Current level and rate of warming determine emissions budgets under ambitious mitigation

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Based on a Nature Geoscience Article of the same name:
rdcu.be/2Use

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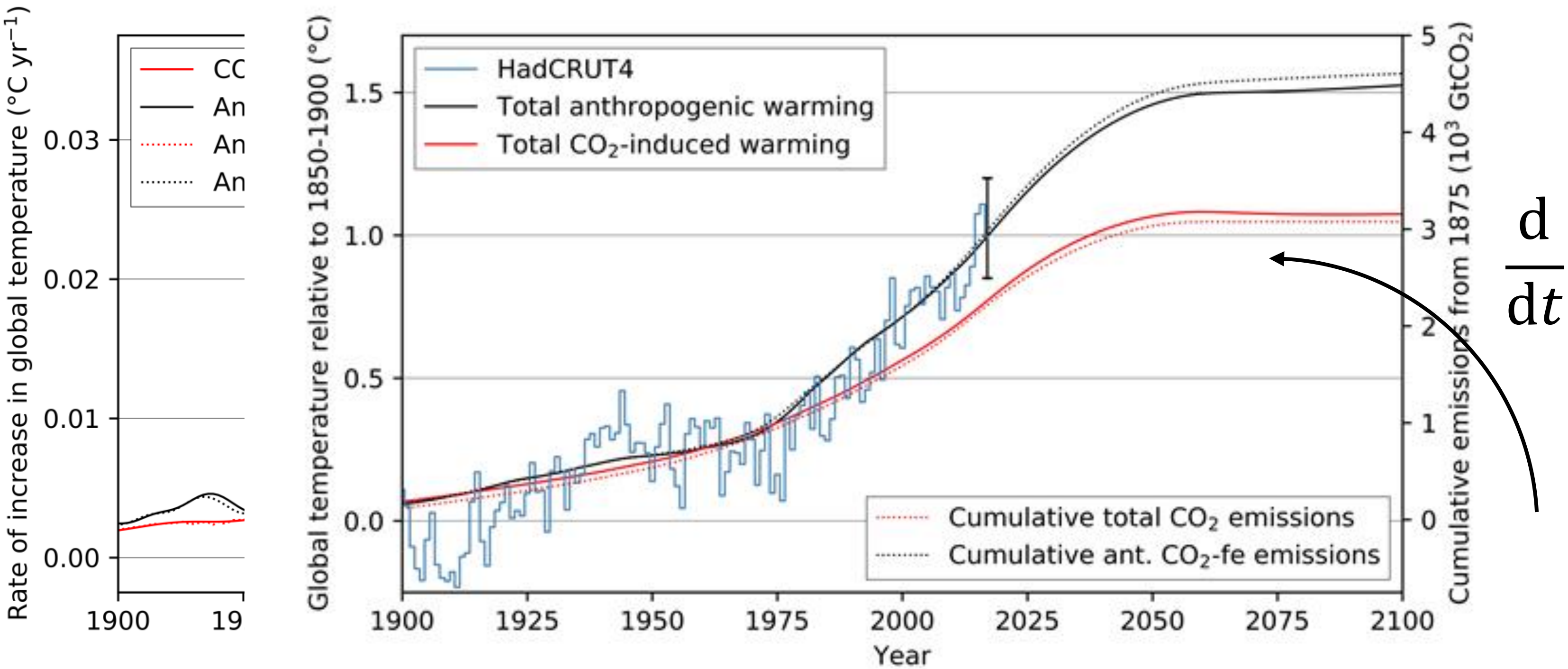
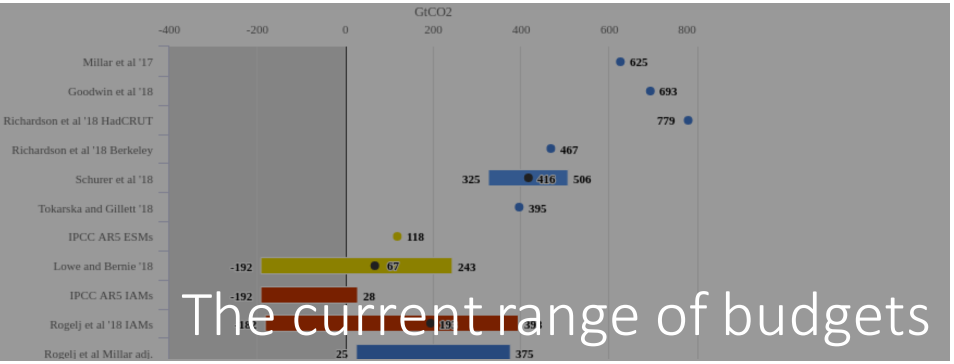
We can estimate the remaining **carbon budget** for ambitious mitigation targets using observations of the **current level and rate** of warming

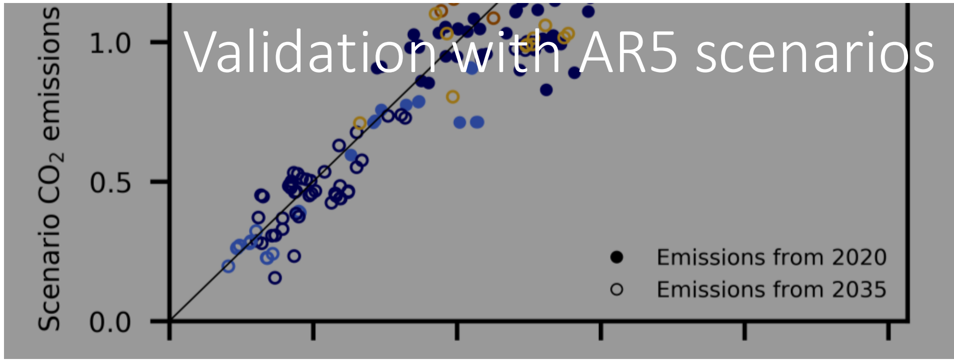
Our calculation is **simple, transparent**, and both model and response independent



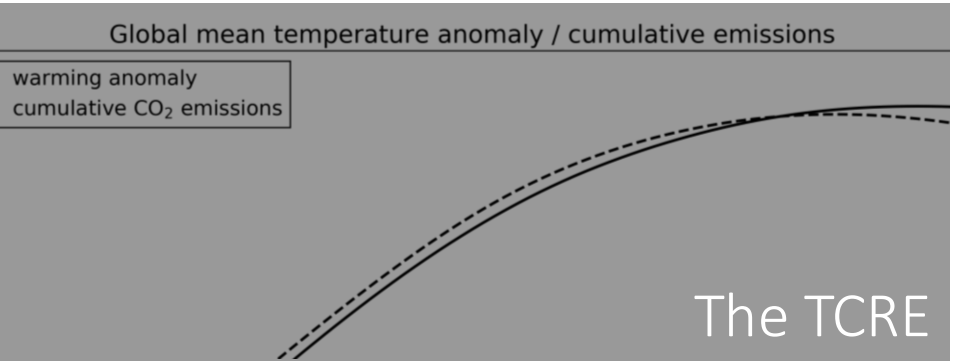
Navigation



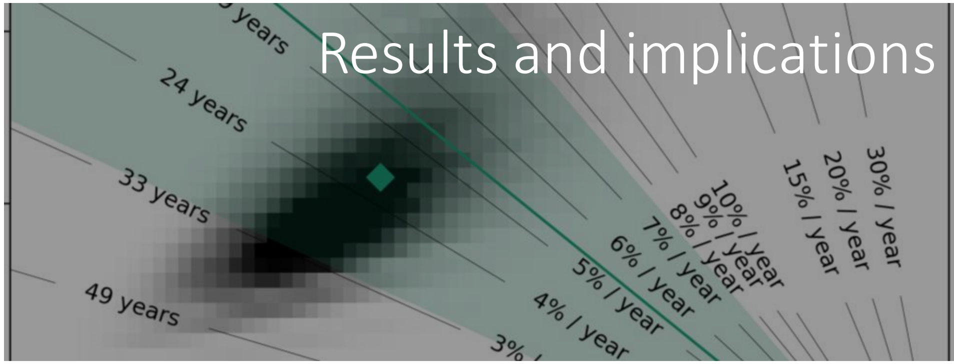
The current range of budgets



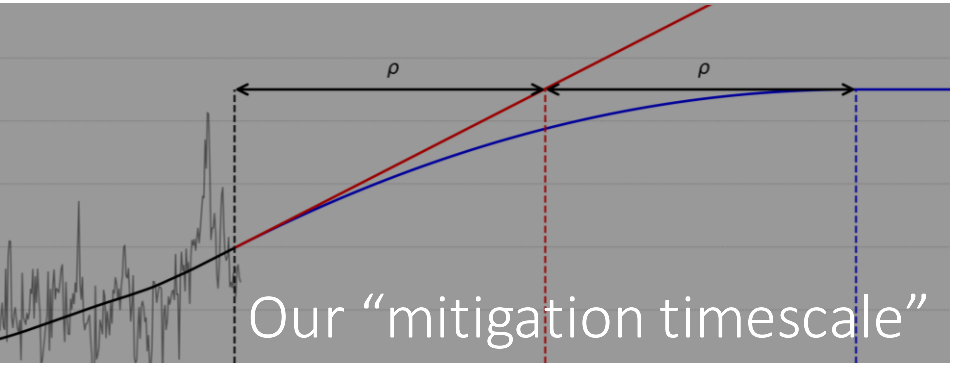
Validation with AR5 scenarios



The TCRE



Results and implications



Our “mitigation timescale”

Summary

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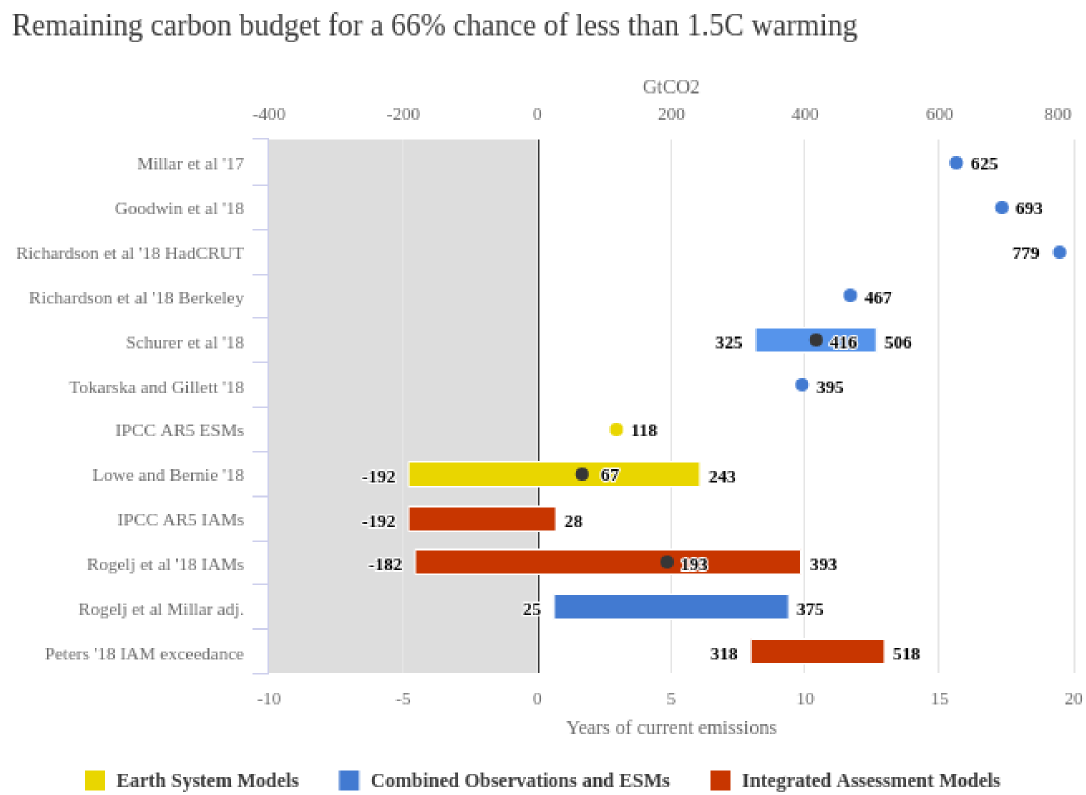
The Budget Problem

- Over the last few years, there have been a wide range of estimates of the remaining carbon budget to key temperature targets.
- Here is a graphic from CarbonBrief showing just how large the difference between many of the estimates for the budget to 1.5°C is.



CB

Source: https://www.carbonbrief.org/analysis-how-much-carbon-budget-is-left-to-limit-global-warming-to-1-5c

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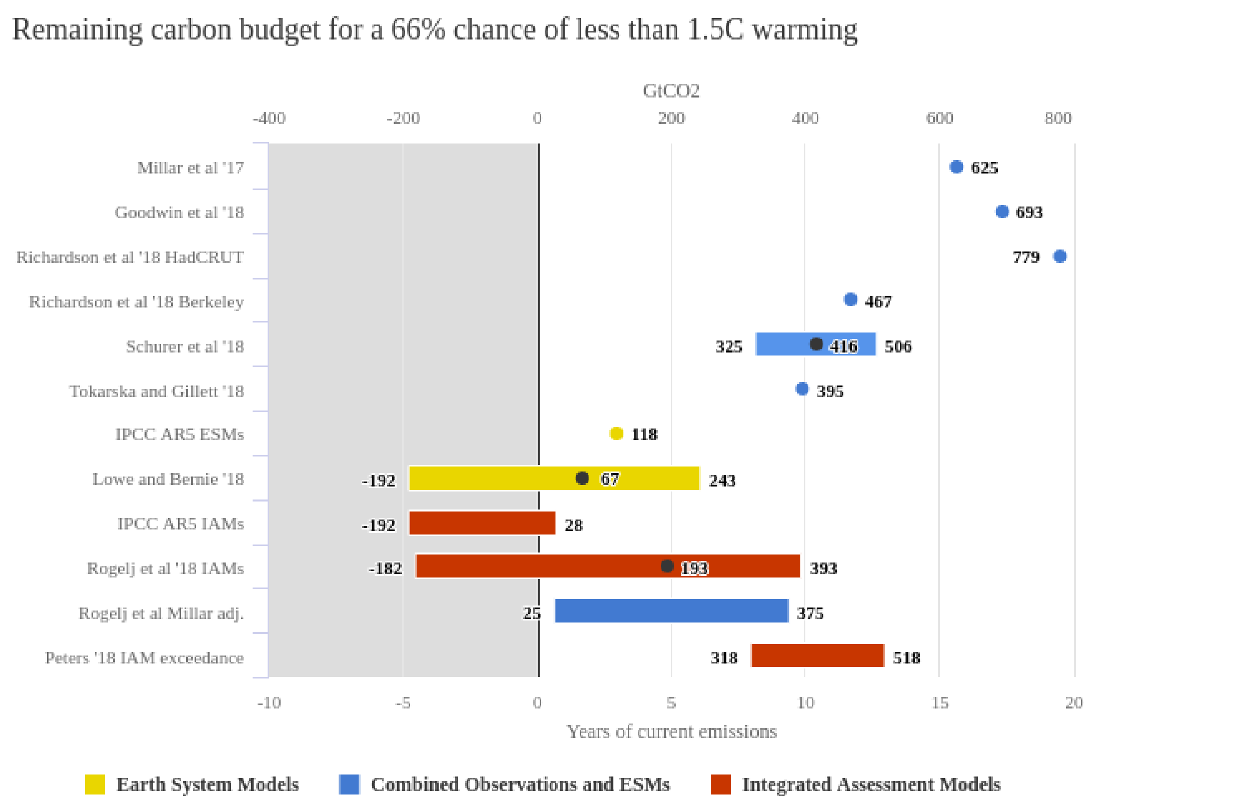
The Budget Problem

- These discrepancies are due to a number of geophysical constraints, such as:

- The current level of warming
- The definition of pre-industrial
- The current and future level of non-CO_2 forcing

- We hope to provide a simple framework for calculating budgets that can explain these differences.



Source: https://www.carbonbrief.org/analysis-how-much-carbon-budget-is-left-to-limit-global-warming-to-1-5c

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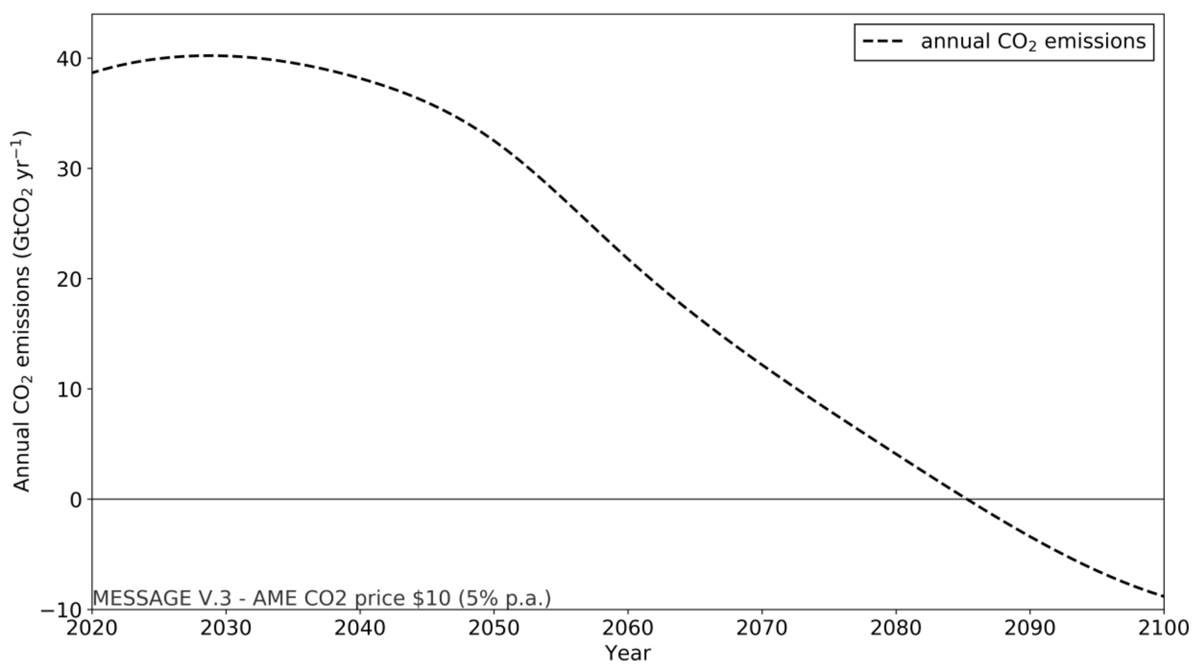
The TCRE

- This shows one CO_2 emission scenario from the AR5 database.



