Quantifying the probability distribution function of the transient climate response to cumulative CO_2 emissions

Emission pathways, carbon budgets, and climate-carbon response: governing mechanisms, limitations, and implications for policymakers

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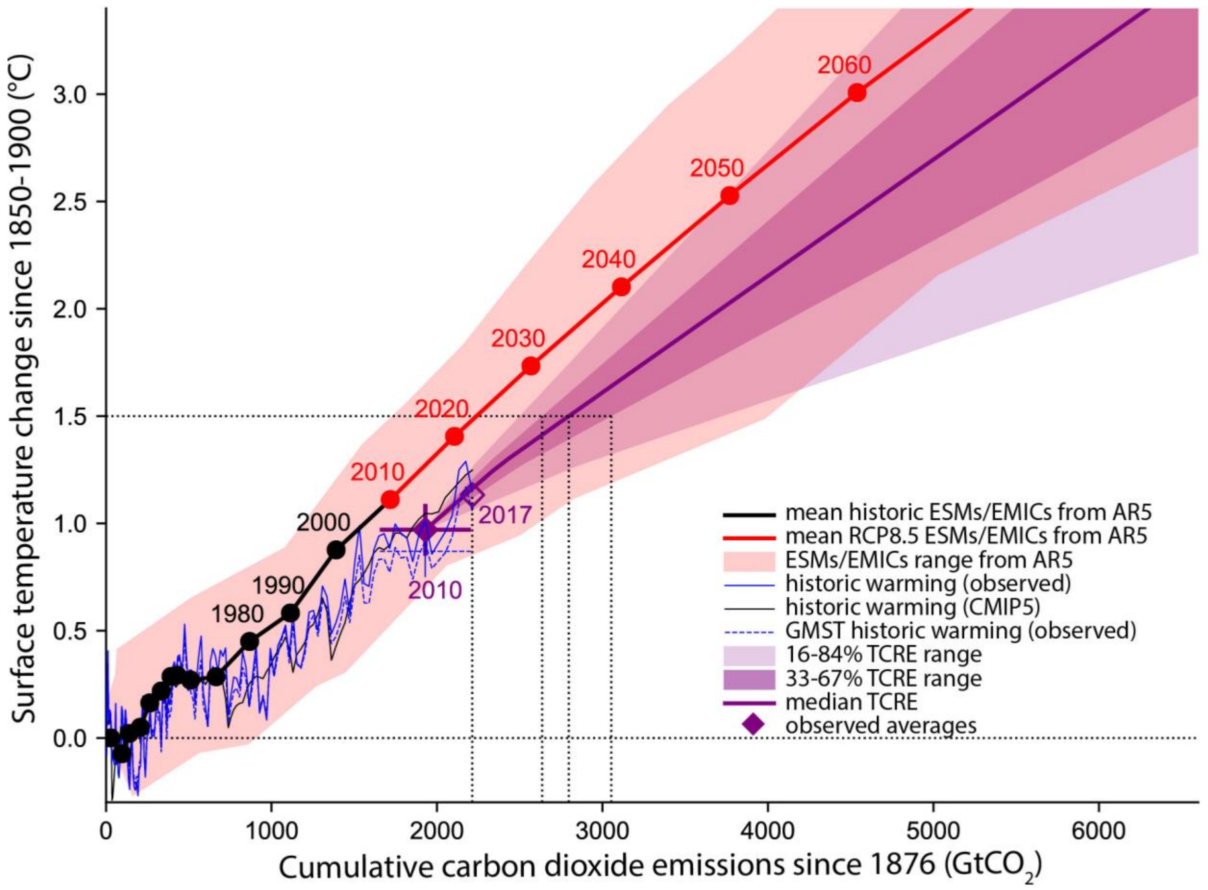
Near Linear ΔTemperature with Total Emitted CO_2

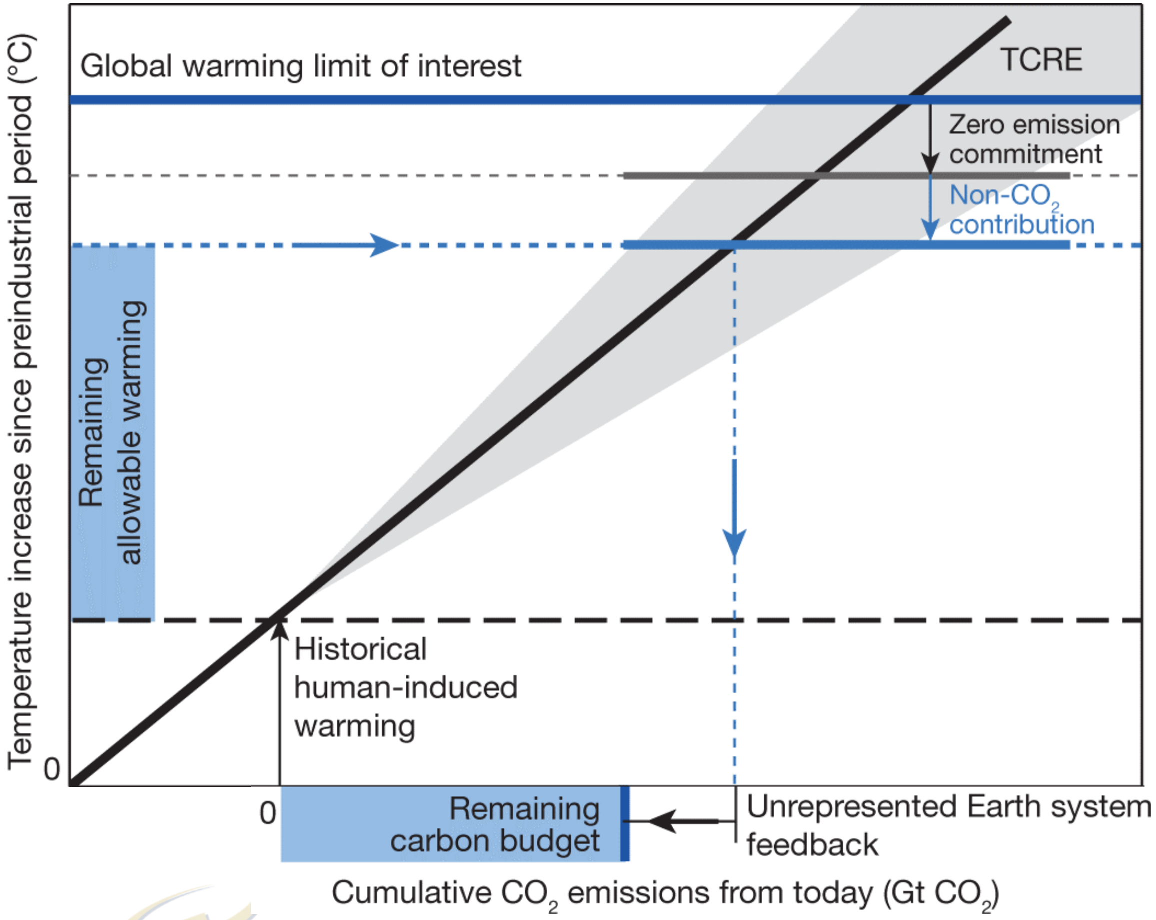
Saturation in radiative forcing per unit CO_2 emission **+** **Reduced heat and carbon uptake efficiency with more CO_2 emissions** **=**



