temperature change as a function of cumulative total carbon emissions. The dotted line in panel (**a**) indicates the present warming level for the recent decade 2006-2015 (0.89 °C; mean from the observational data sets[14-19], *Methods*), and the dashed line indicates the 1.5°C warming threshold. The asterisk in panel (**d**) indicates of the observed historical cumulative carbon emissions for the period 1870-2010 with the median value of 515 PgC (± 20 PgC; Ref. 8,12), where end of year 2010 represents the middle of the 2006-2015 decade. Anomalies are relative to 1861-1880, and were calculated with respect to the corresponding year in the pre-industrial control simulation to remove the effects of any drift.

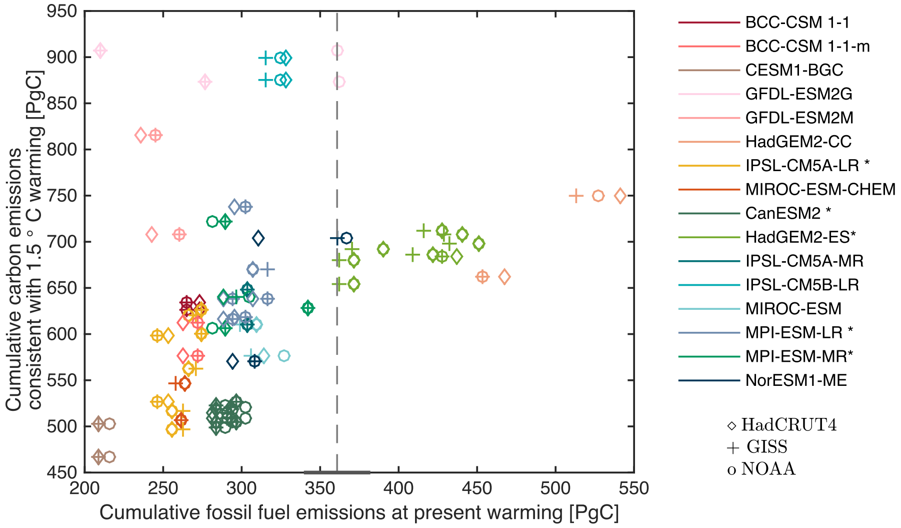


**Figure 2. Cumulative total carbon budgets consistent with 1.5 °C warming (for RCP 4.5 and RCP 8.5 scenarios, as a function of simulated cumulative fossil-fuel carbon emissions at present warming.** The dashed line indicates an estimate of the observed historical cumulative fossil fuel emissions for the period 1870-2010 with the median value of 360.8 PgC (Ref. 13; the ± 20 PgC uncertainty of this estimate is indicated by the horizontal black bar). Different symbols (indicated in the legend) represent cumulative emissions budgets calculated using different observational data sets of temperature. Models shown in shades of blue or green passed the consistency test based on the 2006-2015 period (see *Methods*), while models in shades of red and orange failed it.