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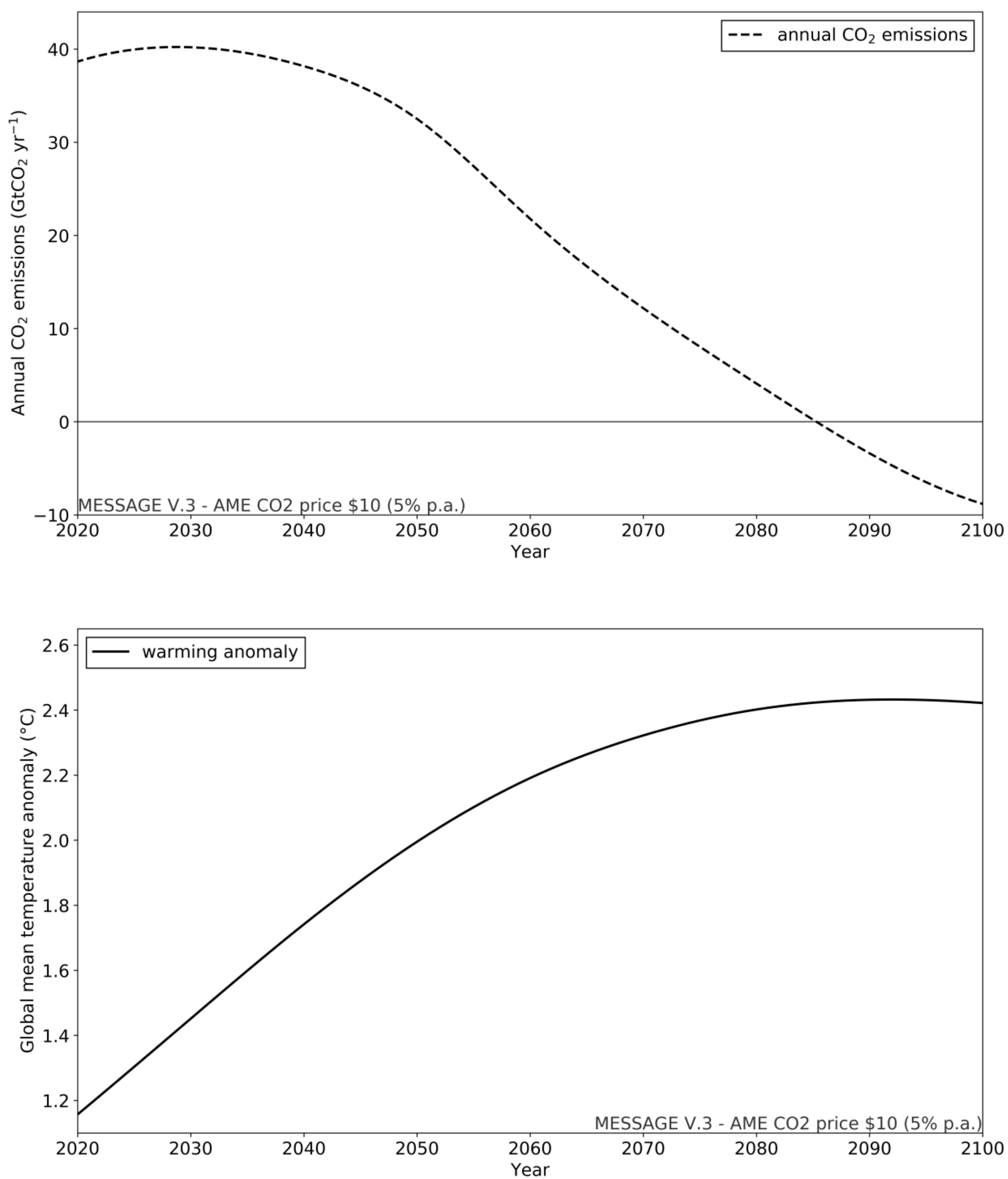
The TCRE

- Here is the temperature anomaly within the same scenario.



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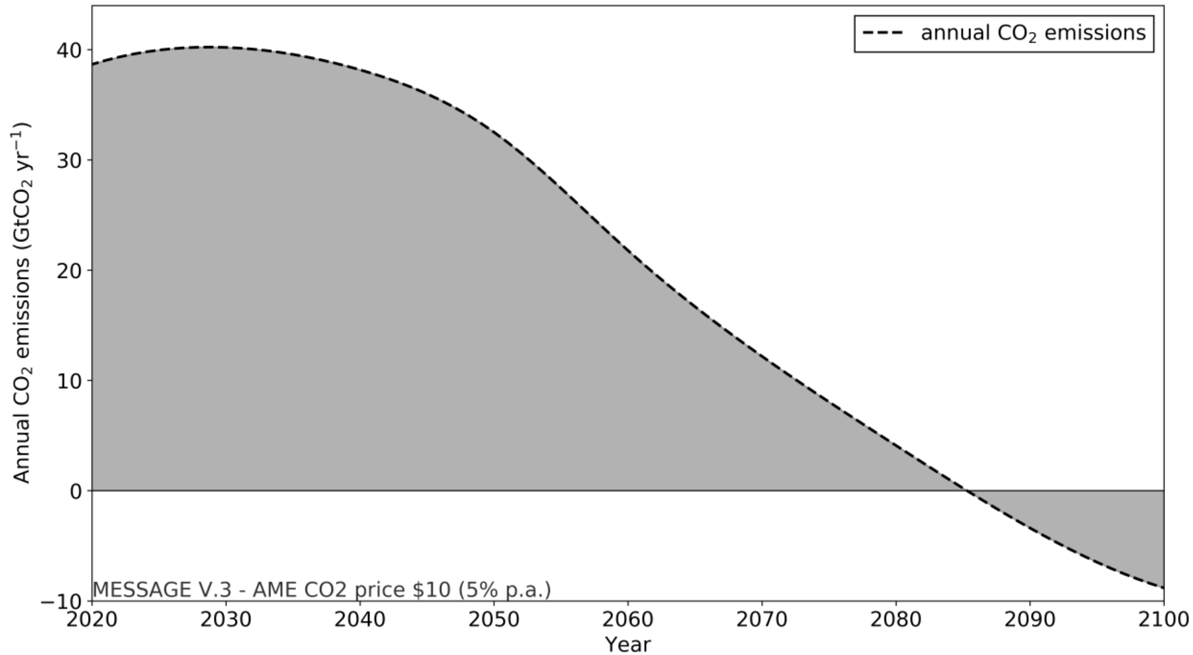
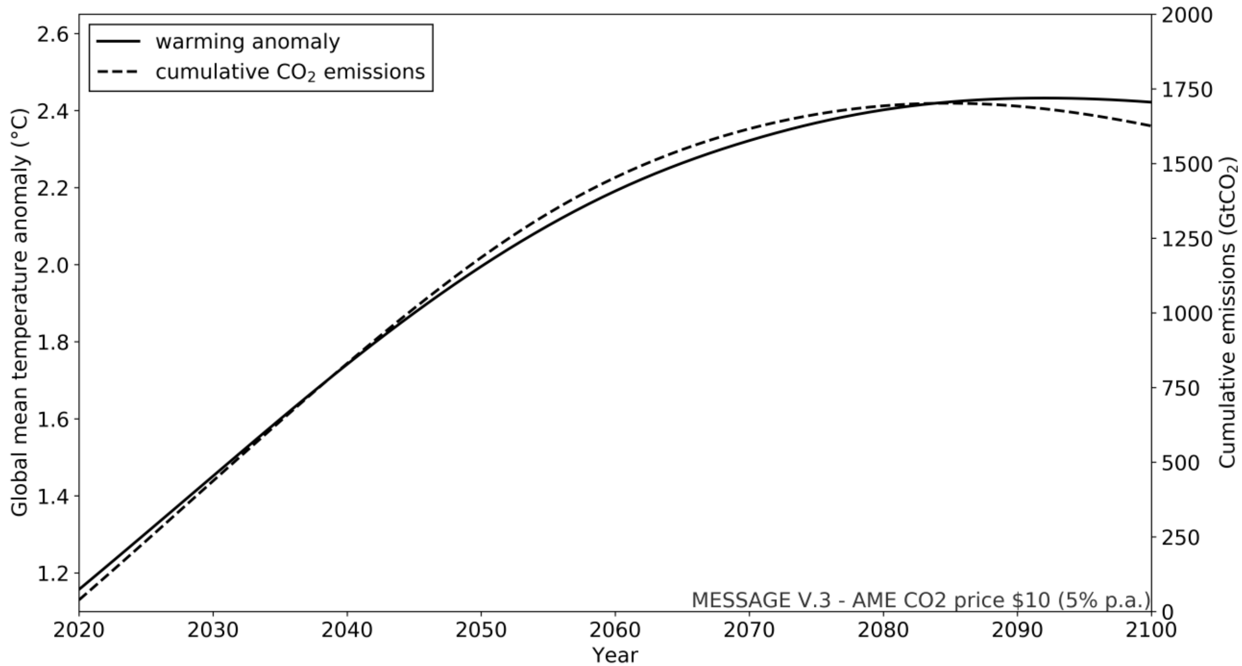
The TCRE

- If we integrate annual emissions to get cumulative CO_2 emissions…
- … we find that they are almost proportional to temperature anomaly, so we can write:

$$T = r \int E \, \mathrm{d}t$$





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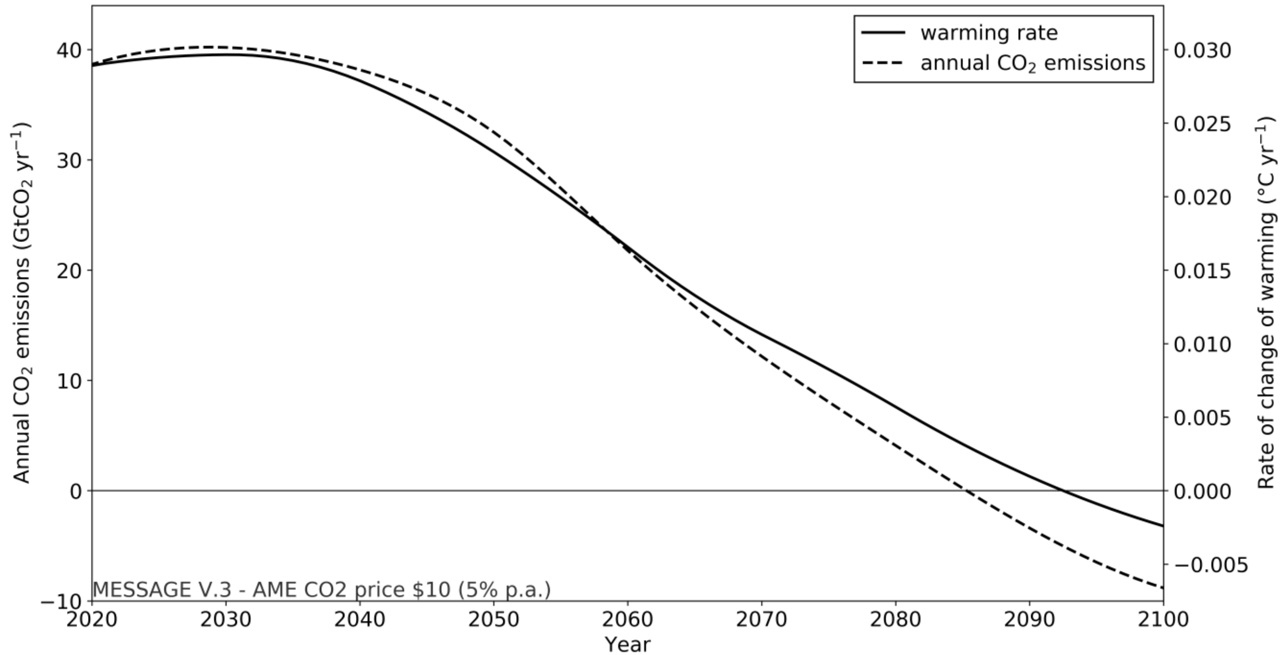
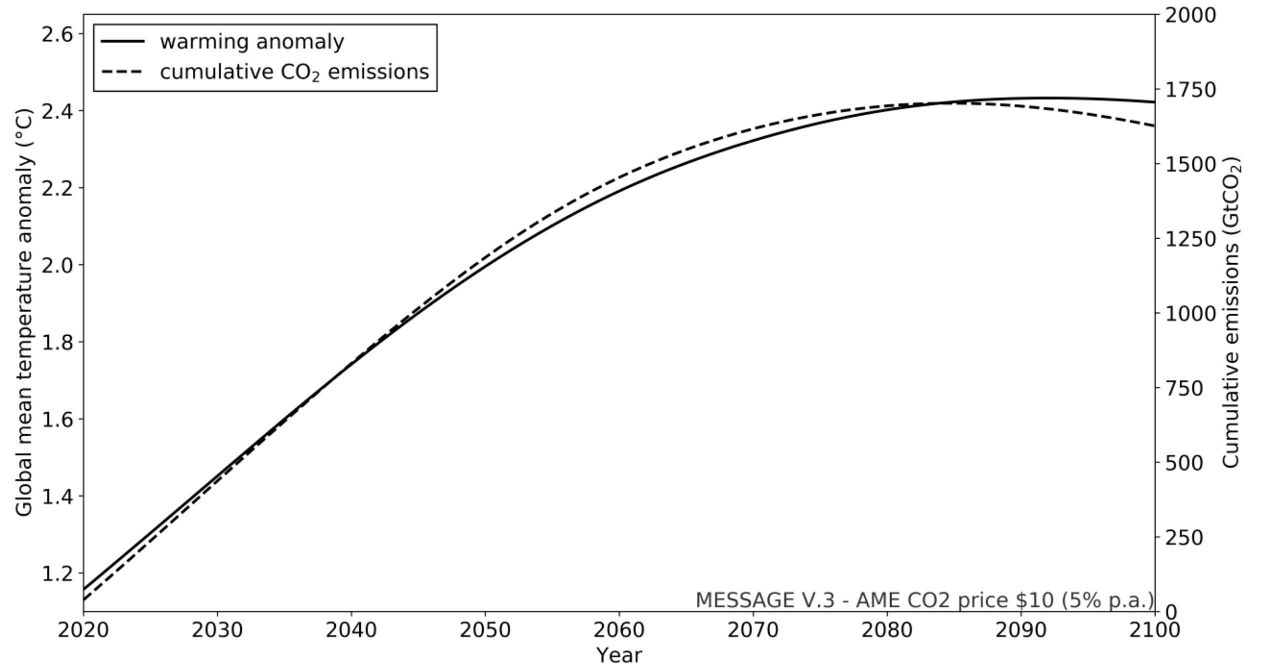
The TCRE

- Clearly the rate of change of temperature anomaly is also almost proportional to annual CO_2 emissions, so we have:

$$\boldsymbol{T = r\int E\,\mathrm{d}t}$$

$$\boldsymbol{\frac{\mathrm{d}T}{\mathrm{d}t} \equiv T' = rE}$$





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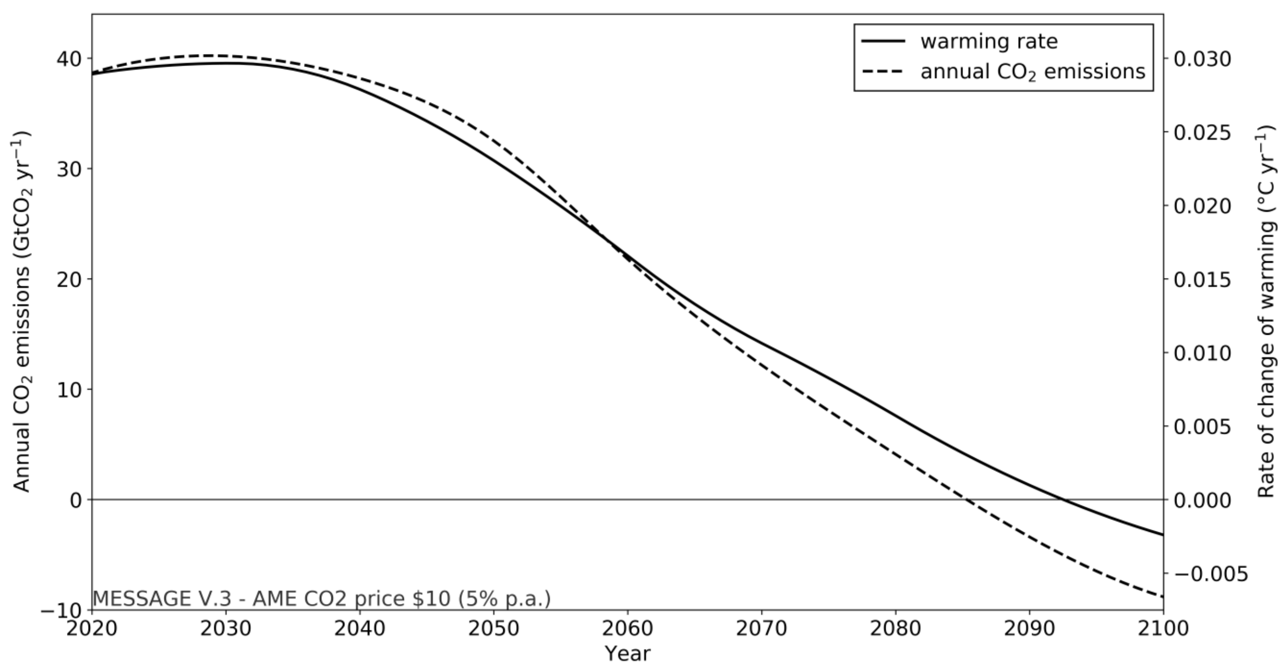
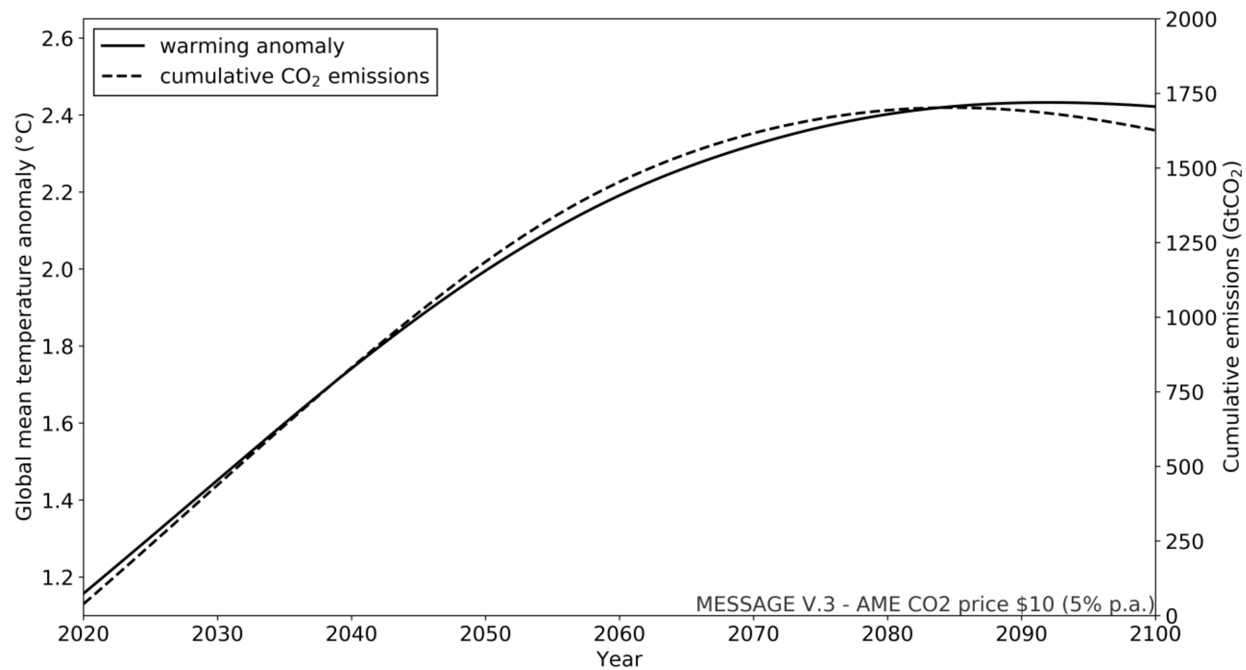
The TCRE

- The constant of proportionality, r, is an emergent property of ESMs consistent with observations of the climate system called the Transient Response to Cumulative Carbon Emissions (TCRE).