Transient **C**limate **R**esponse to Cumulative CO_2 **E**missions (TCRE)

IPCC SR1.5, 2018; Allen et al., 2009; Matthews et al., 2009

Implications of the TCRE



- Fixed quantity of total CO_2 emissions consistent with not exceeding a threshold in global warming (ie. 2°C or 1.5°C) :
  carbon budget = warming goal ÷ TCRE
- Pathway independence – for typical emission scenarios, the TCRE holds, so mitigation policies can follow a carbon budget rather than emissions pathway
- Ultimately need to reach net-zero emissions to limit global warming

Limitations for carbon budgets from the TCRE:

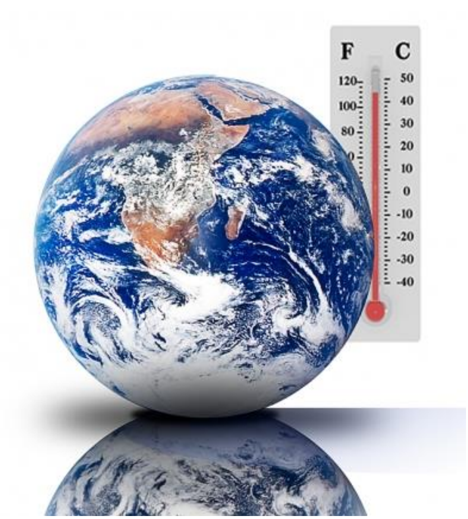
- Non-CO2 radiative forcing
- Zero emission commitment
- Earth system feedbacks
- Constant, declining, zero, or negative CO_2 emissions