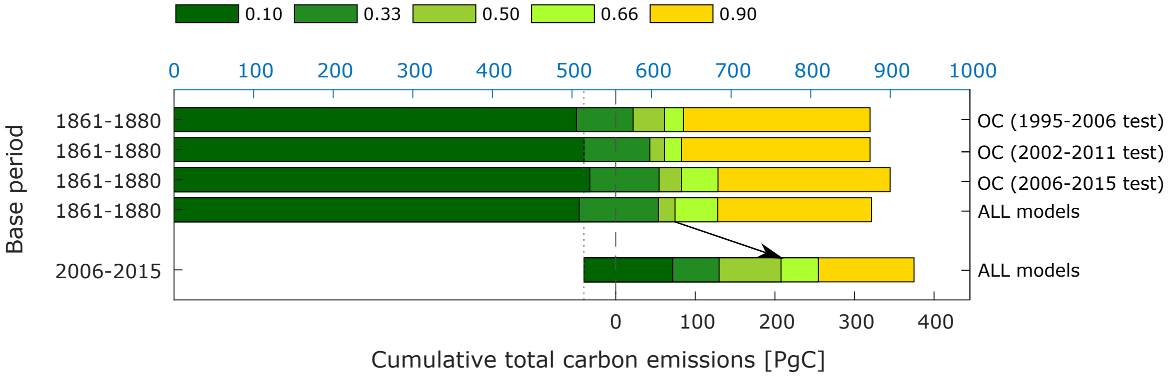


**Figure 3. Cumulative frequency distribution of carbon budgets consistent with staying below 1.5 °C global warming. Two lower bars are based on all (unconstrained) CMIP5 models considered here (ALL), and top three bars represent observationally-constrained budgets based on models consistent with observations (OC) at the 0.1 significance level.** The grey dashed line indicates the observational total cumulative carbon emissions for 1870-2015, with the median value of 555 PgC (Ref.12), while the dotted line indicates cumulative carbon emissions up to end of 2010. The top four bars show carbon budgets relative to 1861-1880 (blue axis), in PgC. The bottom bar shows carbon budgets relative to the recent decade 2006-2015 and the present level of warming (*Methods*, Refs. 14-19), offset by the IPCC estimate of the cumulative carbon emissions up to end of 2010. The lower (black) axis shows carbon budgets from January 2016. The black arrow indicates the extension in 1.5 °C median carbon budget due to change of the baseline of cumulative carbon emissions calculations. See *Methods* for details of how the distributions were calculated. Note: The percentiles indicated in the legend refer to the right hand edge of each bar.

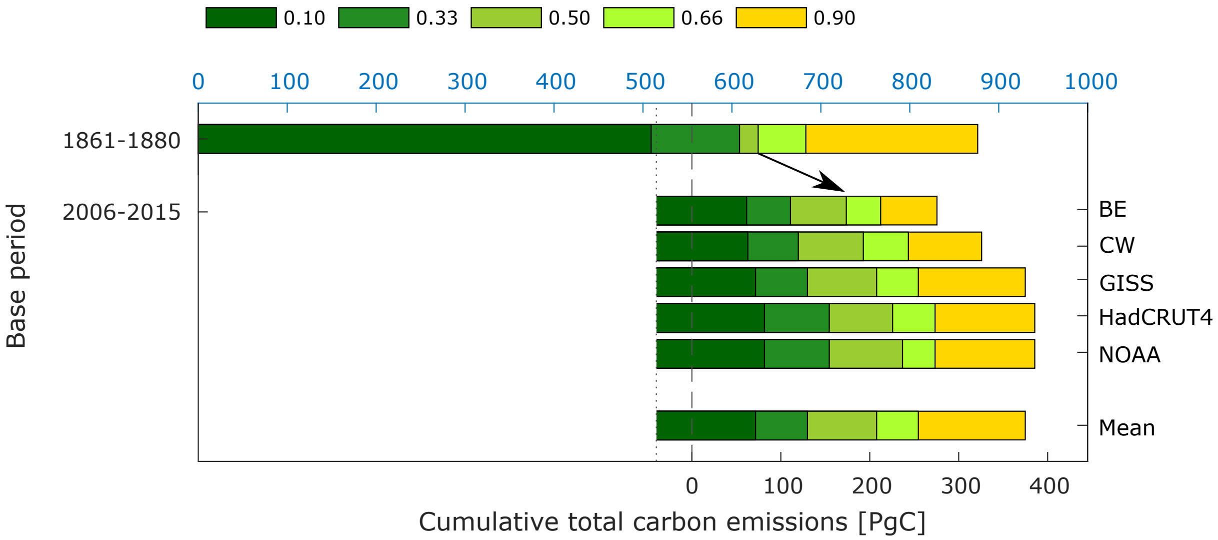


**Figure 4. Cumulative frequency distribution of carbon budgets consistent with staying below 1.5 °C global warming based on all CMIP5 models considered here for two different base periods and five different observational datasets.** The grey dashed line indicates the observational total cumulative carbon emissions for the period 1870-2015, with the median value of 555 PgC (Ref.12), while the dotted line indicates cumulative carbon emissions up to end of 2010. The top bar shows carbon budgets relative to 1861-1880 (blue axis), in PgC. The bottom bars show carbon budgets relative to the recent decade 2006-2015, offset by the IPCC estimate of the cumulative carbon emissions up to end of 2010. The lower (black) axis shows carbon budgets from January 2016. The present levels of warming were determined for each observational temperature data set, indicated on the right hand side (*Methods*, Refs. 14-19). The black arrow indicates the extension in 1.5 °C median carbon budget due to change of the baseline of cumulative carbon emissions calculations. See *Methods* for details of how the distributions were calculated. The carbon budgets consistent with staying below 1.5 °C warming are based on RCP 4.5 and RCP 8.5 scenarios. Note: The percentiles indicated in the legend refer to the right hand edge of each bar.