- It is only strictly true for CO_2 emissions and the warming that they directly cause:

$$T_{CO_2} = r \int E_{CO_2}\, \mathrm{dt}$$





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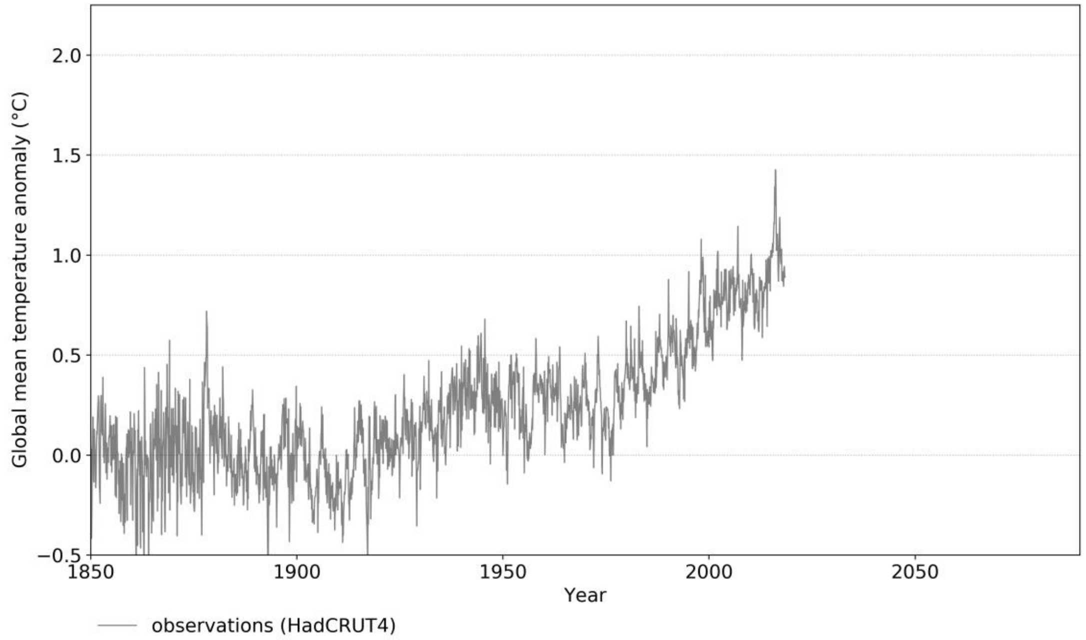
The Mitigation Timescale

- Here we show observations of global mean temperature anomaly from HadCRUT4, relative to 1850-1900.



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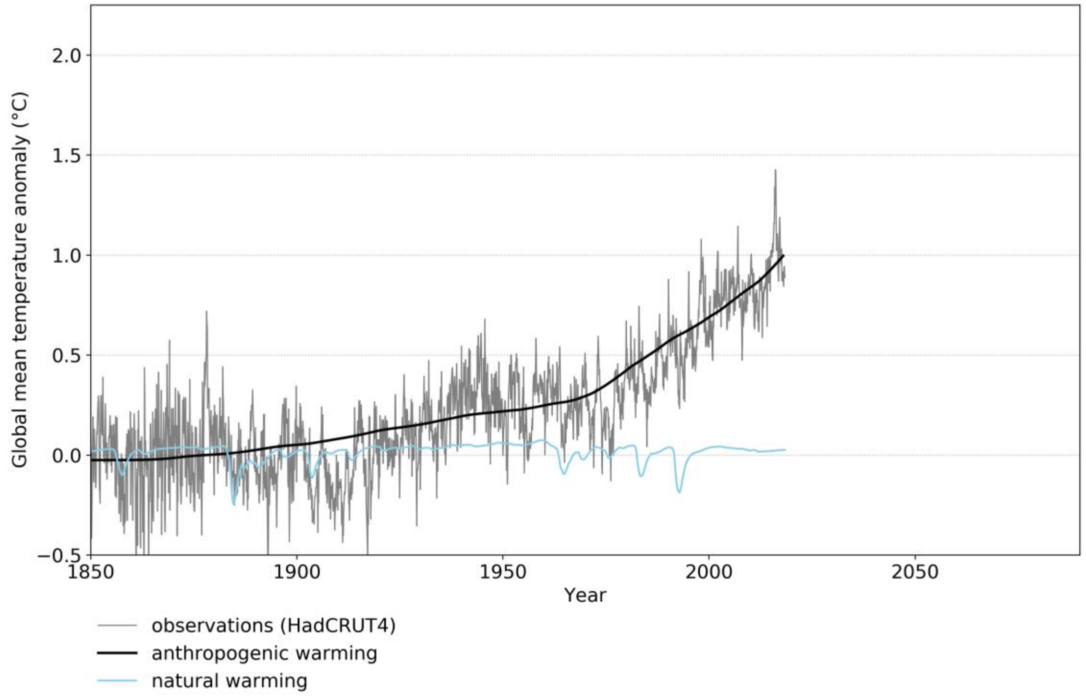
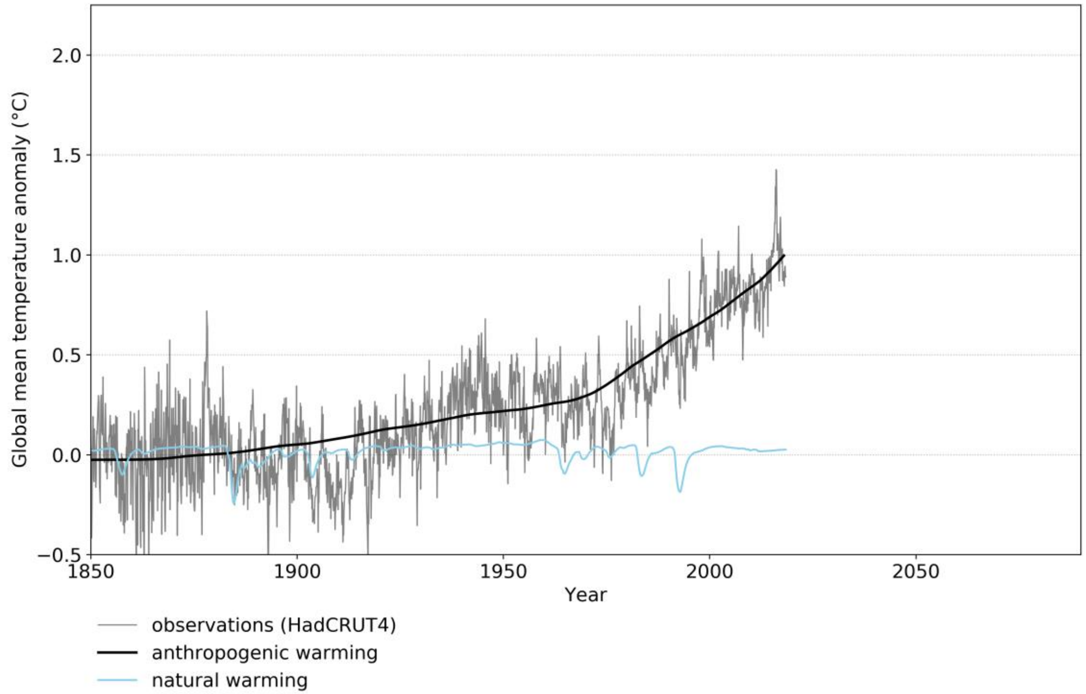
The Mitigation Timescale

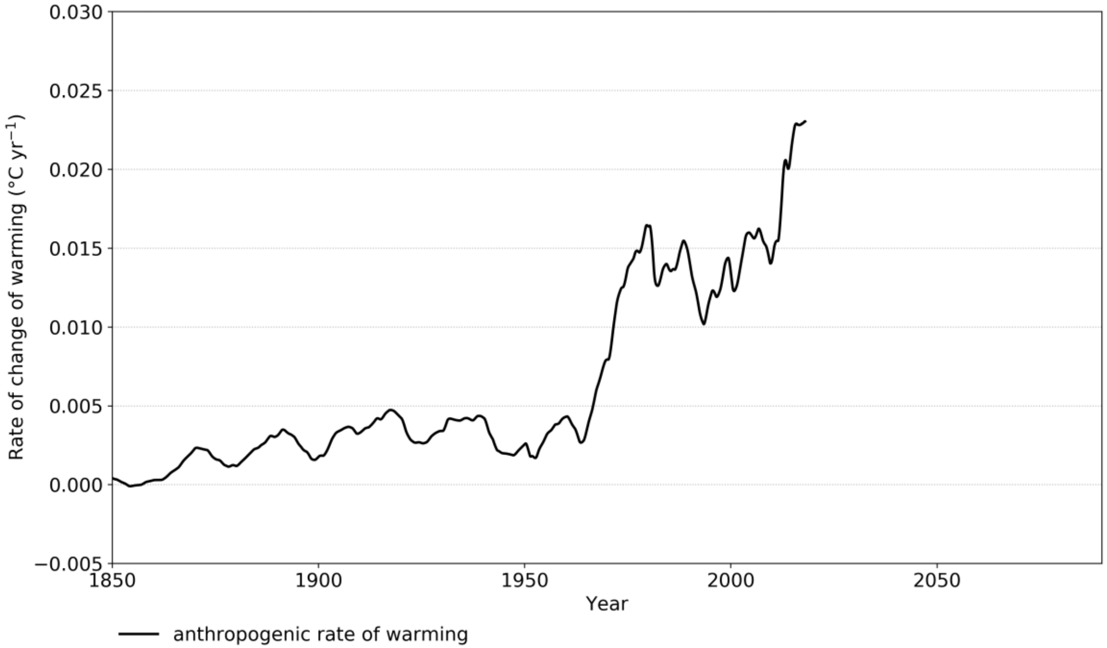
- We decompose this using an OLS regression into anthropogenic and natural signals based on best estimates of the corresponding forcing components.
- This allows us to calculate the current warming rate by reducing the noise without changing the current level (present day natural warming is ≈ 0.02°C).



The Mitigation Timescale

- Here we show the rate of change of anthropogenic warming, currently around 0.22°C / decade.





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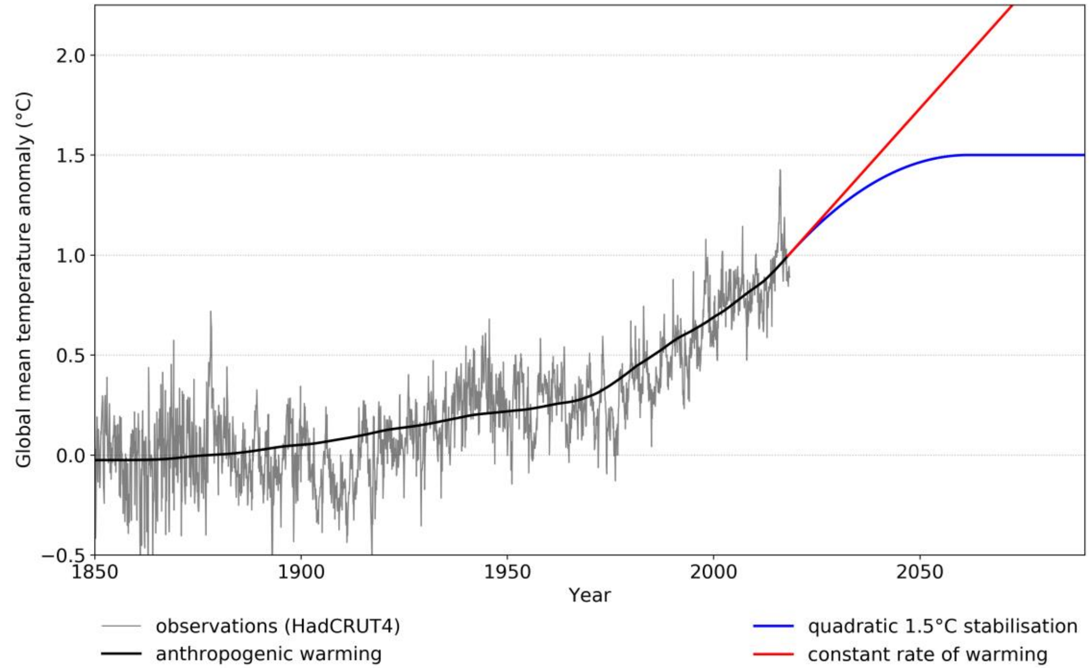
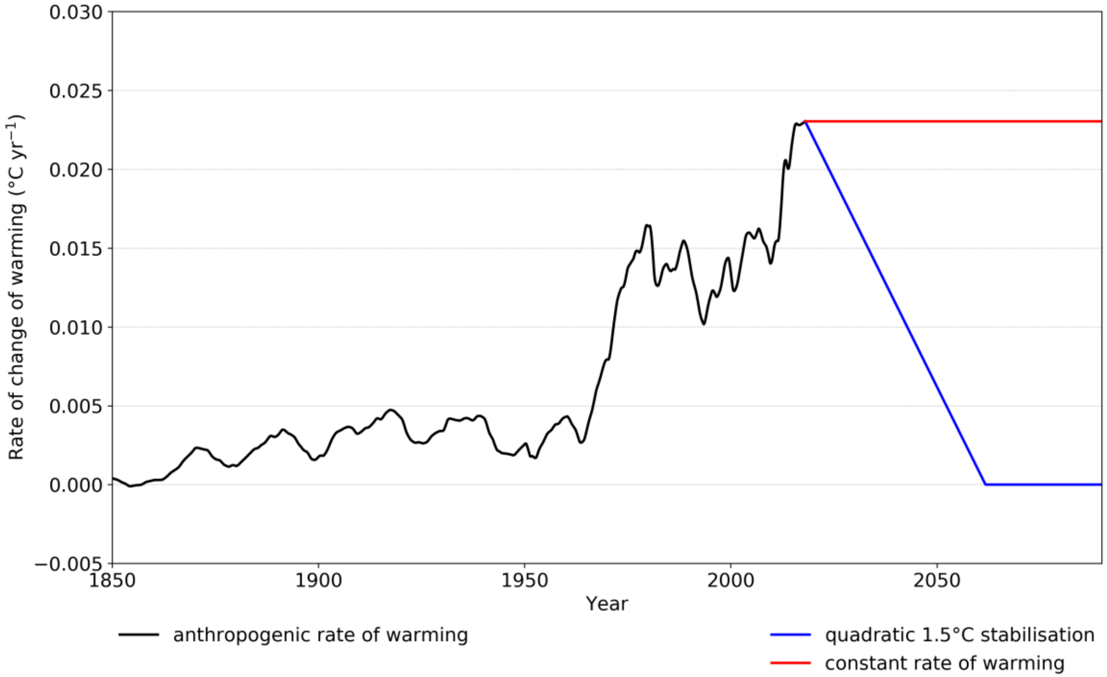
The Mitigation Timescale

- We now extend the warming trajectory in two ways:

1. A linear reduction in warming rate (quadratic stabilisation)
2. Keeping a constant warming rate (linear temperature increase)





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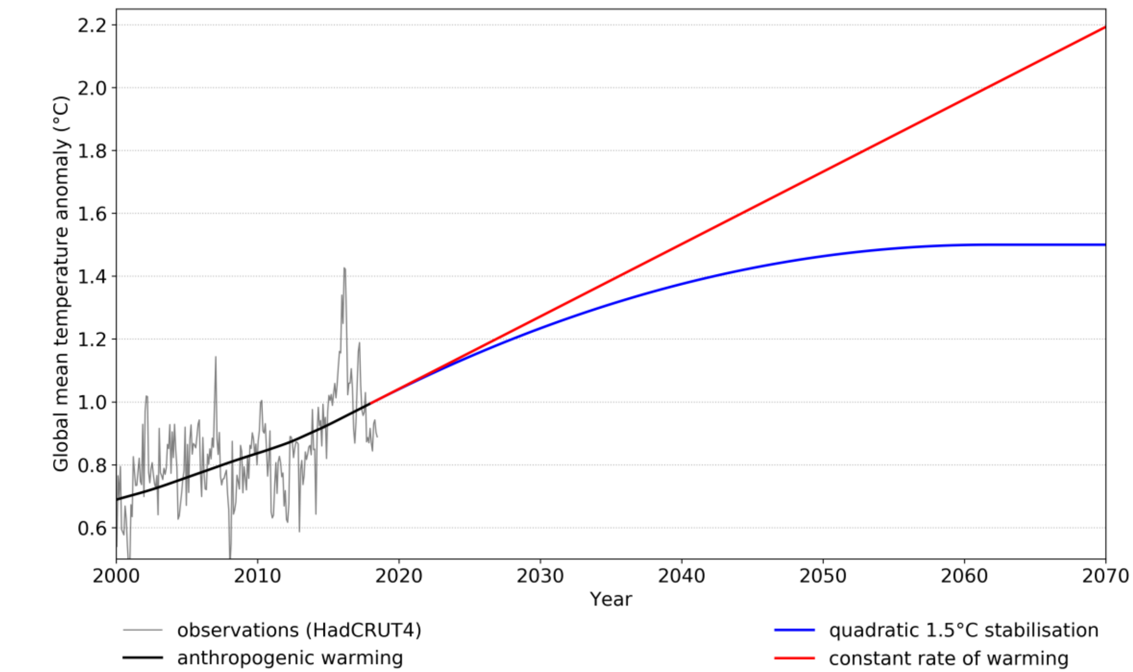
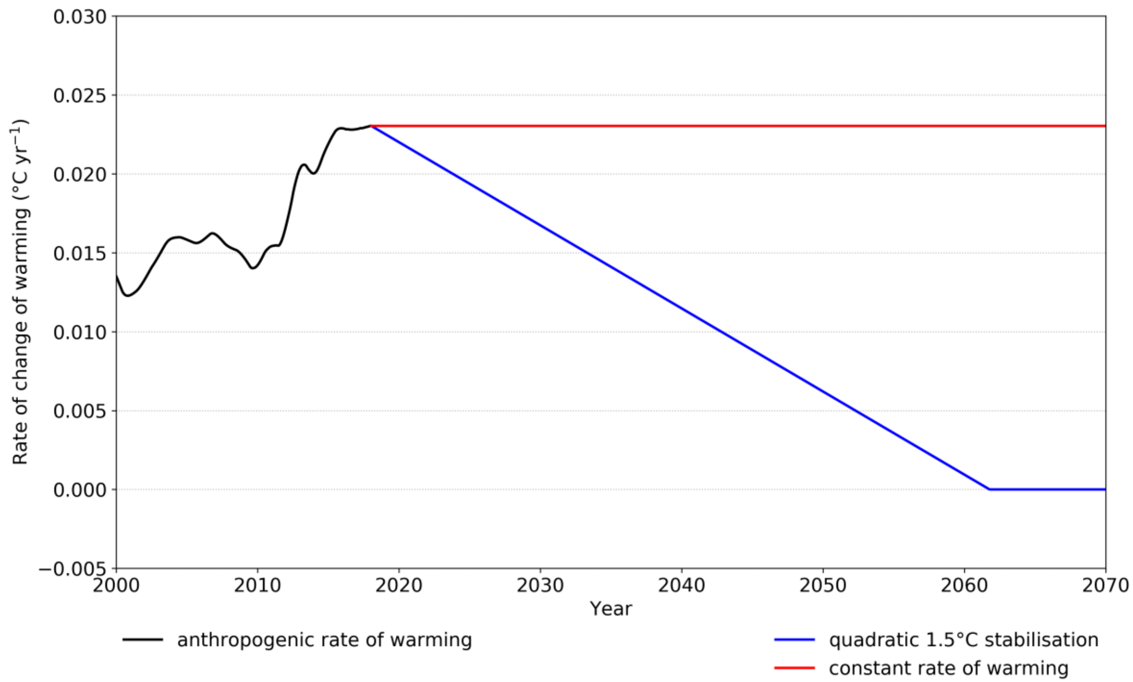
The Mitigation Timescale