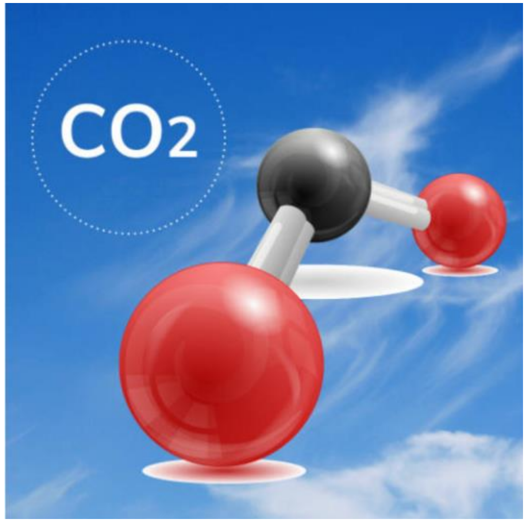
Rogelj et al., 2019

TCRE Components

1. Climate sensitivity to atmospheric CO_2 concentration

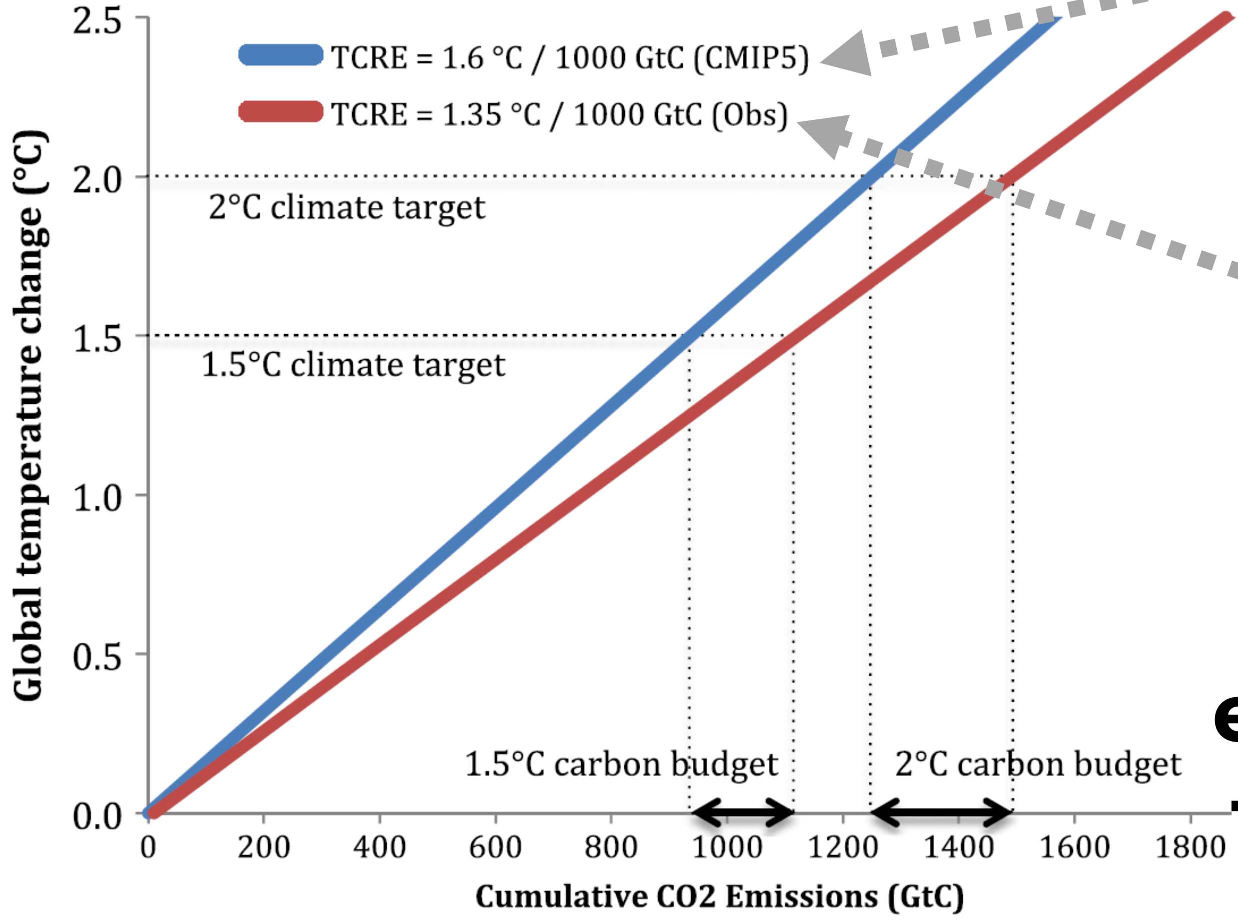
2. Carbon cycle response to cumulative CO_2 emissions





Kodda, 2020; Danilof, 2010

TCRE uncertainty



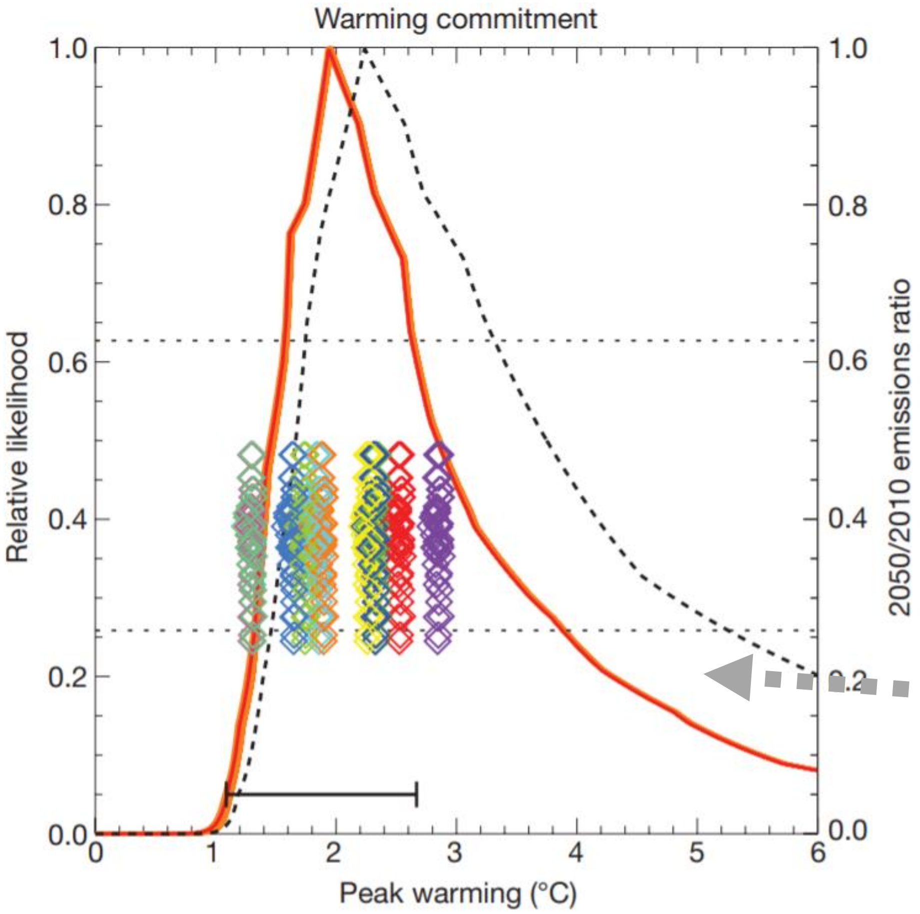
Modelling studies often report a higher mean and greater spread of TCRE values (ie. Gillett et al. (2013) – CMIP5: median:1.6°C/EgC, 5-95% confidence: 0.8-2.4°C/EgC)