# Cumulative carbon emissions budgets consistent with 1.5 °C global warming

**Katarzyna B. Tokarska[1,2*] and Nathan P. Gillett[3]**

[1] School of Earth and Ocean Sciences, University of Victoria, 3800 Finnerty Road, Victoria, British Columbia V8W 3V6, Canada.

[2] School of Geosciences, University of Edinburgh, Edinburgh EH9 3JW, UK.

[3] Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, University of Victoria, PO Box 1700, STN CSC, Victoria, British Columbia V8W 2Y2, Canada.

Contact: kasia.tokarska@ed.ac.uk

## Supplementary Information

Carbon budgets consistent with 1.5 °C

Cumulative emissions from 1870 in PgC ($GtCO_2$)

| | **66%** | **50%** | **33%** |
|---|---|---|---|
| IPCC SYR | 613<br>(2250) | 613<br>(2250) | 695<br>(2550) |
| ALL models | 609<br>(2234) | 630<br>(2310) | 683<br>(2507) |

Cumulative emissions from January 2016 in PgC ($GtCO_2$)

| | **66%** | **50%** | **33%** |
|---|---|---|---|
| IPCC SYR | 55<br>(200) | 55<br>(200) | 136<br>(500) |
| ALL models | 130<br>(477) | 208<br>(763) | 255<br>(936) |

Supplementary Table S1. Comparison tables with IPCC results (Refs.1,2).

The IPCC SYR results are from Table 2.2 from the IPCC Synthesis Report (2014) (Ref.1), based on responses from ESMs and EMICs to RCP 8.5 scenario, originally reported in $GtCO_2$, rounded to the nearest 50 $GtCO_2$. The percentiles (bold row headers) refer to cumulative frequency distributions of carbon budgets, as described in *Methods*, and should not be treated as probabilistic estimates.

*Note: The numbers presented here are subject to rounding. Cumulative emissions from 2015 in the IPCC SYR row were calculated by subtracting 2050* $GtCO_2$ *that was emitted for the period (1870-2015), from the IPCC SYR values since 1870, as in Ref.1. An amount of 555 PgC has been emitted for the period 1870-2015 (Ref.4). Reported amounts are subject to uncertainties due to conversion between* $GtCO_2$ *and PgC. The original* $GtCO_2$ *amounts were originally reported to the nearest 50* $GtCO_2$*, in Ref. 1. Calculated values were rounded to the nearest PgC, or to the nearest* $GtCO_2$ *after the conversion of units.*