- Focusing on the interesting time period…





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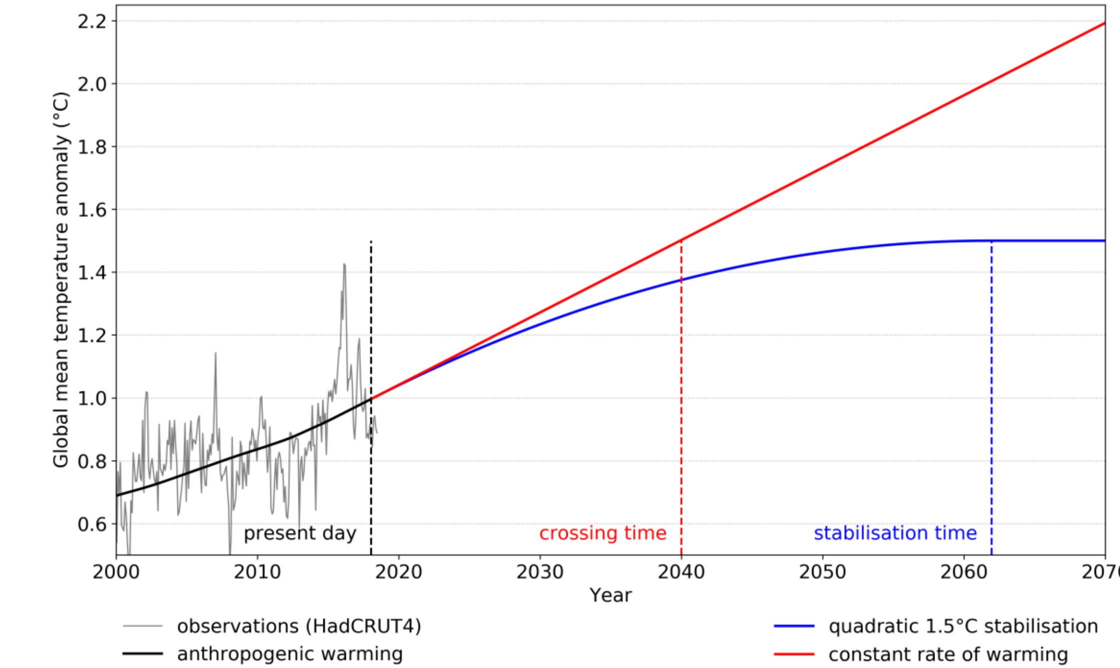
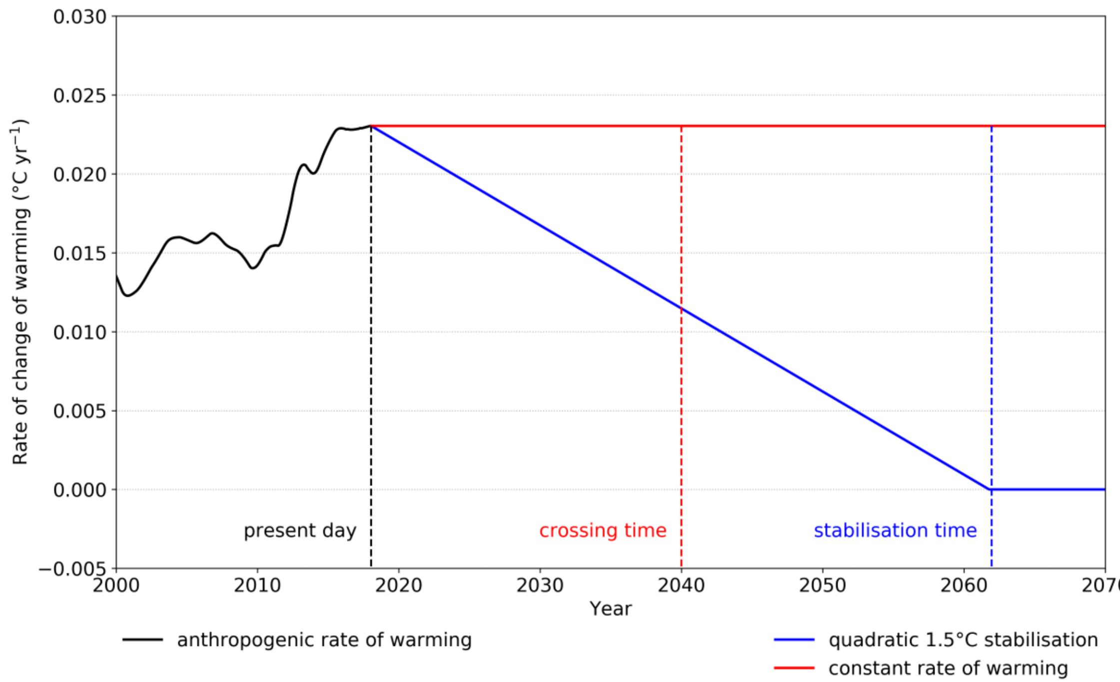
The Mitigation Timescale

- Marking three key times on the diagram:

1. Present day
2. The time to 1.5°C for a constant rate of future warming
3. The time to stabilisation for a linear reduction in the warming rate





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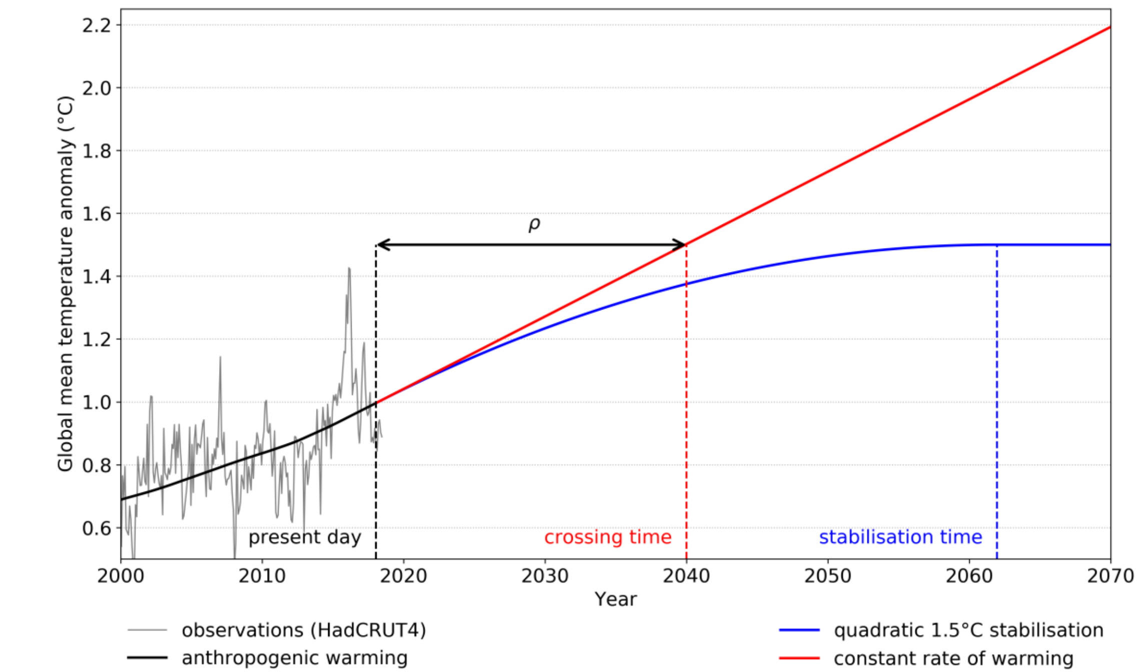
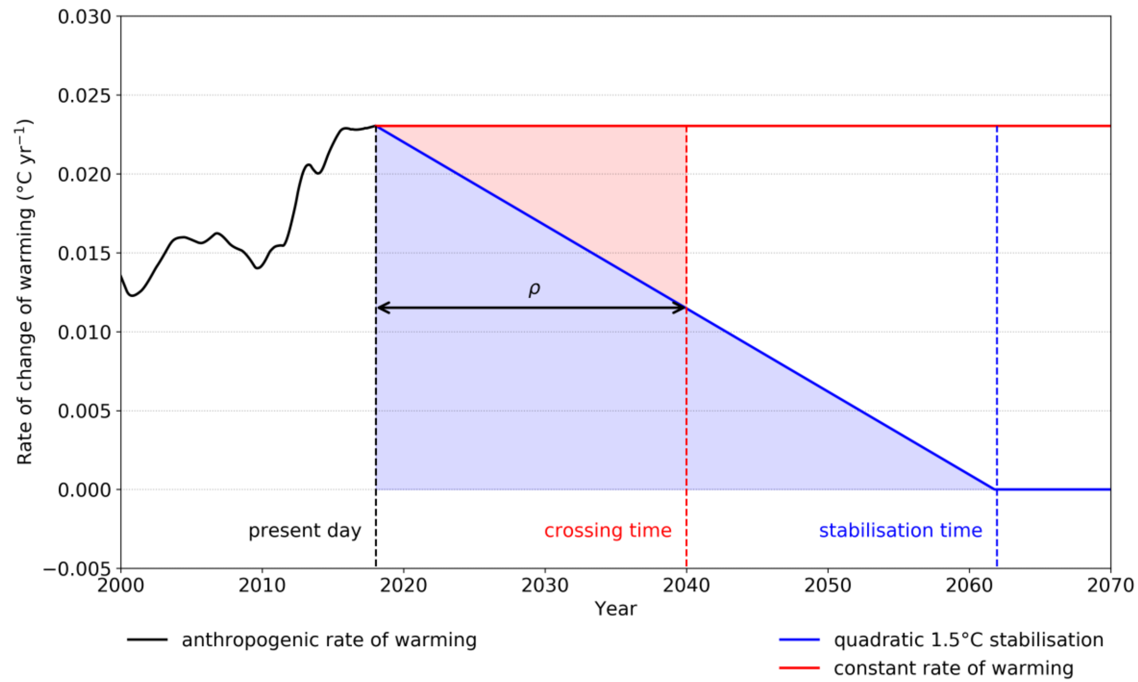
The Mitigation Timescale

- To find the crossing time, simply divide the warming remaining, ΔT (the shaded area under the constant rate curve), by the current warming rate, T_0':

$$\boldsymbol{\rho = \Delta T / T_0'}$$





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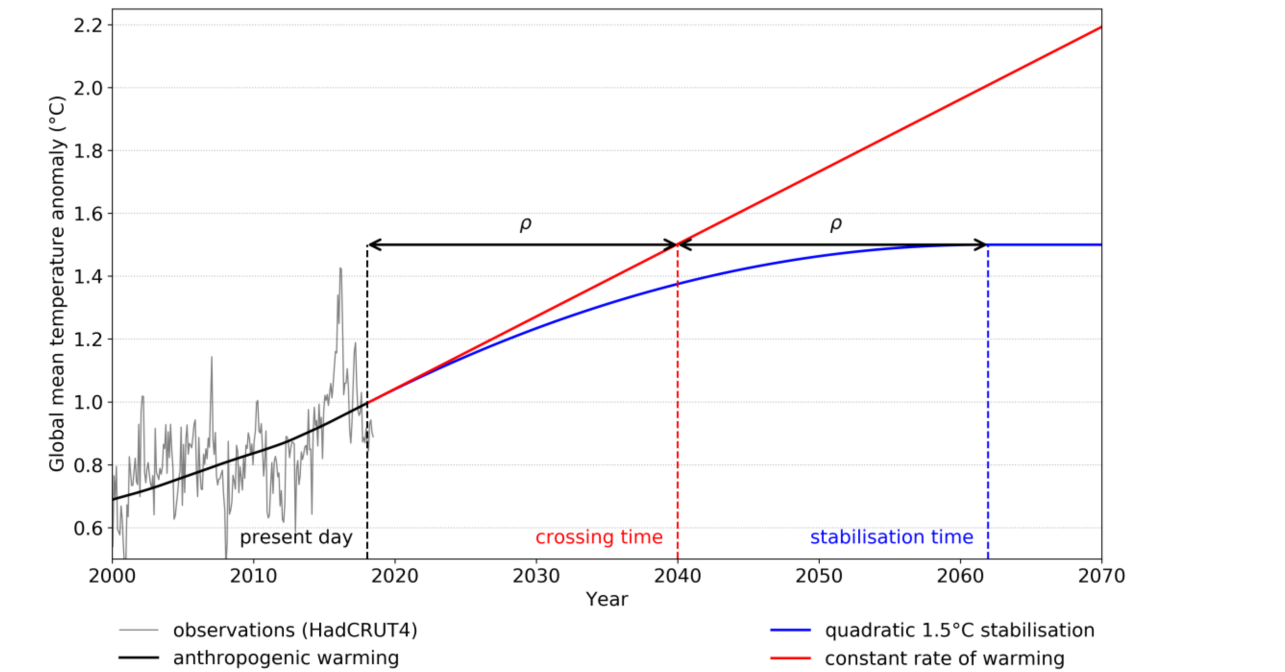
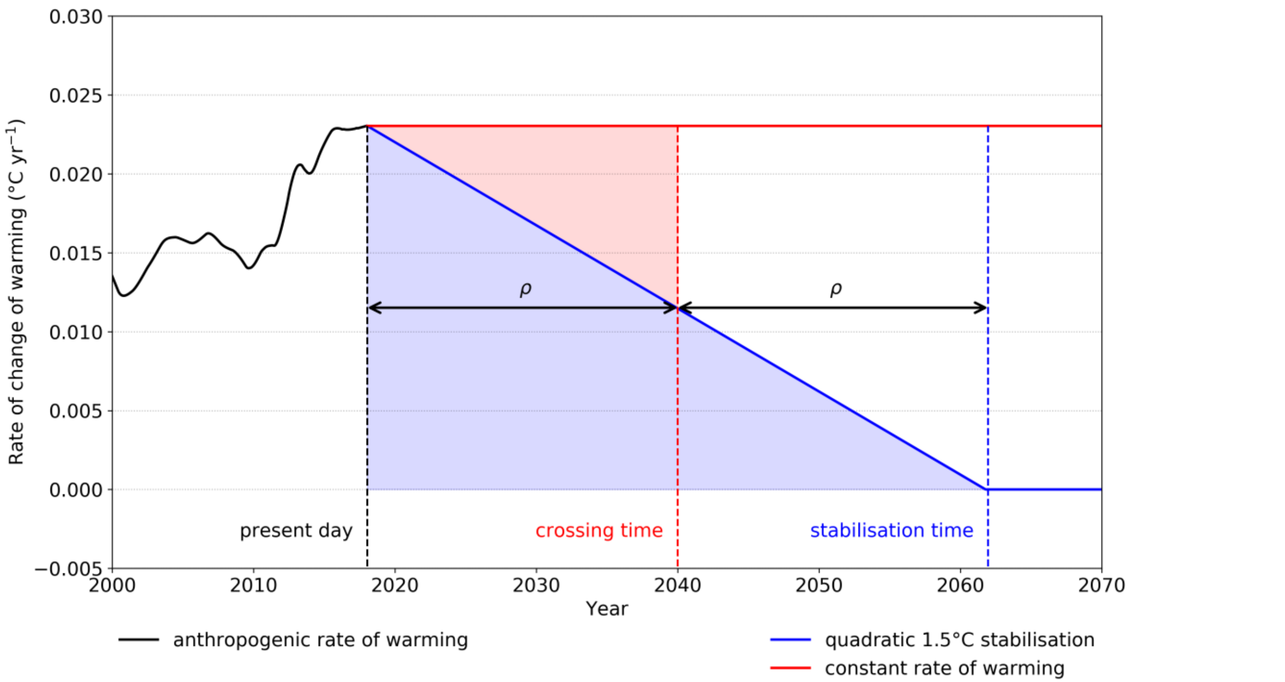
The Mitigation Timescale

- We call the crossing time, ρ, **the mitigation timescale**, since it is also **half the time to stabilisation** – the shaded areas under the red and blue lines are equal (proof **here**).

$$\rho = \Delta T / T_0'$$

- Note that for every year's delay in reducing emissions, as long as warming continues at the current rate, ρ falls by one year, and hence the time remaining to reduce the warming rate linearly to zero to meet any given temperature stabilization goal falls by two years.