Observational studies often report a lower mean and reduced spread of TCRE values (ie. Gillett et al. (2013) : $\bar{x}$:1.35°C/EgC, 5-95% confidence: 0.7-2.0°C/EgC)

No study to date has explicitly addressed whether the TCRE is normally or non-normally distributed

Matthews et al., 2017; Gillett et al., 2013

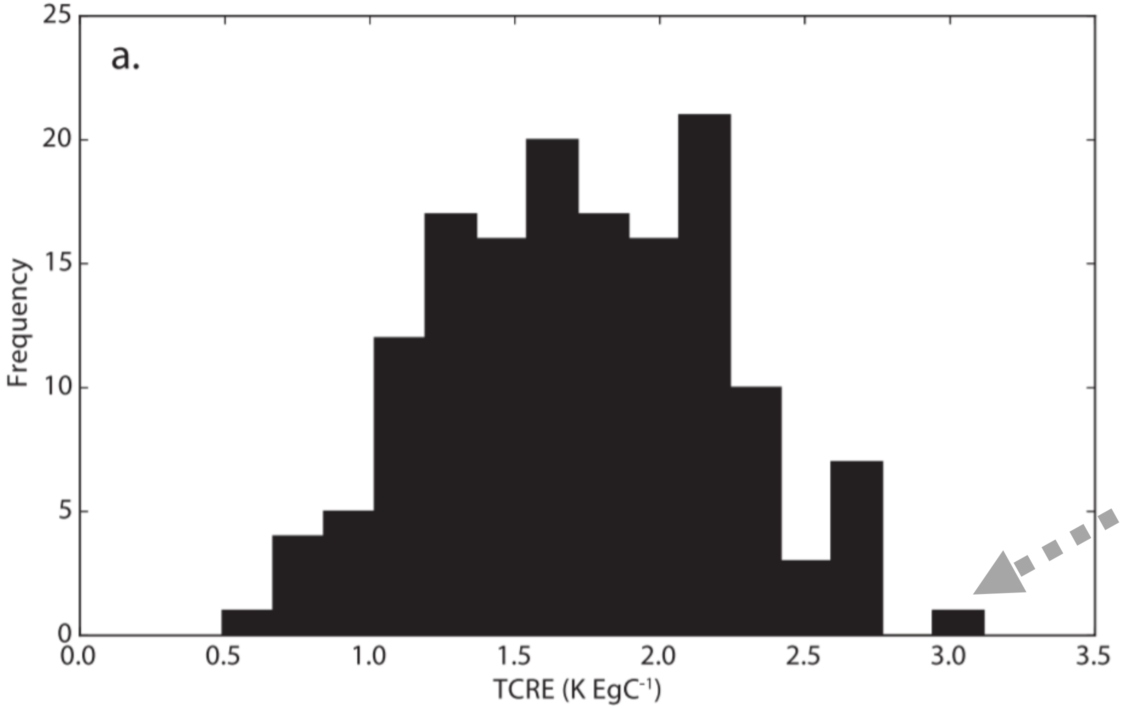
TCRE Probability Distribution Function (PDF)?



In a study of the Cumulative Warming Commitment (CWC) (equivalent to the TCRE assuming a negligible zero emissions commitment), Allen et al. (2009) reports asymmetry in the distribution of the CWC

Allen et al., 2009

TCRE Probability Distribution Function (PDF)?



In a study of the TCRE using a perturbed physics approach, MacDougall et al. (2017) show the TCRE PDF may be well described by a normal distribution, though there is a slight positive skew suggested to be due to climate sensitivity

MacDougall et al., 2017

The IPCC SR1.5 report shows this uncertainty in whether or not the TCRE is normally distributed has a considerable influence upon remaining carbon budget calculations, though did not advocate for one distribution over the other

Table 2.2 from IPCC SR1.5: The assessed remaining carbon budget and its uncertainties.

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	±250	–400 to +200	+100 to +200	±250	±20
0.4		530	350	230						
0.5		770	530	380						
0.53	**~1.5°C**	**840**	**580**	**420**						
0.6		1010	710	530						
0.63		1080	770	570						

Objectives

1. Calculate the TCRE based upon current understandings of the interactions between climate and carbon processes.

2. Examine the probability distribution function of the TCRE using a Monte-Carlo error propagation.

3. Explore the sensitivity of the TCRE to various Earth system parameters.

4. Compute the CO_2-only carbon budget consistent with 2°C warming.

Methods: ZD²OM – **Z**ero Dimensional **D**iffusive **O**cean Heat and Carbon Uptake **M**odel

$$\Lambda = \frac{R(1-l)}{\lambda}\left(\frac{\ln\left(\frac{C_A}{C_{AO}}\right)}{1+\frac{f_o\rho C_p\tau\epsilon\sqrt{\beta}}{\sqrt{\mu\lambda^2\ln\left(\frac{C_A}{C_{AO}}\right)}}}\right)\times\left(\frac{1}{C_A - C_{AO} + \frac{2B_o\Gamma\ln\left(\frac{C_A}{C_{AO}}\right)^{\frac{3}{2}}}{3\sqrt{\mu\beta}}}\right)$$

TCRE

Monte-Carlo simulation with 10 million ZD²OM iterations drawing randomly from 5 Earth System parameter PDFs

Methods: ZD^{2}OM

$$\Lambda = \frac{R(1-l)}{\lambda}\left(\frac{\ln\left(\frac{C_A}{C_{AO}}\right)}{1+\frac{f_o \rho C_p \tau \epsilon \sqrt{\beta}}{\sqrt{\mu \lambda^2 \ln\left(\frac{C_A}{C_{AO}}\right)}}}\right) \times \left(\frac{1}{C_A - C_{AO} + \frac{2B_o \Gamma \ln\left(\frac{C_A}{C_{AO}}\right)^{\frac{3}{2}}}{3\sqrt{\mu\beta}}}\right)$$