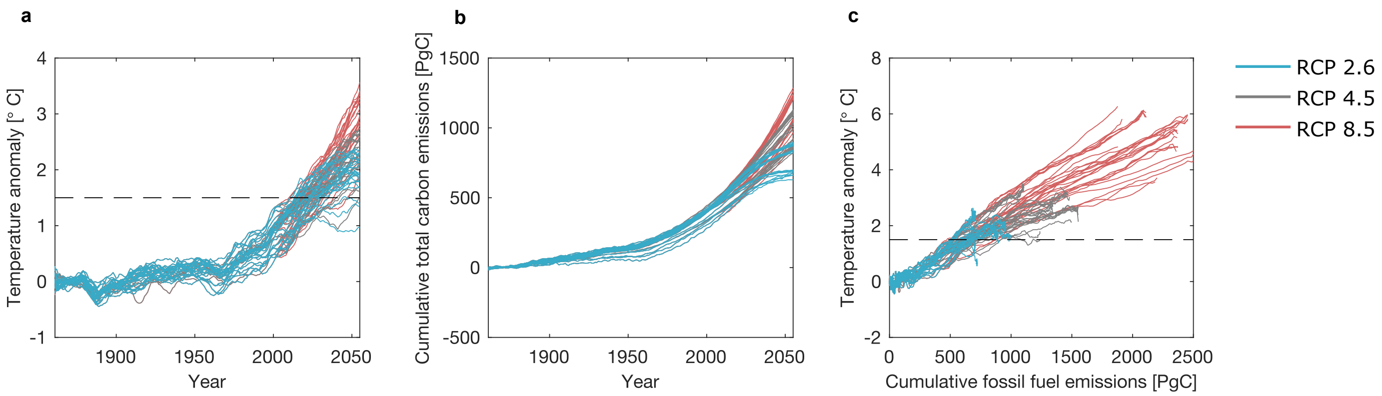
| Model name | OC (2006-2015) | OC (2002-2011) | OC (1995-2006) |
|---|---|---|---|
| BCC-CSM 1.1 | N | **Y** | **Y** |
| BCC-CSM 1.1-M | N | Y | **Y** |
| CanESM2* (5) | **Y** | **Y** | **Y** |
| CESM-BGC | N | N | **Y** |
| GFDL-ESM-2G | N | **Y** | **Y** |
| GFDL-ESM-2M | N | N | **Y** |
| HadGEM2-CC | N | N | N |
| HadGEM2-ES* (4) | **Y** | N | N |
| IPSL-CM5A-LR* (4) | N | **Y** | **Y** |
| IPSL-CM5A-MR | **Y** | **Y** | **Y** |
| IPSL-CM5B | **Y** | **Y** | **Y** |
| MIROC-ESM | **Y** | **Y** | **Y** |
| MIROC-ESM-CHEM | N | **Y** | **Y** |
| MPI-ESM-LR* (3) | **Y** | **Y** | **Y** |
| MPI-ESM-MR* (3) | **Y** | **Y** | **Y** |
| Nor-ESM1-ME | **Y** | **Y** | **Y** |

**Supplementary Table S2. Consistency test results.** The results are based on a comparison of simulated cumulative fossil fuel emissions at observed warming with that observed, for the three different base periods (indicated in the top row).

*Note: '**Y**' indicates that the model passed the consistency test based on the observational constraints for the given base period considered (indicated in the top row), at a 0.1 significance level (see Methods). Conversely, 'N' indicates that the model did not pass it. An asterisk indicates models with multiple ensemble members, where the number of ensemble members used is indicated in the brackets*