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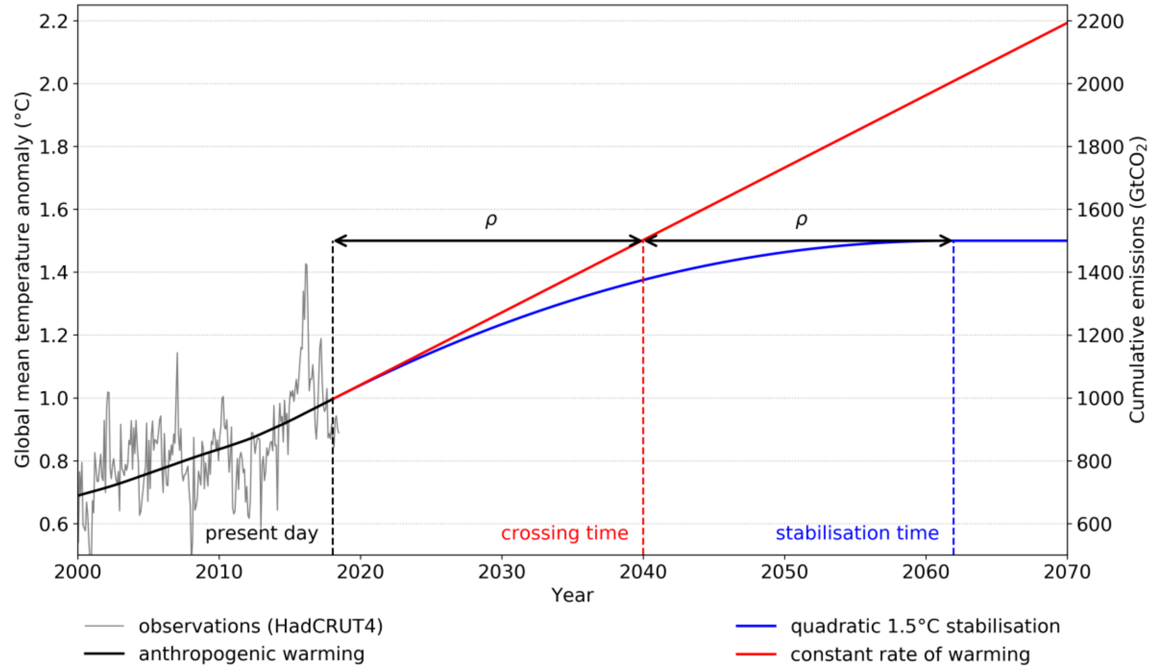
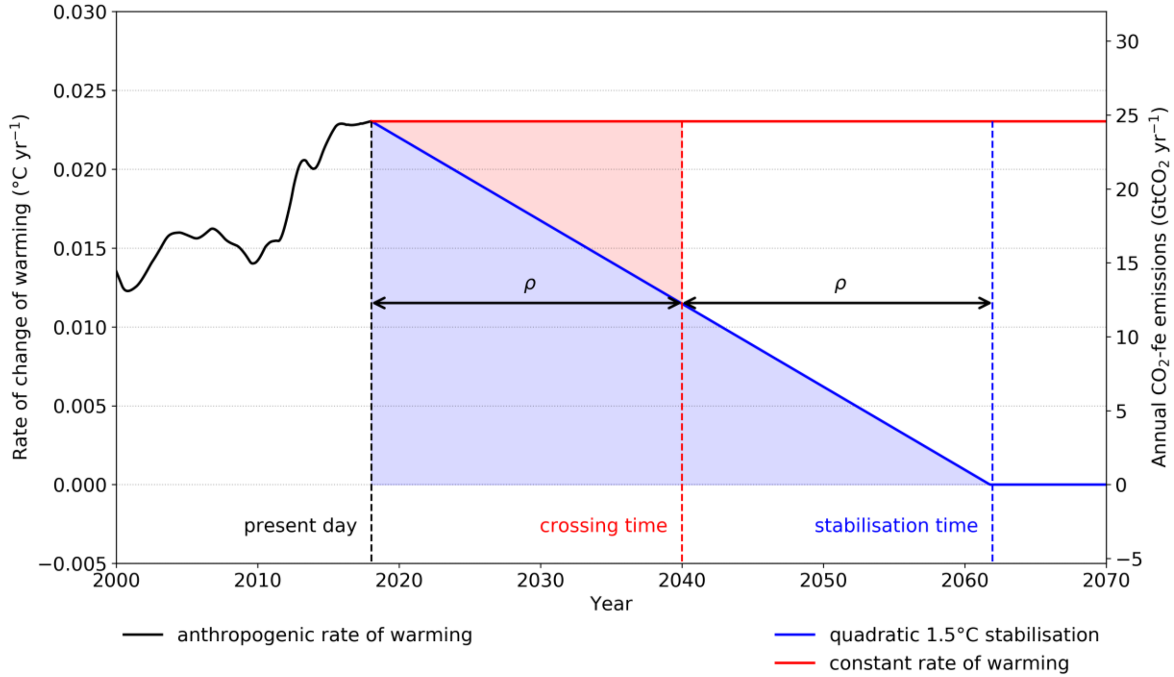
The Mitigation Timescale

- The TCRE then allows us to treat these warming trajectories as if they were CO_2-forcing-equivalent emission timeseries.
- This means we can calculate the remaining CO_2 budget to 1.5°C:

$$\rho = \Delta T / T'_0$$

$$\int E \, dt = E_0 \cdot \rho$$





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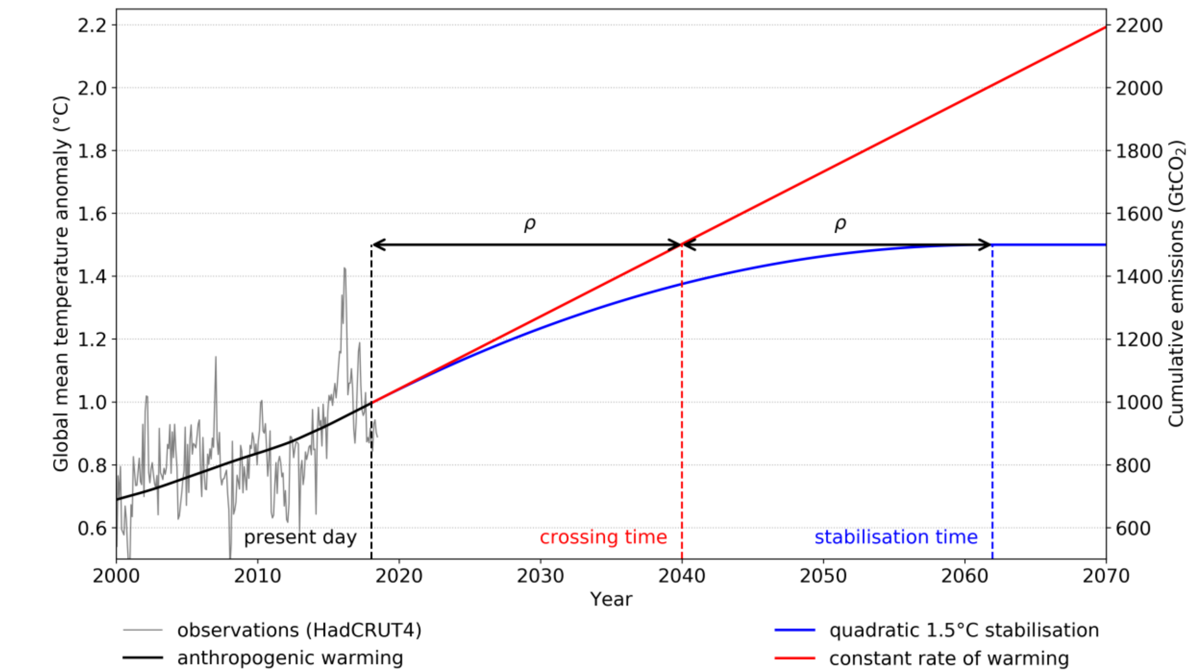
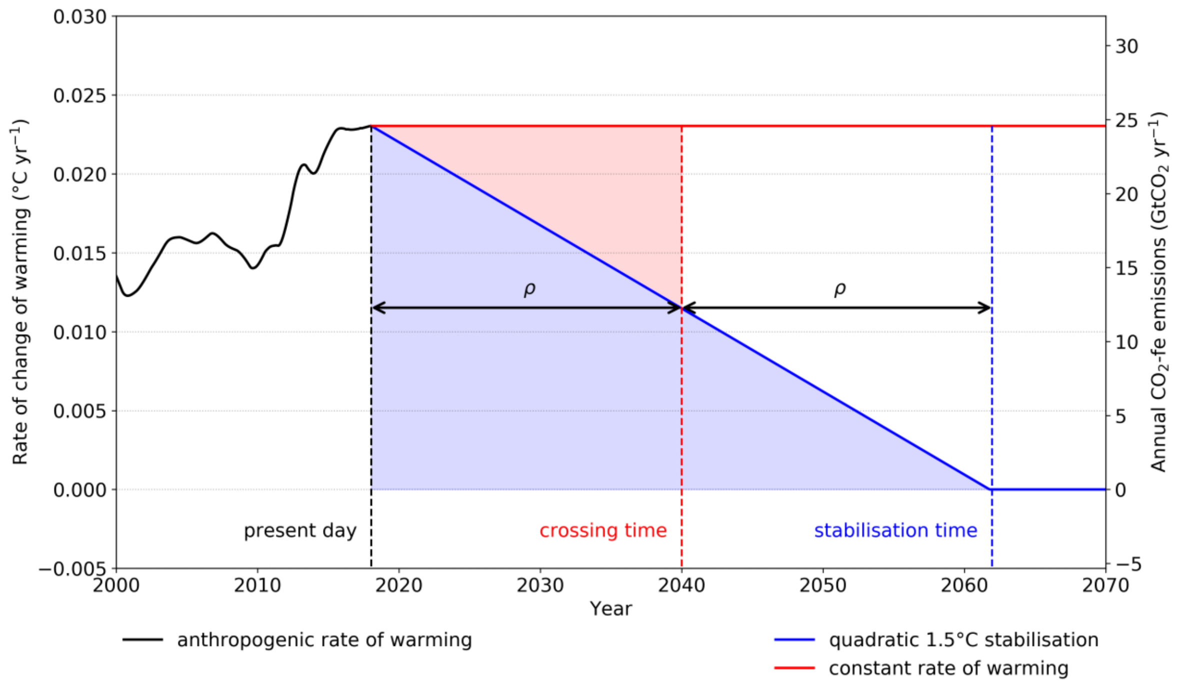
The Mitigation Timescale

- As mentioned before, this is only strictly true for CO_2-forcing-equivalent emissions, *or* using CO_2 induced warming.
- However, the equations below do still hold generally for many ambitious scenarios – see next section…

$$\rho = \Delta T / T'_0$$

$$\int E \, dt = E_0 \cdot \rho$$





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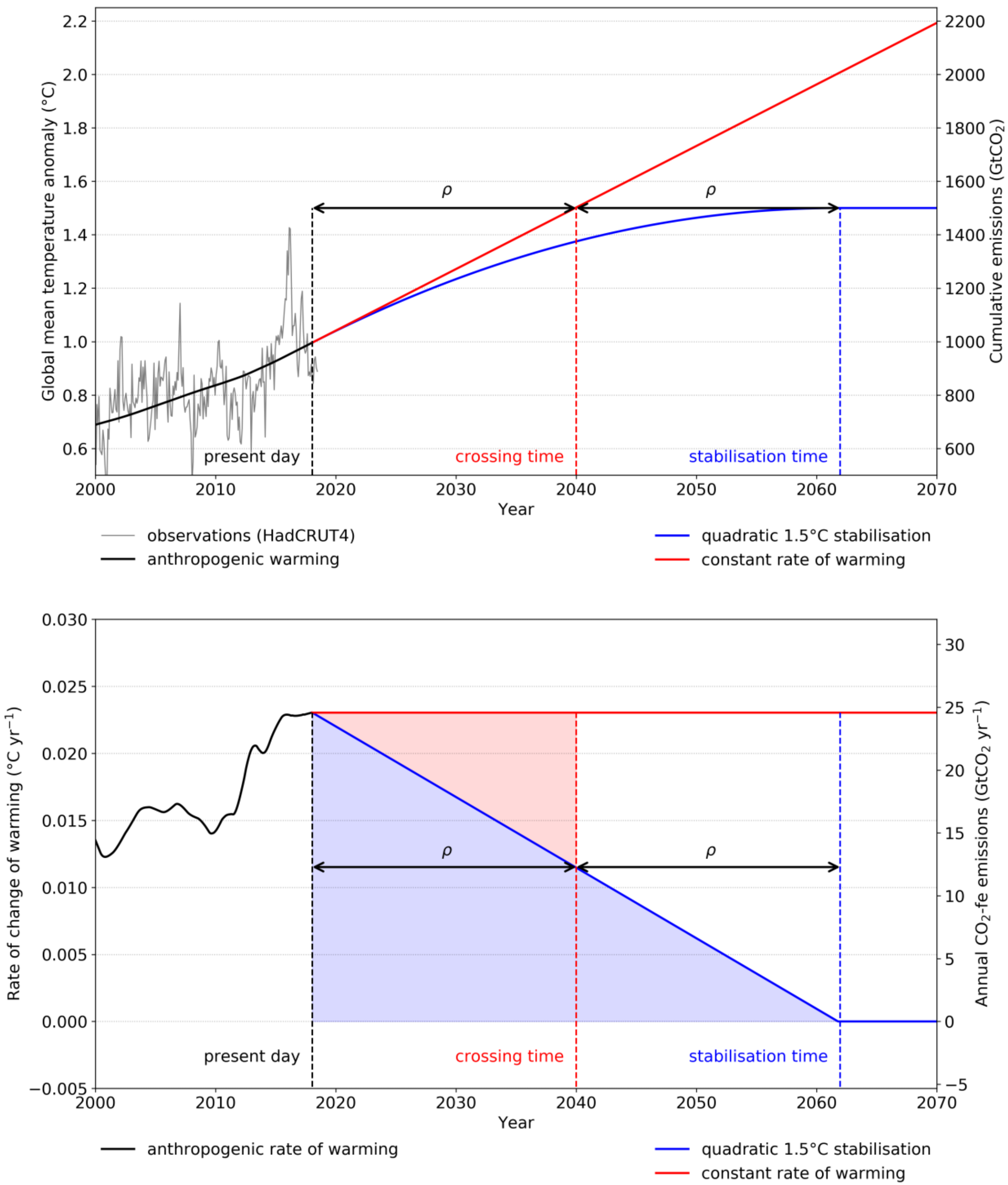
The Mitigation Timescale

- ρ is also equal to the time constant for an exponential decay in emissions (or equivalently warming rate).

- Click **here** for all the mathematical derivations behind this section.



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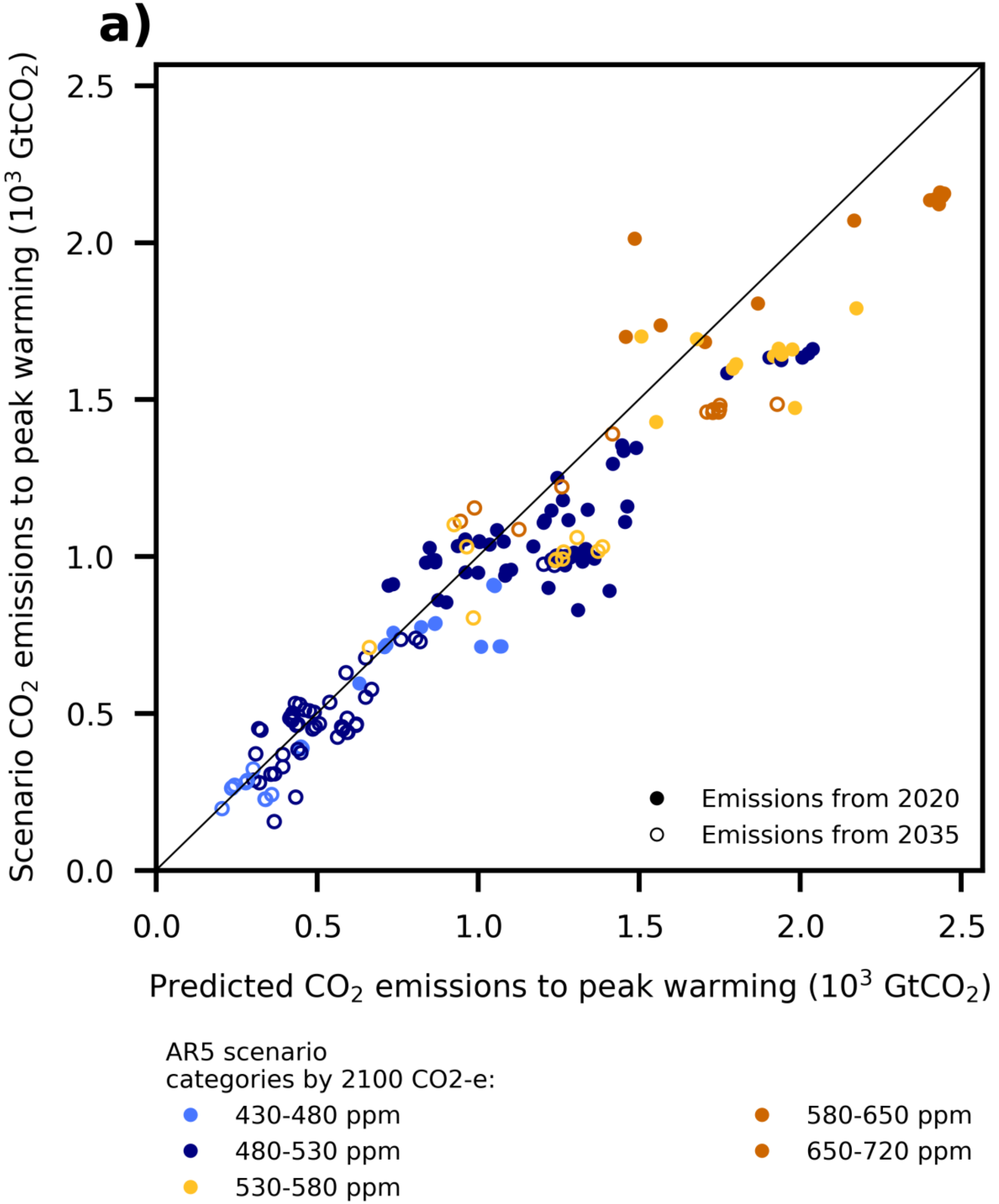
Model Scenario Experiments