Radiative forcing from an e-fold increase in atmospheric CO_2

Methods: ZD^{2}OM

$$\Lambda = \frac{R(1-l)}{\lambda}\left(\frac{\ln\left(\frac{C_A}{C_{AO}}\right)}{1+\frac{f_o \rho C_p \tau \epsilon \sqrt{\beta}}{\sqrt{\mu\lambda^2 \ln\left(\frac{C_A}{C_{AO}}\right)}}}\right) \times \left(\frac{1}{C_A - C_{AO} + \frac{2B_o\Gamma \ln\left(\frac{C_A}{C_{AO}}\right)^{\frac{3}{2}}}{3\sqrt{\mu\beta}}}\right)$$

Land-borne fraction of carbon

Methods: ZD^{2}OM

$$\Lambda = \frac{R(1-l)}{\lambda}\left(\frac{\ln\left(\frac{C_A}{C_{AO}}\right)}{1+\frac{f_o \rho C_p \tau \epsilon \sqrt{\beta}}{\sqrt{\mu\lambda^2 \ln\left(\frac{C_A}{C_{AO}}\right)}}}\right) \times \left(\frac{1}{C_A - C_{AO} + \frac{2B_o\Gamma \ln\left(\frac{C_A}{C_{AO}}\right)^{\frac{3}{2}}}{3\sqrt{\mu\beta}}}\right)$$

Climate feedback

Methods: ZD^{2}OM

$$\Lambda = \frac{R(1-l)}{\lambda}\left(\frac{\ln\left(\frac{C_A}{C_{AO}}\right)}{1+\frac{f_o \rho C_p \tau \epsilon \sqrt{\beta}}{\sqrt{\mu \lambda^2 \ln\left(\frac{C_A}{C_{AO}}\right)}}}\right) \times \left(\frac{1}{C_A - C_{AO} + \frac{2B_o \Gamma \ln\left(\frac{C_A}{C_{AO}}\right)^{\frac{3}{2}}}{3\sqrt{\mu\beta}}}\right)$$

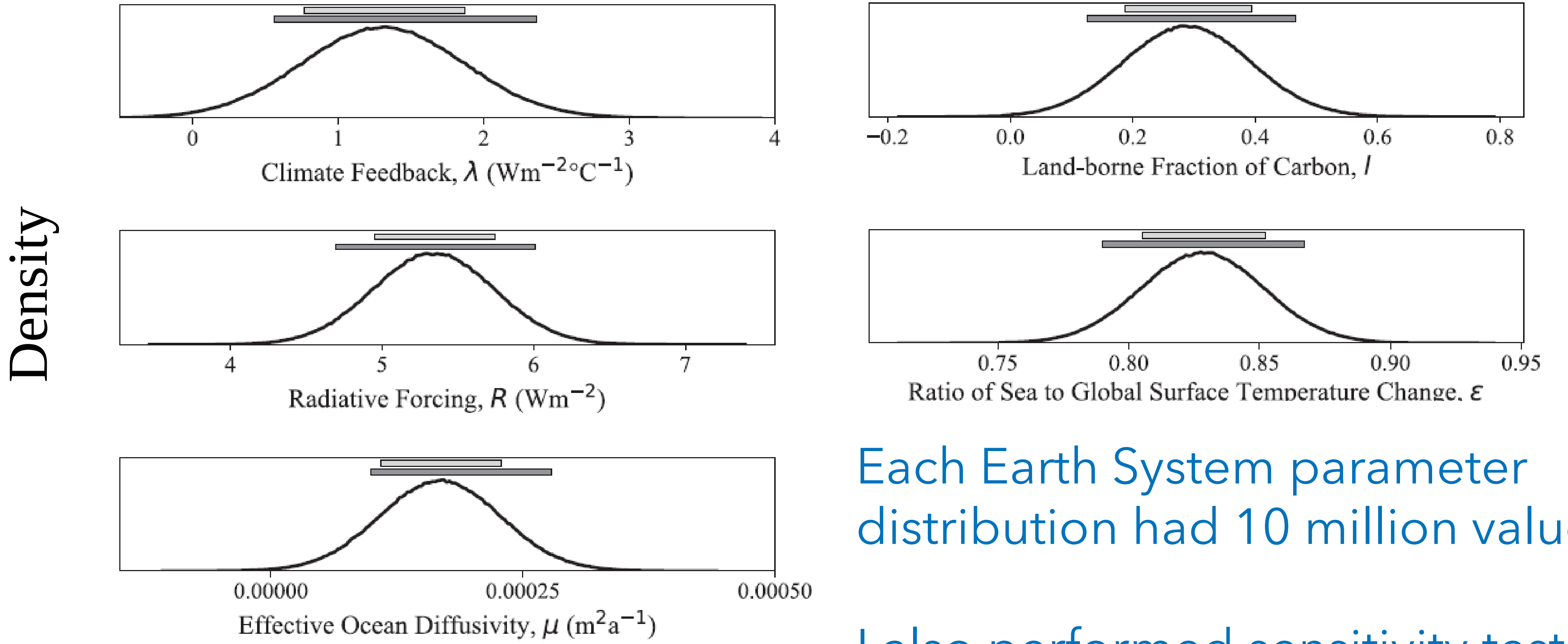
Effective ocean diffusivity

Methods: ZD^{2}OM

$$\Lambda = \frac{R(1-l)}{\lambda}\left(\frac{\ln\left(\frac{C_A}{C_{AO}}\right)}{1+\frac{f_o \rho C_p \tau \epsilon \sqrt{\beta}}{\sqrt{\mu \lambda^2 \ln\left(\frac{C_A}{C_{AO}}\right)}}}\right) \times \left(\frac{1}{C_A - C_{AO} + \frac{2B_o \Gamma \ln\left(\frac{C_A}{C_{AO}}\right)^{\frac{3}{2}}}{3\sqrt{\mu\beta}}}\right)$$