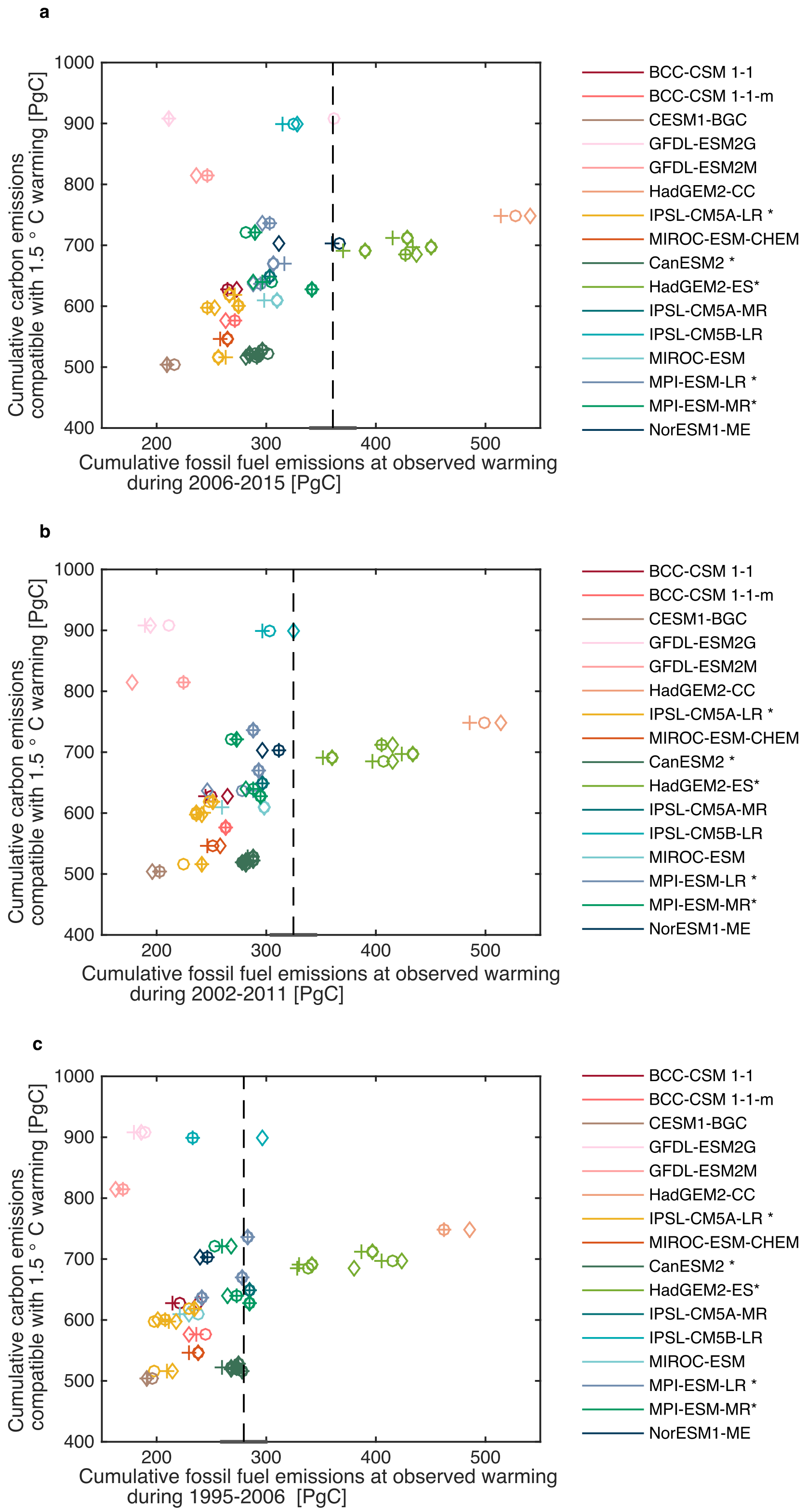
| Model name | RCP 2.6 and 8.5 (1861-1880) | RCP 2.6 and 8.5 (2006-2015) | RCP 2.6 and 4.5 (1861-1880) | RCP 2.6 and 4.5 (2006-2015) |
|---|---|---|---|---|
| **CanESM2 (5)** | h=0; p=0.60 | h=0; p=0.61 | h=0; p=0.06 | h=0; p=0.13 |
| **HadGEM2-ES (4)** | h=0; p=0.45 | h=0; p=0.24 | h=0; p=0.11 | h=0; p=0.38 |
| **IPSL-CM5A-LR(4)** | h=0; p=0.47 | h=0; p=0.67 | h=0; p=0.20 | h=0; p=0.13 |
| **MPI-ESM-LR (3)** | h=0; p= 0.96 | h=0; p=0.87 | h=0; p=0.29 | h=0; p=0.37 |

**Supplementary Table S3. Results of a two-sample t-test for differences in 1.5 °C carbon budgets between different RCP scenarios and relative to different base periods**. The RCP scenarios and base periods are indicated in the top row (and explained in *Methods*). The tests were carried for models that had more than one ensemble member available for each RCP scenario (at a 0.05 significance level). The number of ensemble members of each model is indicated in brackets next to the model name.



**Supplementary Figure S1. Time series of global mean temperature and cumulative carbon emissions for RCP 4.5, RCP 2.6, and RCP 8.5 scenarios, relative to 1861-1880.** (**a**) global mean temperature anomaly (decadal mean); (**b**) cumulative total carbon emissions; (**c**) temperature change as a function of cumulative total carbon emissions. As noted in the manuscript, we do not use RCP 2.6 simulations in our analysis, to avoid bias towards models that warm more strongly, because some of the RCP 2.6 simulations do not reach 1.5 °C global warming by 2100.