- This shows the budget predicted using our equation (below) versus the actual budget within a subset of the AR5 scenarios (subset details **here**).
- We have calculated the budget with ***total*** warming and CO_2 emissions:

$$\int E\,dt = E_0 \cdot \Delta T / T'_0$$



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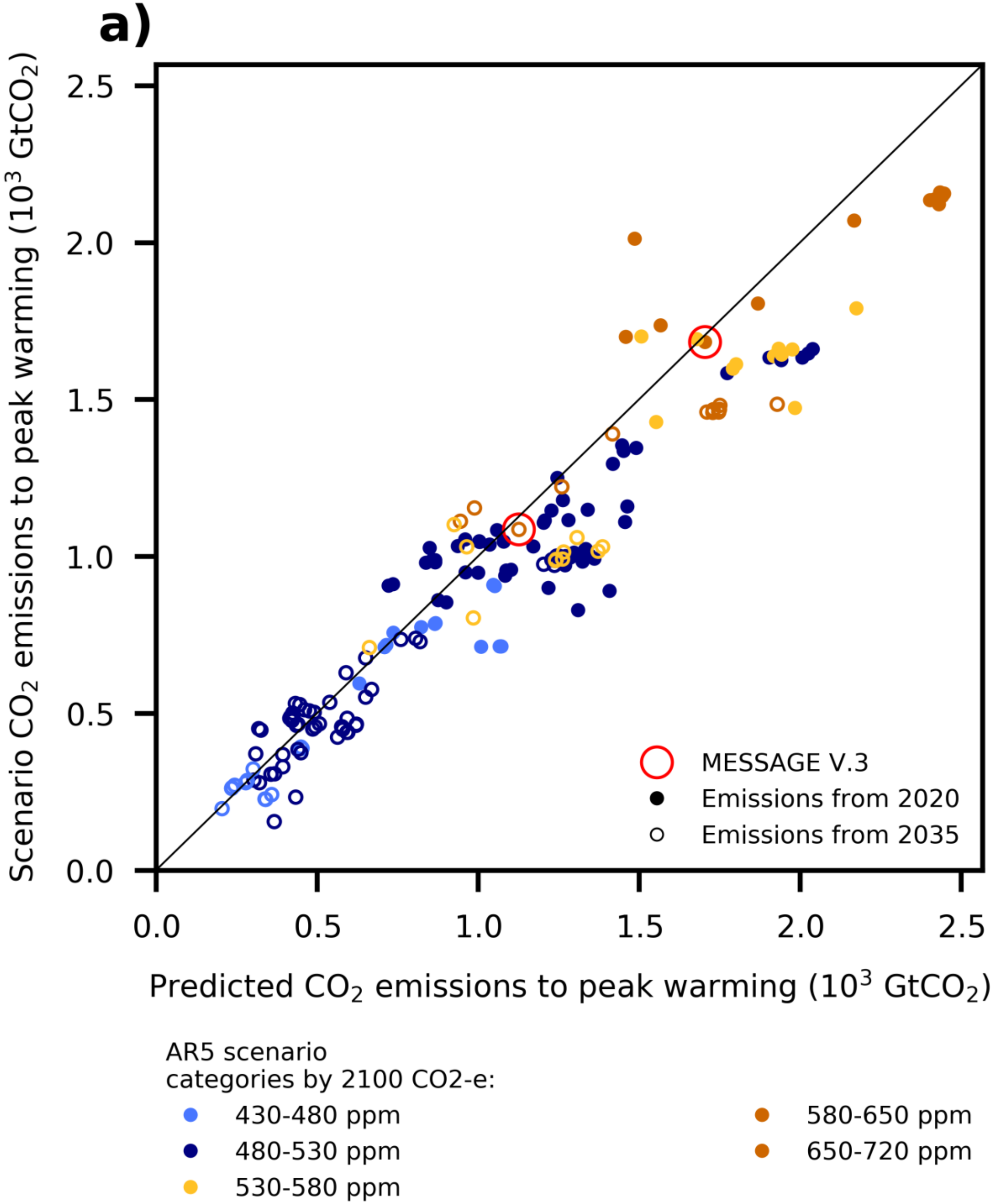
Model Scenario Experiments

- Two questions arise:

1. Why do most of the lines lie below the 1:1 line?

2. Why does the scenario shown in the first section (circled) lie so close to the 1:1 line?



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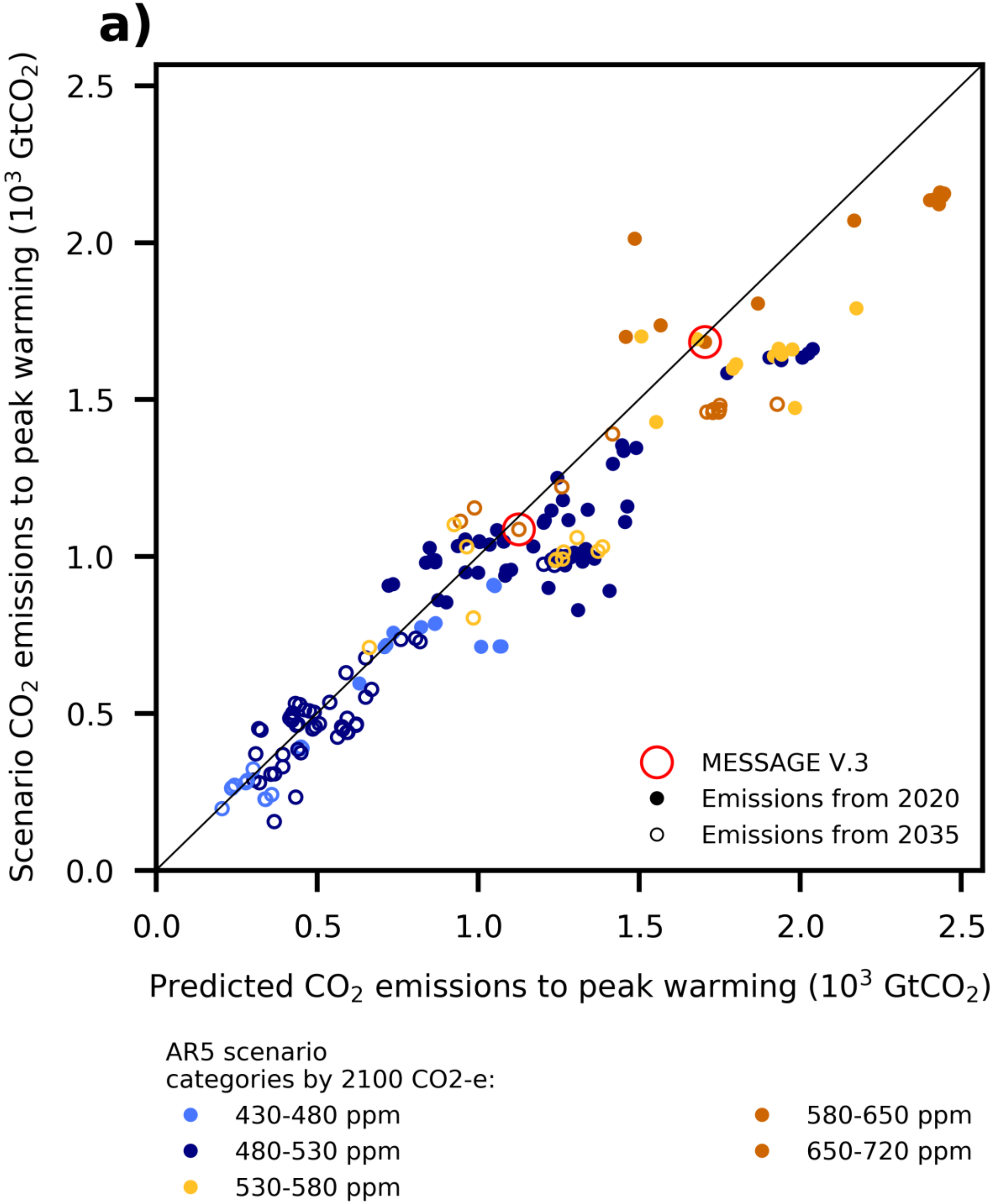
Model Scenario Experiments

- These are both due to the future non-CO_2 forcing fraction.
- If the non-CO_2 forcing fraction increases into the future, it "takes up" more warming than predicted by our equation, therefore reducing the CO_2 budget, i.e.:

$$\int E\,\mathrm{d}t \approx (E_0 + \alpha F'_0) \cdot \rho - \alpha \Delta F,$$

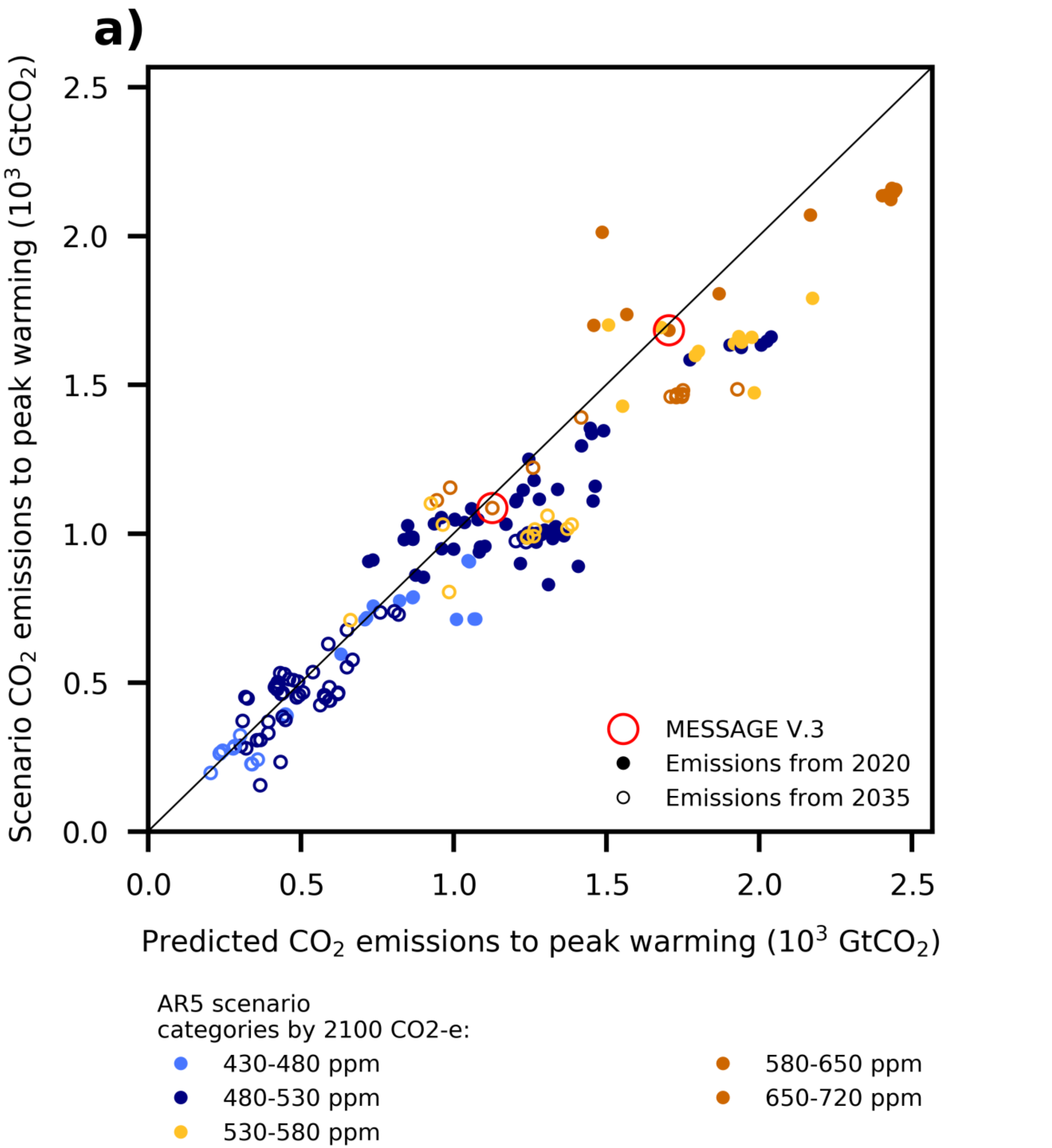
where ΔF is the net change in non-CO_2 forcing between the present day and peak warming, and α is approximately 1200 $GtCO_2$ / Wm^{-2}.



Model Scenario Experiments

- Since this fraction either increases or remains approximately constant in the future for most scenarios, our predictions tend to overestimate the budget for these scenarios as they do not account for the extra warming taken up by non-CO_2 forcers:

$$\int E \, dt \leq E_0 \, \rho$$



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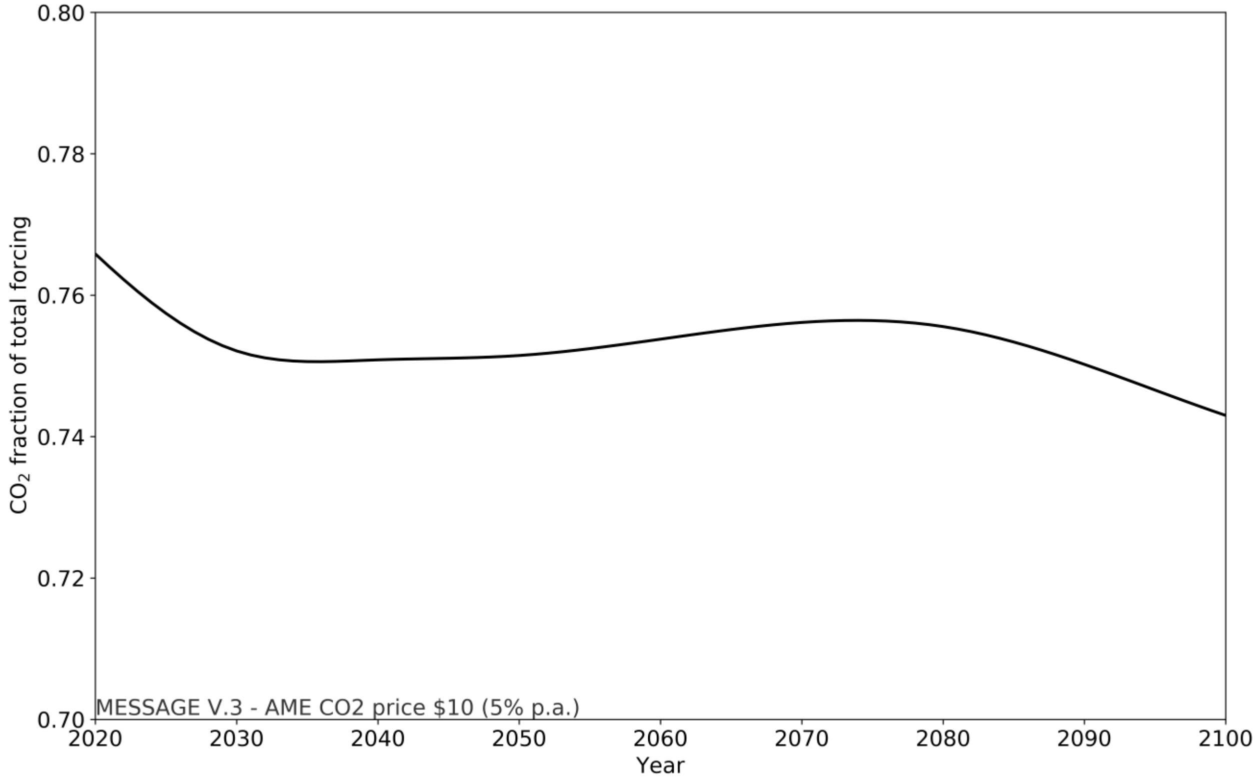
Model Scenario Experiments

- Here is the CO_2 forcing fraction for the circled scenario.
- The predicted budget for this scenario is almost exactly equal to the actual number since this fraction is very nearly constant after 2020.



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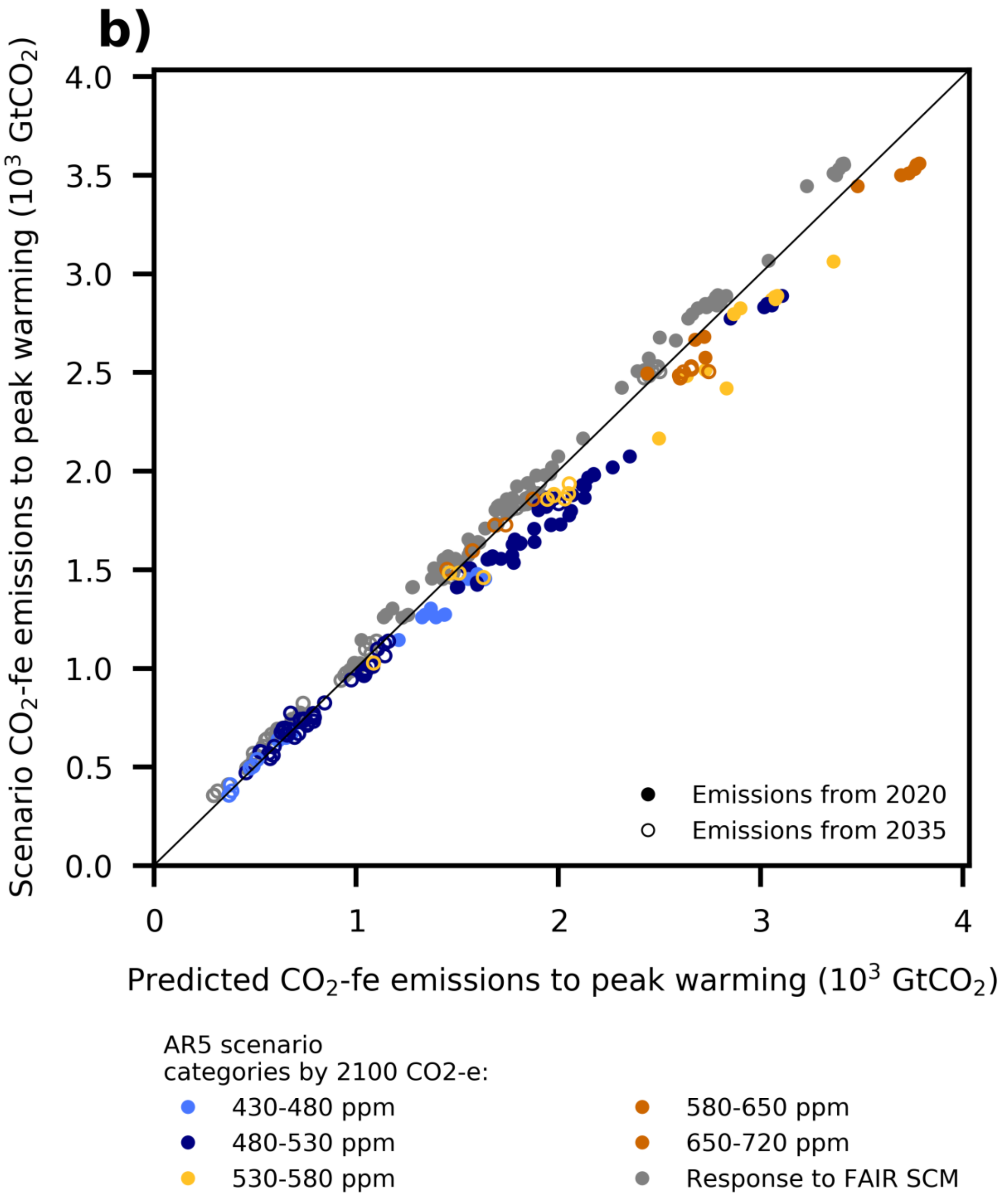
Model Scenario Experiments

- If we incorporate all anthropogenic climate forcers using **CO_2-fe emissions,** which behave exactly like CO_2 emissions, we find the prediction matches the actual budgets almost exactly.