Ratio of sea surface temperature change to global temperature change

Methods: Source Parameter PDFs



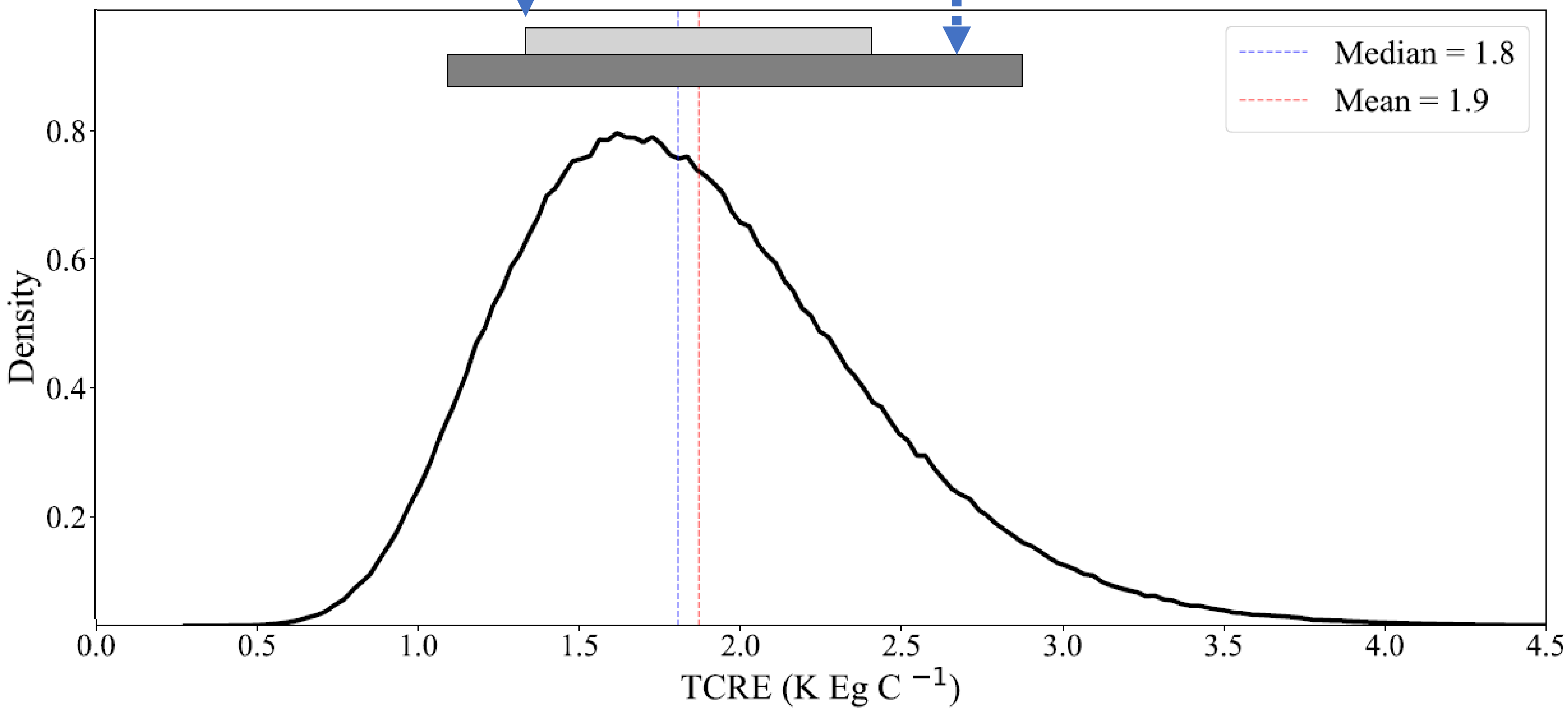
Each Earth System parameter distribution had 10 million values