*Note: The dashed line in panel (**a**) and panel (**c**) indicates the 1.5 °C warming threshold. Anomalies are calculated relative to 1861-1880 period, and with respect to the pre-industrial control simulation to remove the effects of any drift.*



**Supplementary Figure S2. Simulated cumulative fossil-fuel carbon emissions at present warming (horizontal axis), and cumulative total carbon budgets consistent with 1.5 °C warming (vertical axis) for the RCP 4.5 scenario, which had the largest number of models and ensemble members available.**

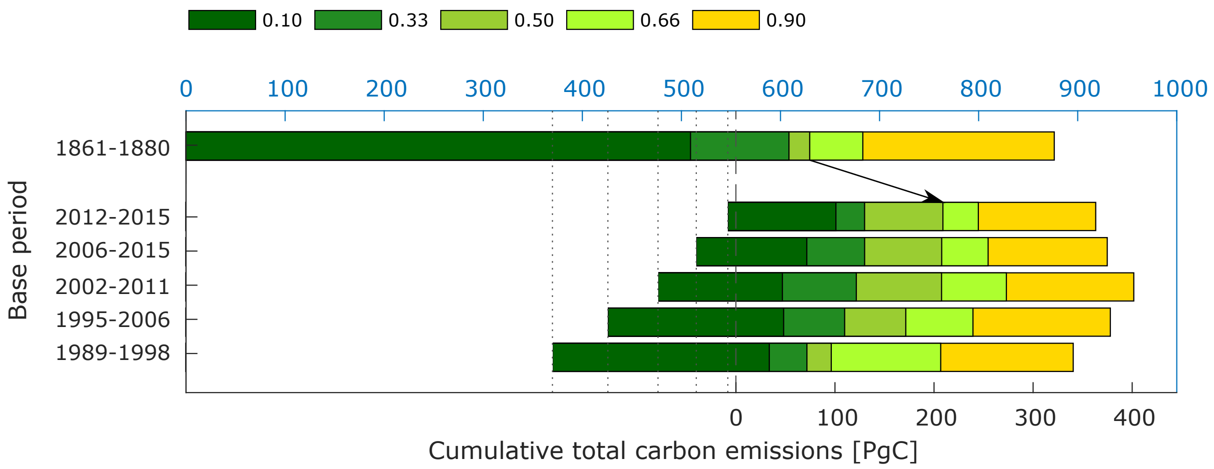
Panel **a**: the dashed line indicates an estimate of the observed historical cumulative fossil fuel emissions for the period 1870-2010 with the median value of 360.8 PgC (Ref. 12), where end of year 2010 represents the middle of the recent decade (the ± 20 PgC uncertainty of this estimate is indicated by the horizontal black bar).

Panel **b**: similarly to panel **a**, the dashed line indicates an estimate of cumulative fossil fuel emissions for the period 1870-2006, where year 2006 represents the middle of the 2002-2011 period.

Panel **c**: similarly to panel **a**, the dashed line indicates an estimate of cumulative fossil fuel emissions for the period 1870-2000, where year 2000 represents the middle of the 1995-2006 period.

Different symbols (indicated in the legend) represent cumulative emissions budgets calculated using different observational data sets of temperature. Models shown in shades of blue or green passed the consistently test based on 2006-2015 period (see *Methods*), while models in shades of red and orange failed it.

*Note: the colour scheme for panels **b** and **c** is identical to that one in panel **a**, to avoid confusion.*



**Supplementary Figure S3. Cumulative frequency distribution of carbon budgets consistent with staying below 1.5 °C global warming based on all CMIP5 models considered here for different base periods.** The grey dashed line indicates the observational total cumulative carbon emissions for the period 1870-2015, with the median value of 555 PgC (Ref.4), while the dotted lines indicate cumulative carbon emissions up to the middle of each baseline period (Ref.4,5). The top bar shows carbon budgets relative to 1861-1880 (blue axis), in PgC. The bottom bars show carbon budgets relative to different baseline periods, indicated on the vertical axis. The levels of warming were determined based on the mean of all the observational temperature data sets considered (*Methods*, Refs.6-11). Carbon budgets relative to the 2006-2015 baseline are offset by the IPCC estimate of the cumulative carbon emissions up to the end of 2010, consistent with Figure 4. The black arrow indicates the extension in 1.5 °C median carbon budget due to the change of the baseline of cumulative carbon emissions calculations. See *Methods* for details of how the distributions were calculated. The carbon budgets consistent with staying below 1.5 °C warming are based on RCP 4.5 and RCP 8.5 scenarios.

*Note: The percentiles indicated in the legend refer to the right-hand edge of each bar.*

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