$$\int E^{fe}\,dt \approx E_0^{fe}\,\rho$$



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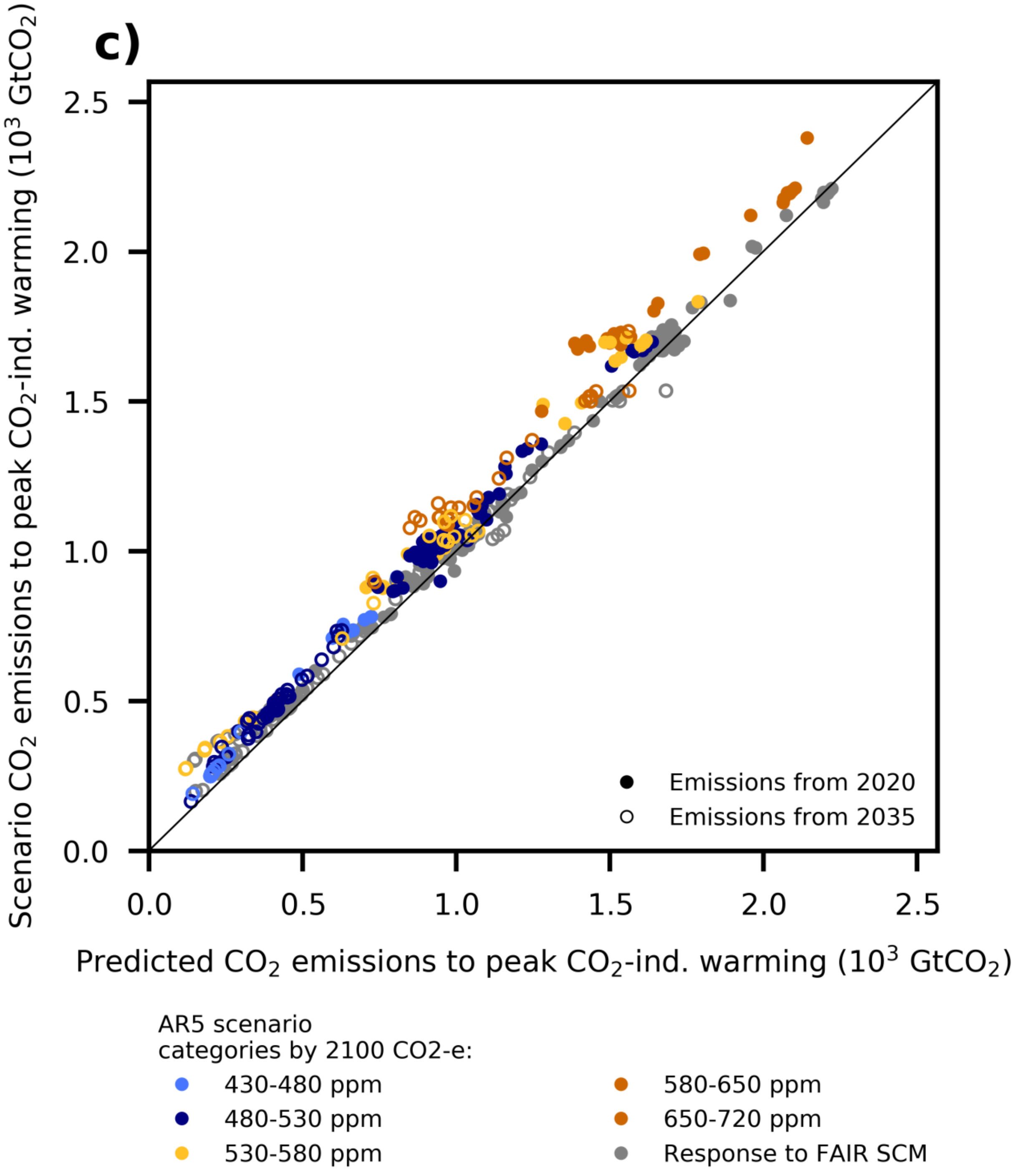
Model Scenario Experiments

- Similarly, if we use **CO_2-induced warming** rather than total warming, our prediction is close to the 1:1 line.

$$\int E\,dt \approx E_0 \cdot \rho^{CO_2}$$



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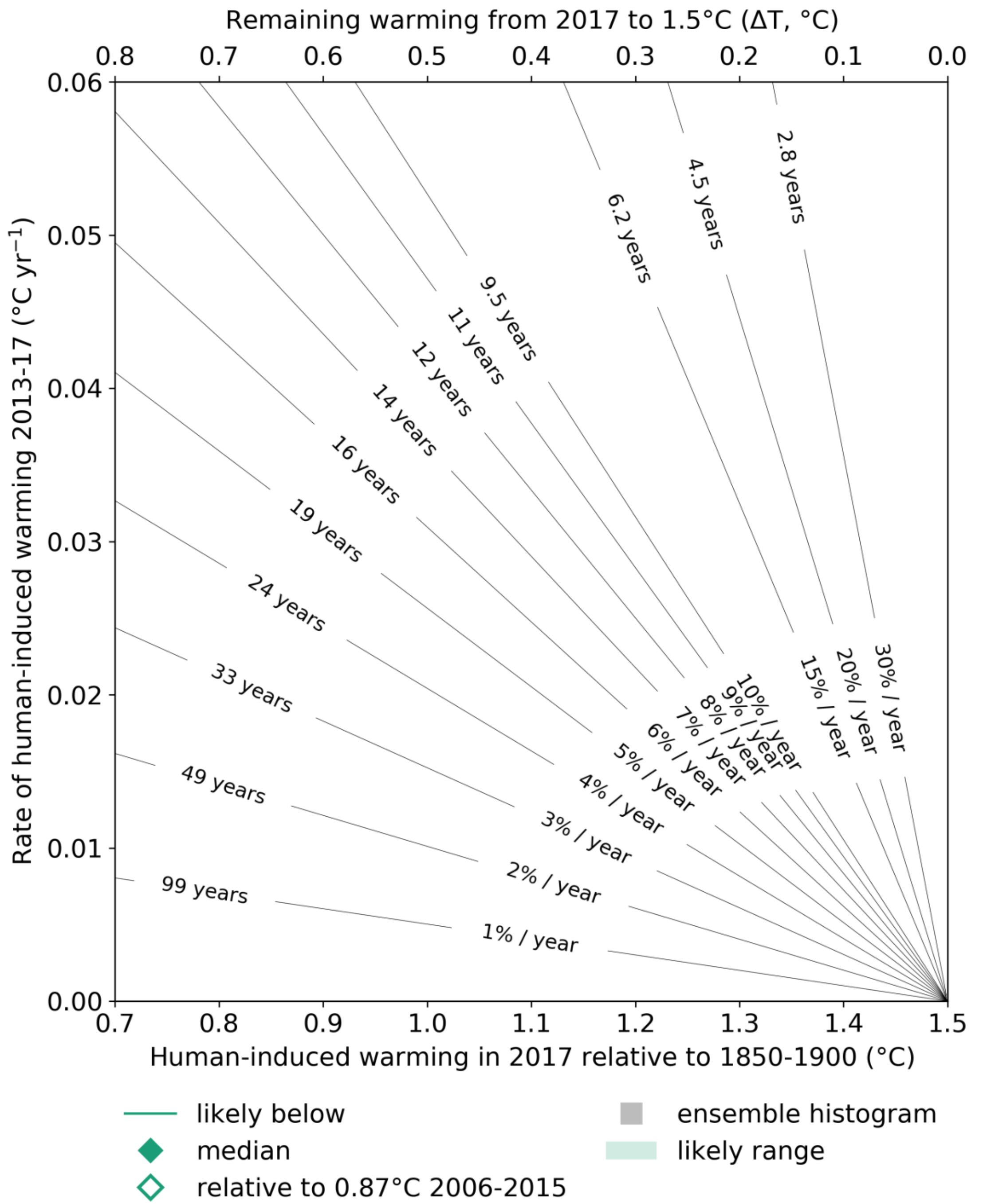
Results

- In $(\Delta T, T_0')$ space constant values of ρ lie on straight lines, from our mitigation timescale equation:

$$\rho = \Delta T / T_0'$$

- We prefer this presentation of the budget as a timescale since it removes the uncertainties associated with the present-day annual emission rate.
- The associated exponential emissions reduction rates are also shown here.



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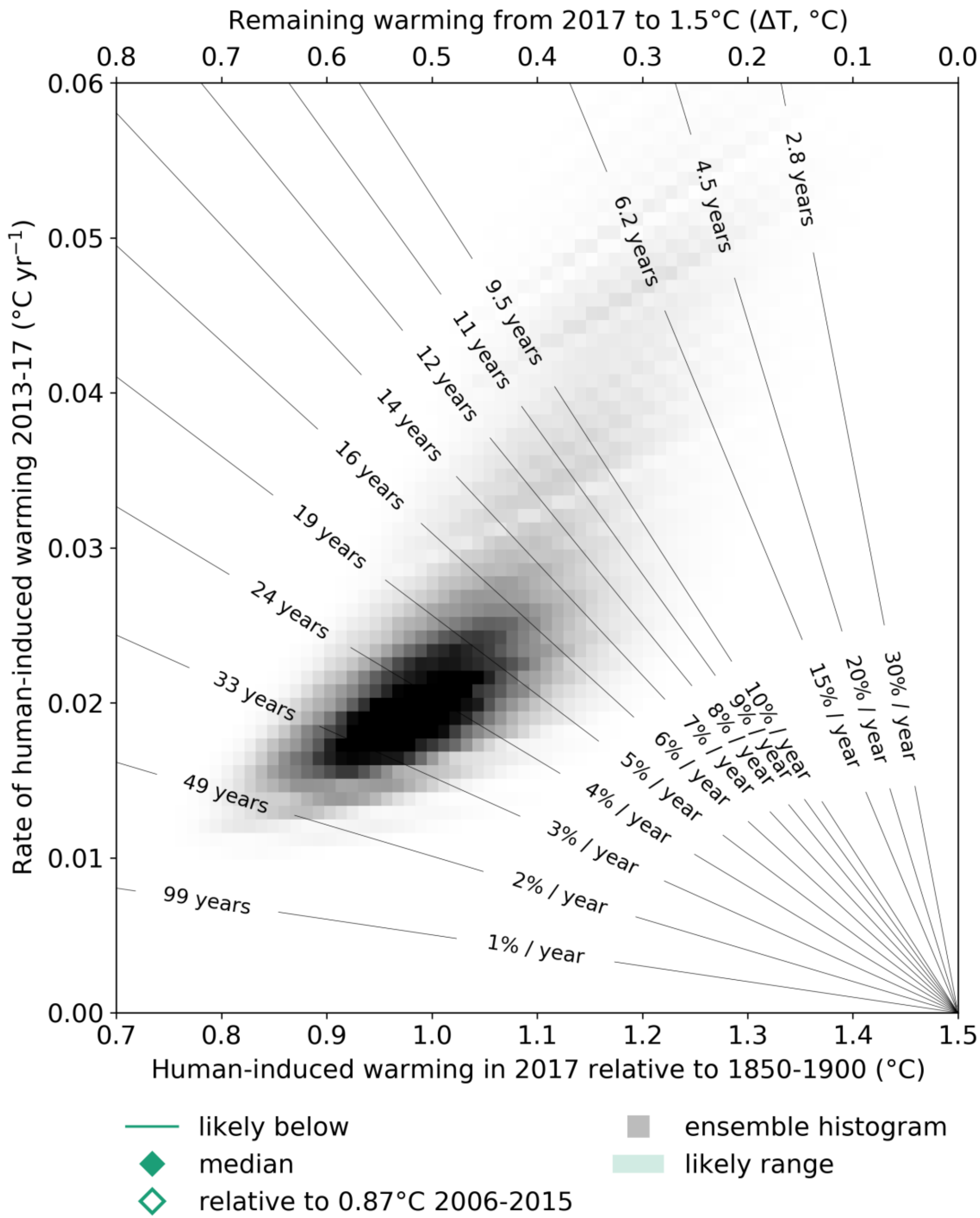
Results

- We compute anthropogenic and natural temperature responses to 200 best-estimate forcing ensemble members for 20 different model parameterisations.
- We then perform OLS regressions against 100 HadCRUT4 temperature observations and 50 CMIP5 PiC internal variability members to derive the anthropogenic signal.
- This results in the 20 million member ensemble of remaining warming to 1.5°C and corresponding present-day rate* shown here.

*taken as the trend of the best fit line of warming over 2013-2017



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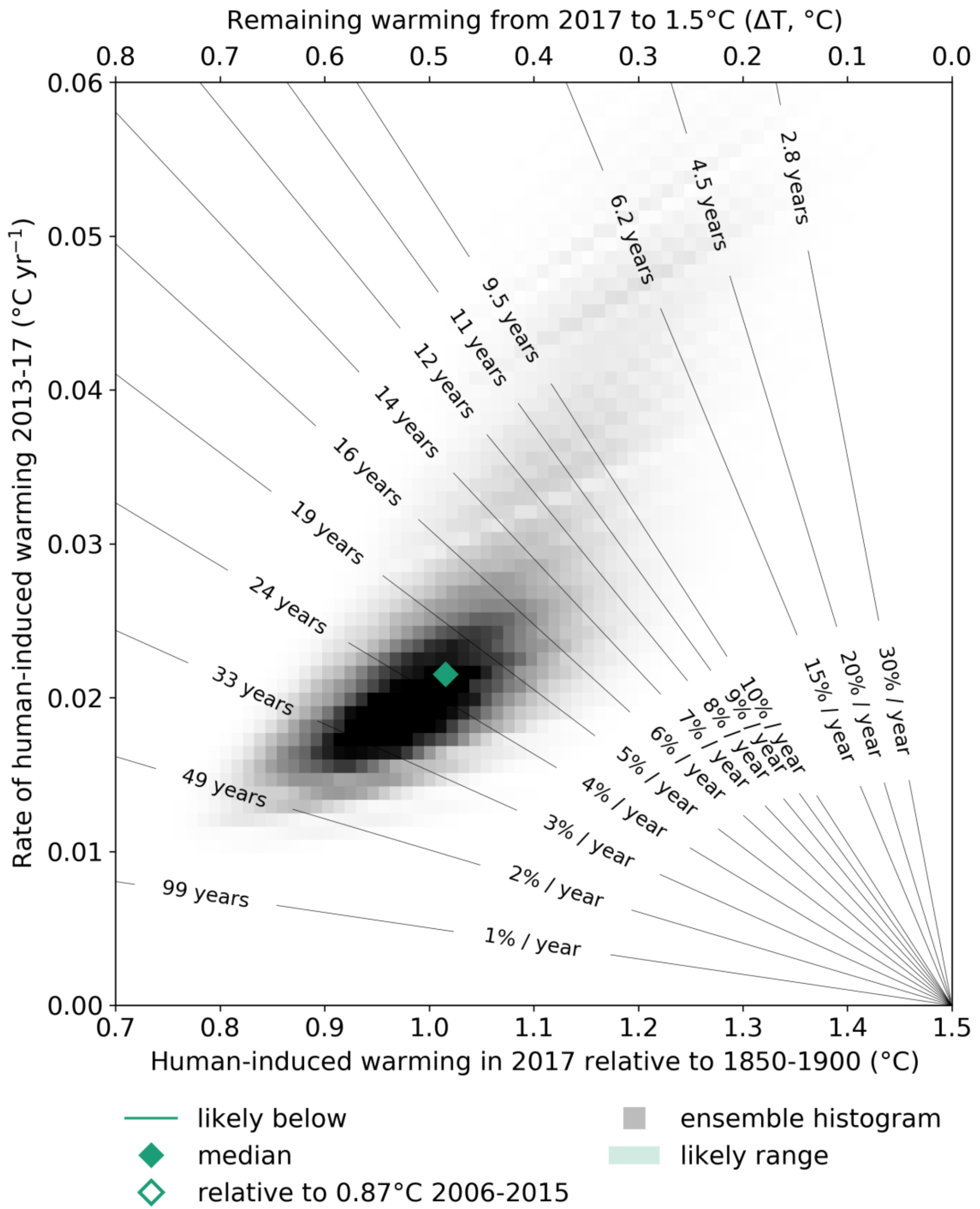
Results

- The median of the distribution lies at a mitigation timescale of 22.5 years.



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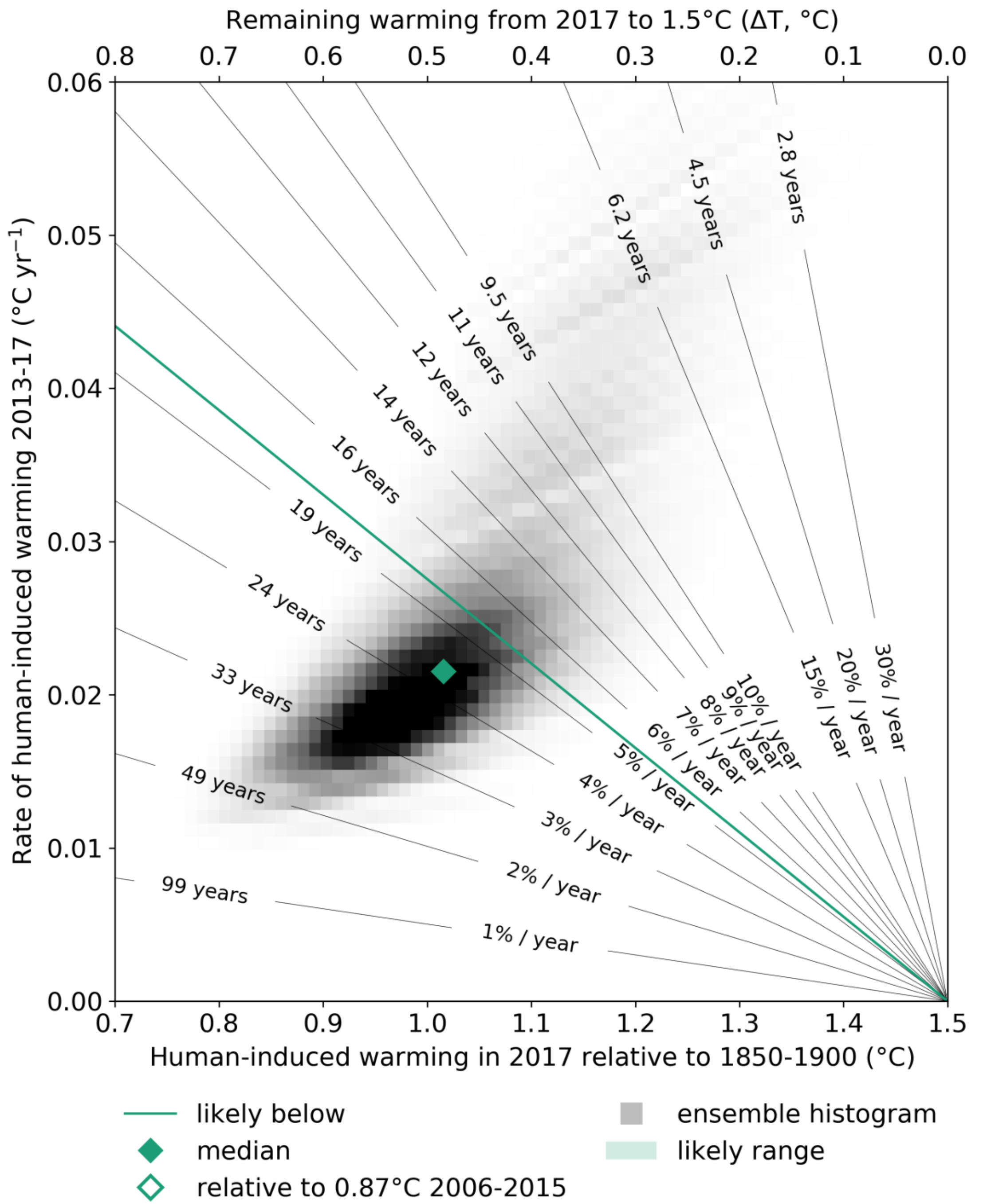
Results

- A reduction rate of 5.5% per year would likely avoid 1.5°C.