I also performed sensitivity tests with normal and uniform priors

Results

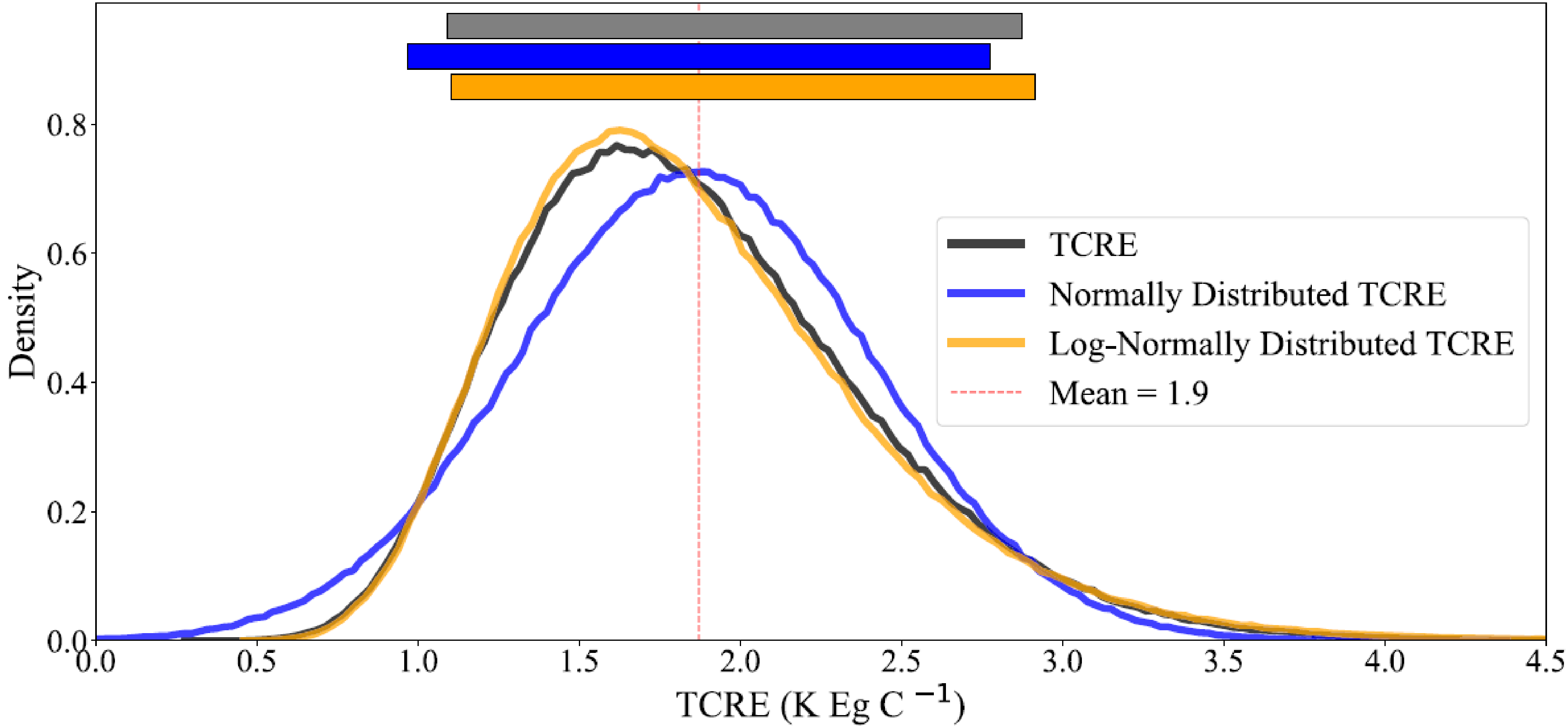
16 – 84% confidence interval: 1.3 to 2.4 °C/EgC