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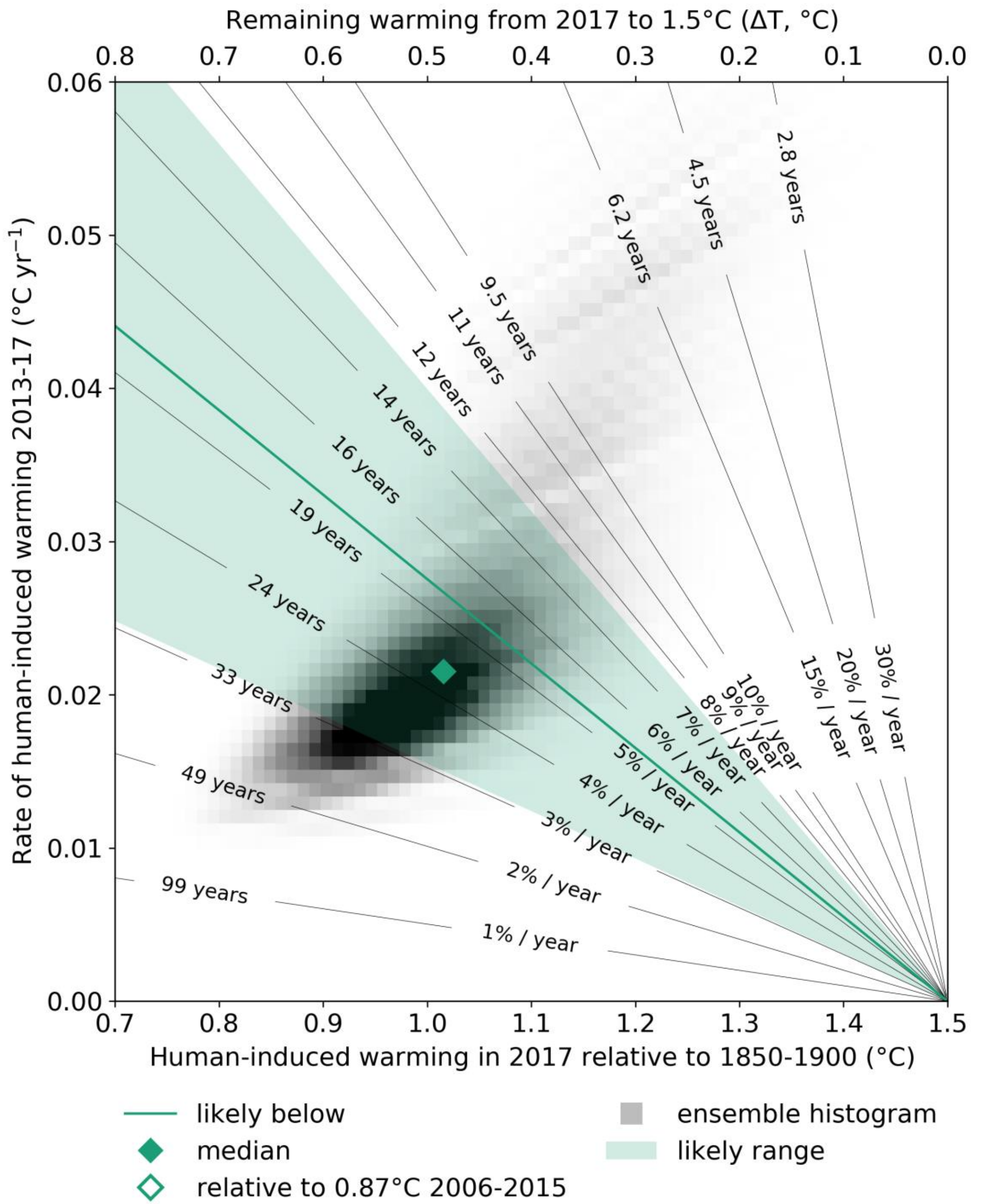
Results

- It is likely that we will cross 1.5°C somewhere between 2030 and 2050 if the current warming rate continues.



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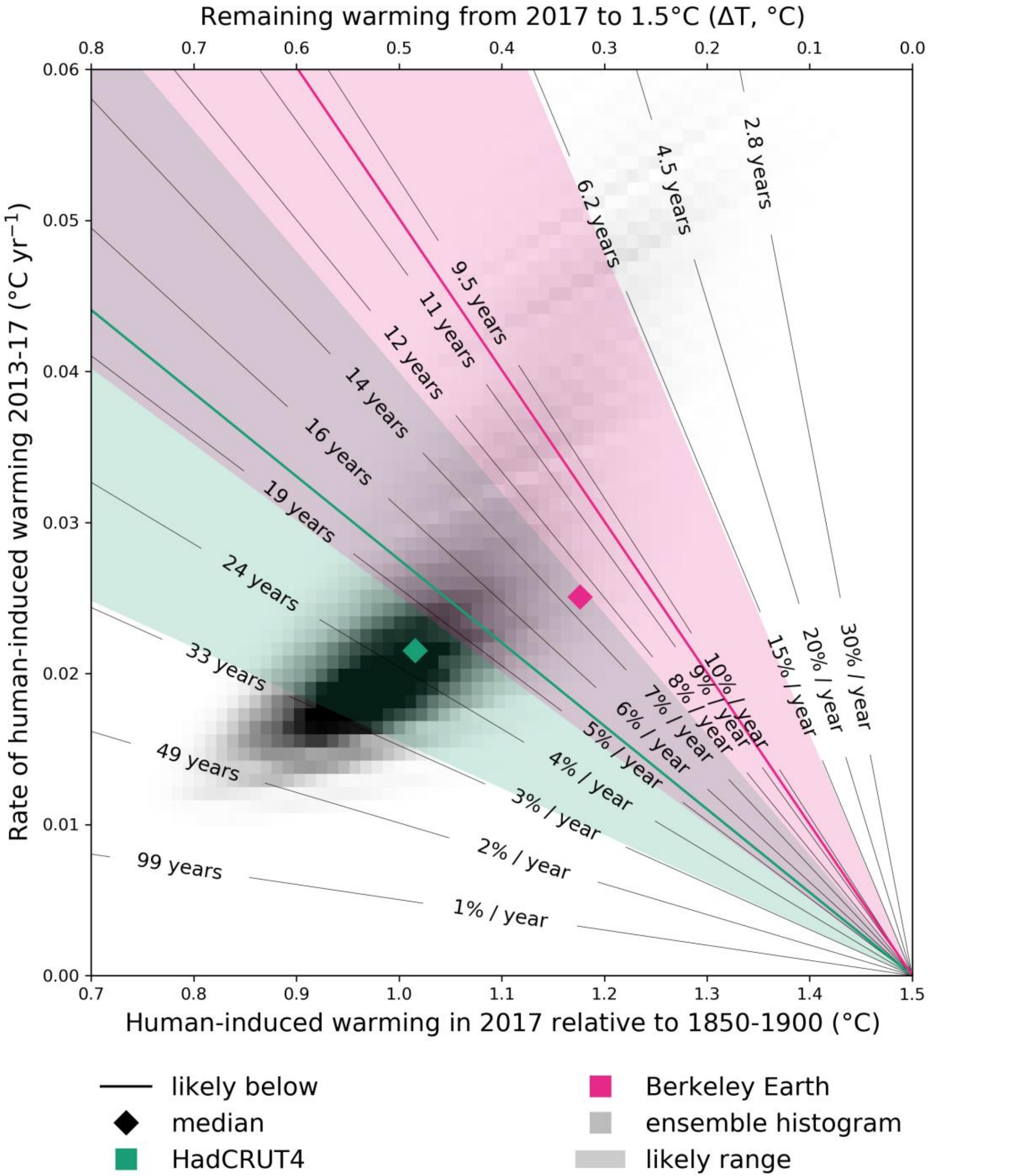
Results

- Here we show results that use Berkeley Earth rather than HadCRUT4 temperature observations in the computation of the ensemble.
- This illustrates the importance of the current level of warming, a factor that has caused some of the discrepancies between previous estimates of the budget.
- However, even if the levels were identical, the higher warming rate in Berkeley Earth still reduces the mitigation timescale by roughly 3 years (see **here** for the impact of defining warming relative to 0.87°C in 2006-2015 as in the Paris Agreement Structured Expert Dialogue).



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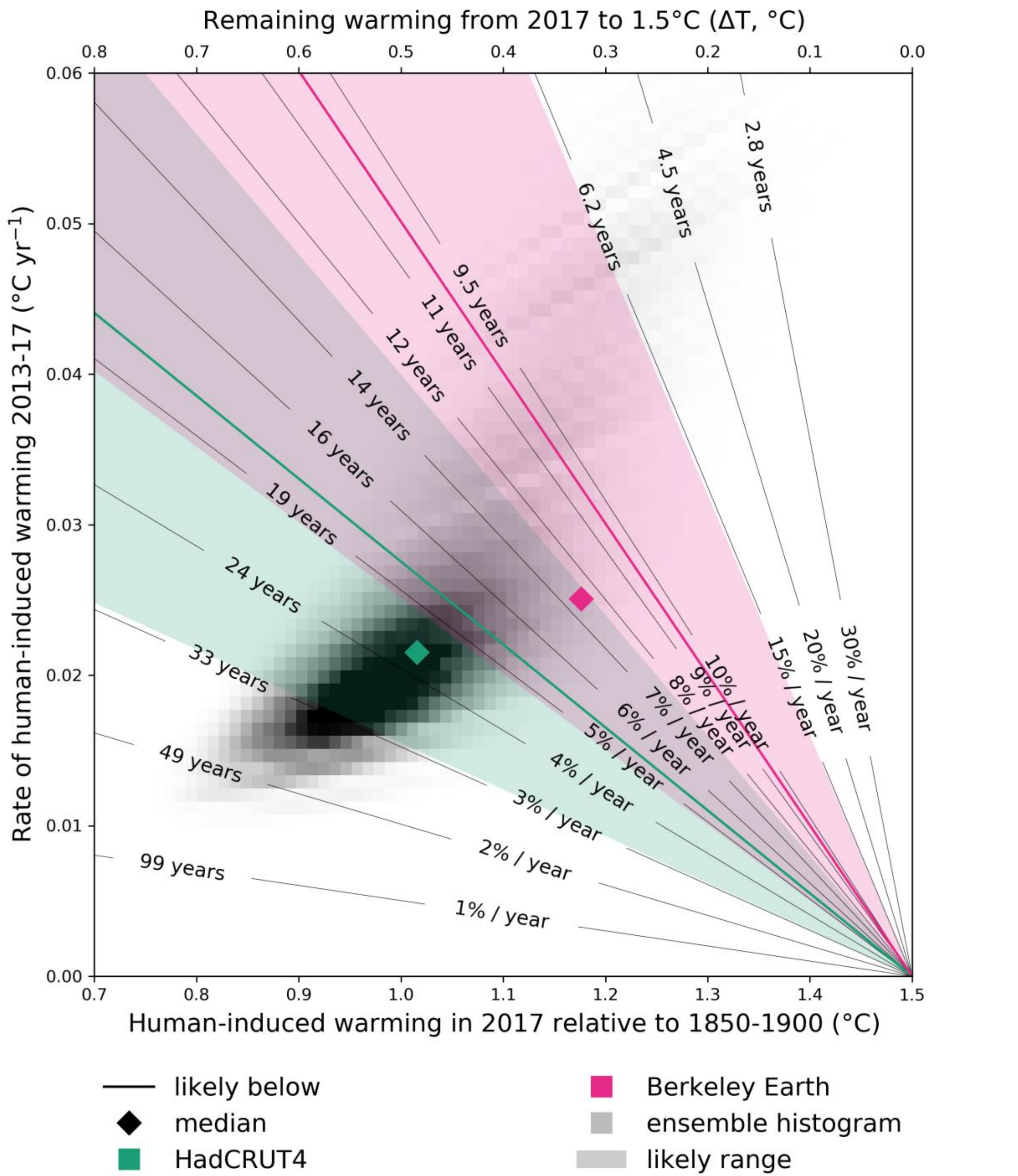
Comparison

- Richardson et al. (2018) used CMIP5 data, blended and interpolated identically to the observational datasets to match their coverage, to compute observationally consistent budgets to likely remain below 1.5°C, finding:

- **800 / 488 GtCO2**
  [HadCRUT4 / Berkeley]

- Combining our estimates of the timescale with emissions from the Global Carbon Project, we find:

- **744 / 407 GtCO2**
  [HadCRUT4 / Berkeley]



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Summary and key messages

- With a simple, transparent and model independent method, we can calculate:
  - the CO_2-fe budget with present day emissions and total warming
  - the CO_2 budget with present day emissions and CO_2-induced warming
  - An upper bound on the CO_2 budget with present day emissions and total warming
- **The current rate of warming is as important as the level, and reducing its uncertainty would help to constrain estimates of the budget**
- This can explain where some previous estimates disagree – even if the models used predict similar levels of warming at present day, if some models are warming faster than others, they will naturally have a reduced budget in comparison.

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Acknowledgements

- **Thanks to Piers Forster** for providing up-to-date forcing data used throughout.
- **Thanks also to Joeri Rogelj** for helpful comments and advice with this study.

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For more information

- Link to paper: **rdcu.be/2Use**
- Correspondences to **nicholas.leach@stx.ox.ac.uk**
- Find me on twitter **@nickleach0**

- **Thank you!**

See next slide for appendices…

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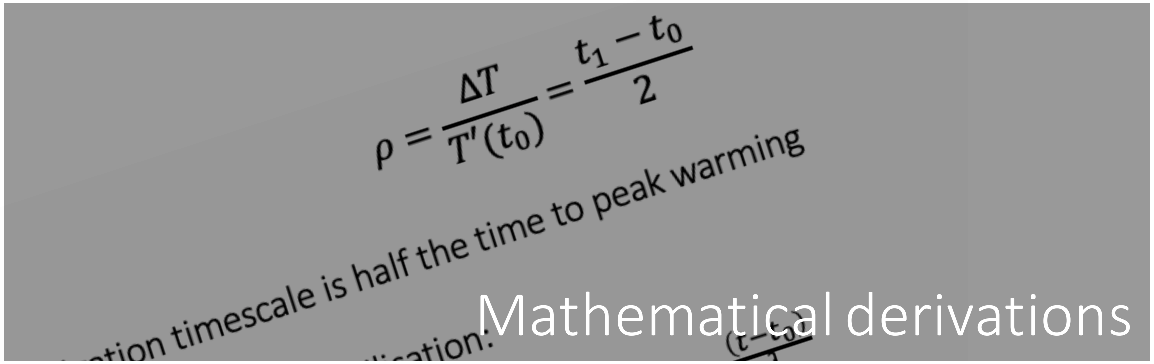
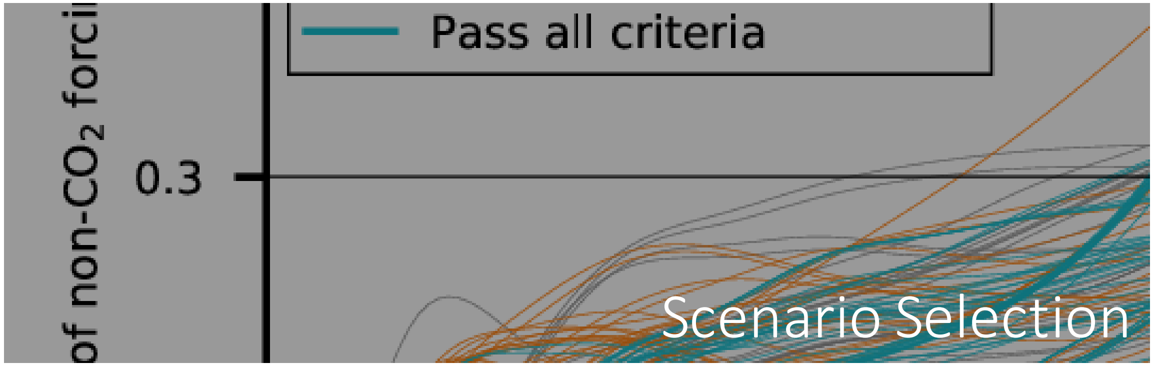
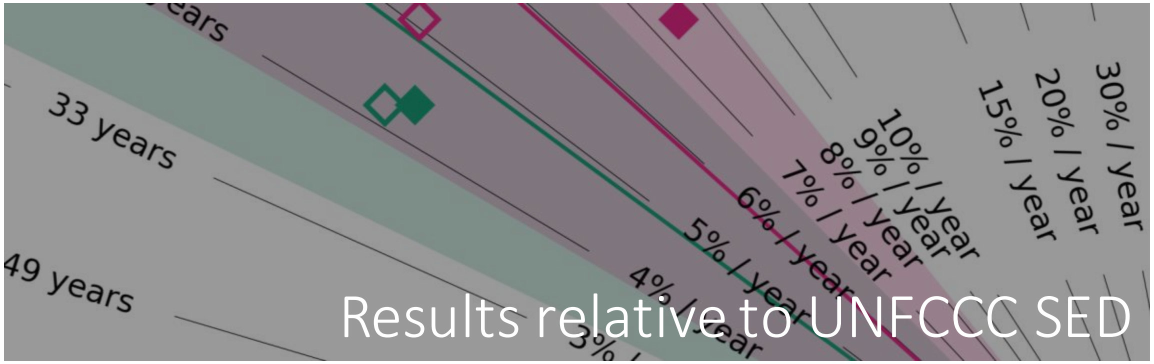
Appendices







Derivations of the mitigation timescale

Linear warming rate reduction from t_0 to t_1:

$$T'(t) = T'(t_0) - T'(t_0) \cdot \frac{t - t_0}{t_1 - t_0}$$

$$T(t) = T_0 + T'(t_0) \cdot (t - t_0) - T'(t_0) \cdot \frac{(t - t_0)^2}{2(t_1 - t_0)}$$

$$T(t_1) - T(t_0) \equiv \Delta T = T'(t_0) \cdot \frac{t_1 - t_0}{2}$$

$$\rho = \frac{\Delta T}{T'(t_0)} = \frac{t_1 - t_0}{2}$$

$\Rightarrow$ mitigation timescale is half the time to peak warming.

General exponential stabilisation:

$$T'(t) = T'(t_0) \cdot e^{-\frac{(t - t_0)}{\lambda}}$$

$$T(t_1) - T(t_0) \equiv \Delta \mathrm{T} = \int_{t_0}^{t_1} T'(\mathrm{t})\ \mathrm{d}t = \lambda T'(t_0)$$

$$\frac{\Delta T}{T'(t_0)} = \rho = \lambda$$

$\Rightarrow$ mitigation timescale is the decay timescale, and the associated reduction rate is

$$\left(1 - e^{-\frac{1}{\rho}}\right) \times 100\% \text{ per year}$$

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Scenario Selection

- We preselected a subset of AR5 database scenarios based on consistency with present-day observations of CO_2 emissions and non-CO_2 forcing gradient.