5 – 95% confidence interval: 1.1 to 2.9 °C/EgC

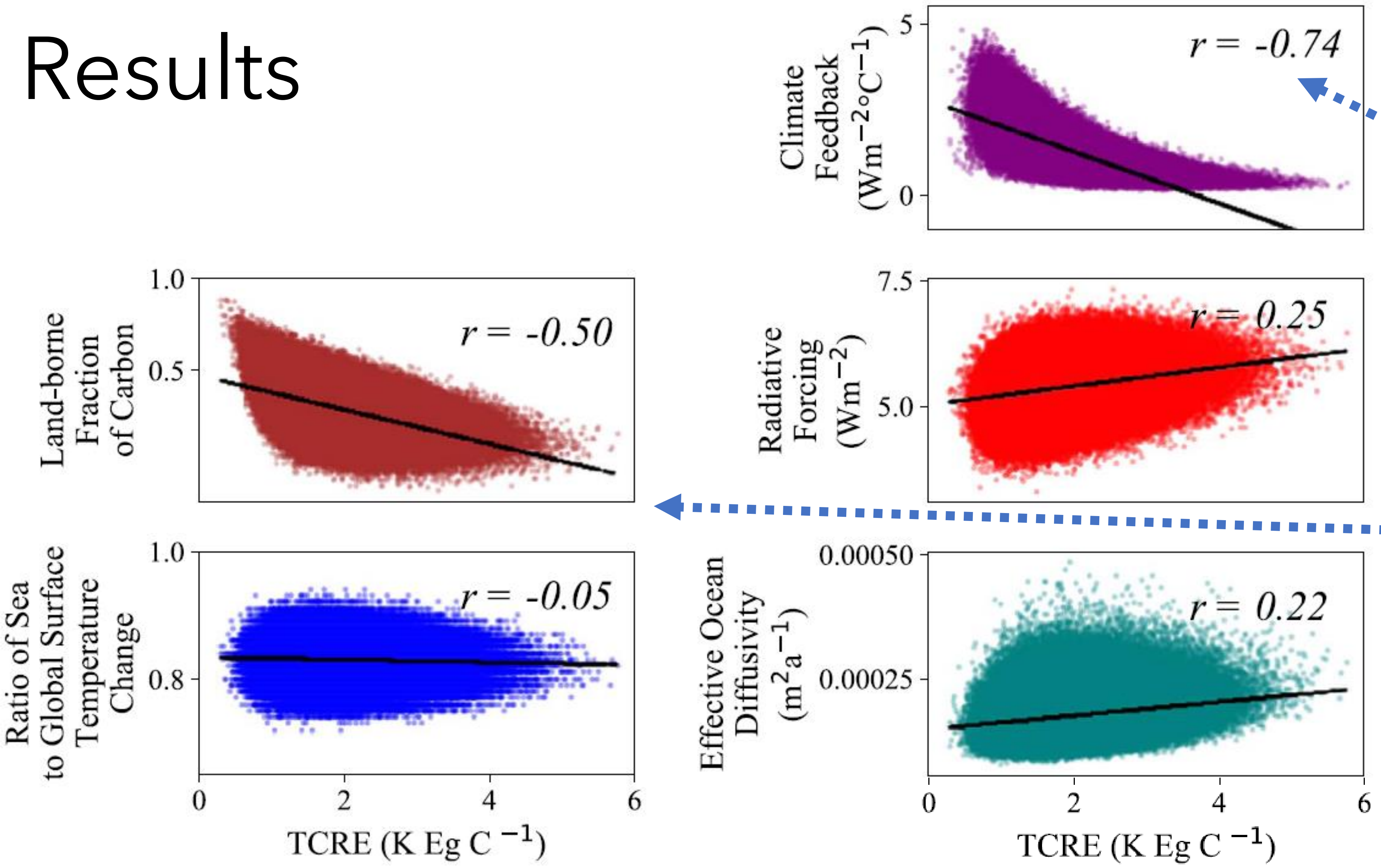


Results

The distribution of TCRE values I calculated is well described by a log-normal distribution, which was robust to the distribution of the priors

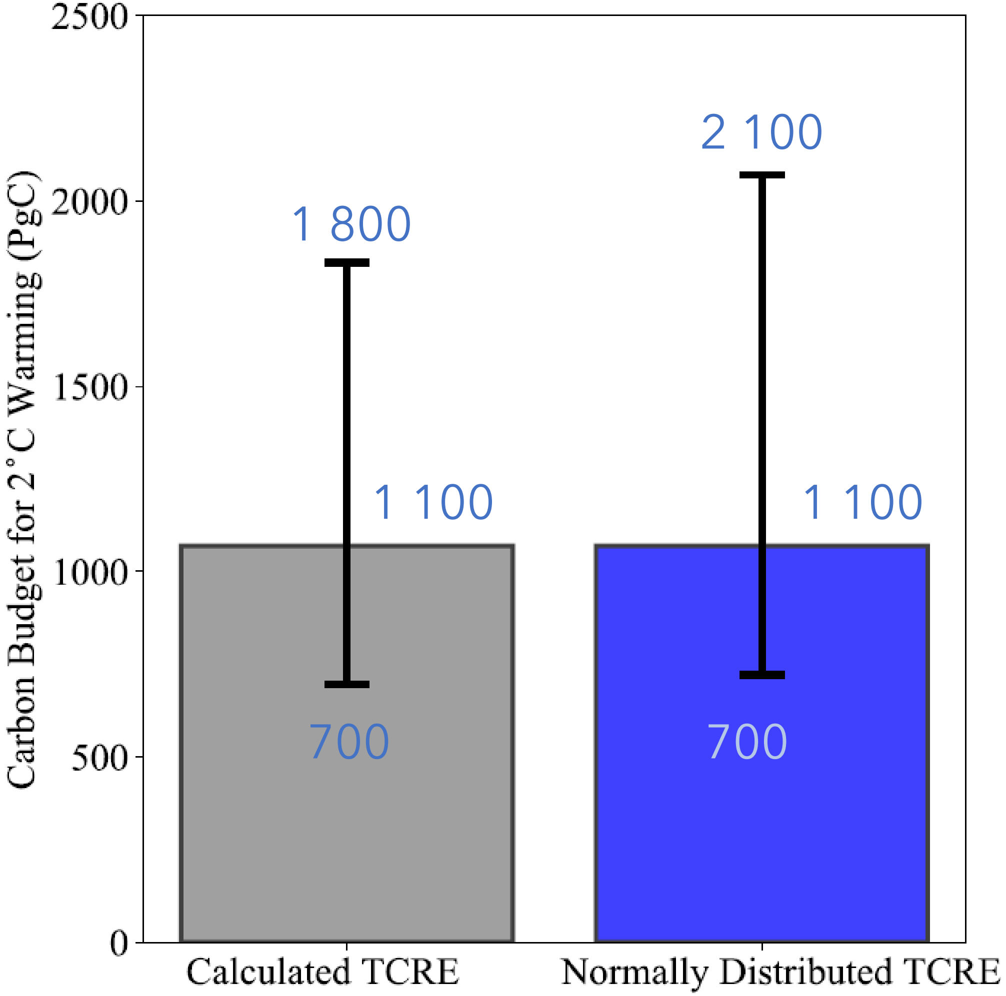


Results



The climate feedback parameter contributed the most uncertainty to the TCRE calculation, followed by the land-borne fraction of carbon

Results



- From the TCRE I calculated, the CO_2-only total carbon budget (including past, present, and future CO_2 emissions) for 2°C warming is 1 100 billion tonnes of carbon (or petagrams - PgC), ranging from 700 - 1 800 PgC at 5-95% confidence
- Assuming a normally-distributed TCRE results in a 700 - 2 100 PgC budget estimate at 5-95% confidence
- While the true TCRE is likely close to the centre of the PDF, assuming a normally distributed TCRE overestimates the upper limit of the carbon budget estimate by ~300 PgC, or ~27 years of emissions at a rate of 11 Pg C yr-1

Conclusions

1. The TCRE is well described by a log-normal distribution.

2. The TCRE we calculated ranges from 1.1 to 2.9 K EgC^{-1} (5-95% confidence), with a mean of 1.9 K EgC^{-1} and median of 1.8 K EgC^{-1}.

3. Climate sensitivity (feedback) is most influential, followed by land-borne fraction of carbon, radiative forcing from an e-fold rise in CO_2, ocean diffusivity, and the ratio of sea to global warming.

4. The CO_2-only carbon budget for 2°C warming is 1100 PgC (700-1800, 5-95% confidence), while assuming a normal TCRE PDF suggests a 2°C budget of 1100 PgC (700-2100, 5-95% confidence).

Conclusions

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Thank You!

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