# Contents

- IPCC AR5 introduced the concept of carbon budgets
  - What's changed since then?
  - Techniques, data, reality

- AR5 to SR15 framework for carbon budgets

- CMIP6 vs CMIP5 results
  - C4MIP and ZECMIP
  - Uncertainty – role of (partially) missing processes?

- Summary

# Components of Carbon budgets: what's changed since AR5?

- How to use data to calculate a remaining carbon budget
  - AR5 to SR15 framework for carbon budgets

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  - CMIP6 vs CMIP5 results

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  - We continue to burn circa 10 PgC per year…

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# Total CO$_2$ emissions are strongly linked to total warming

- A key message from last IPCC report (AR5: 2013/14)

- Long-term warming is linearly related to total emissions of CO$_2$.
  - For a given warming target, higher emissions now imply lower emissions later.
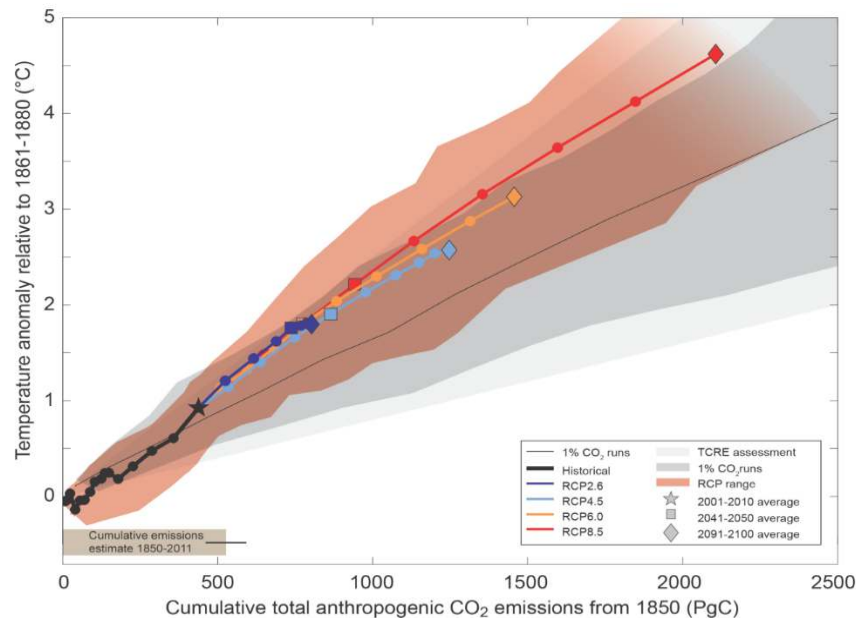
- Allows us to quantify exactly what we must do to meet targets

- Carbon "budget" we can spend

- Quantifying this drew together *ALL* of climate science into a single straight line!



TCRE: Transient Climate Response to cumulative carbon Emissions

# Total CO$_2$ emissions are strongly linked to total warming

- But AR5 usage was fairly simplistic…

- Define a warming level

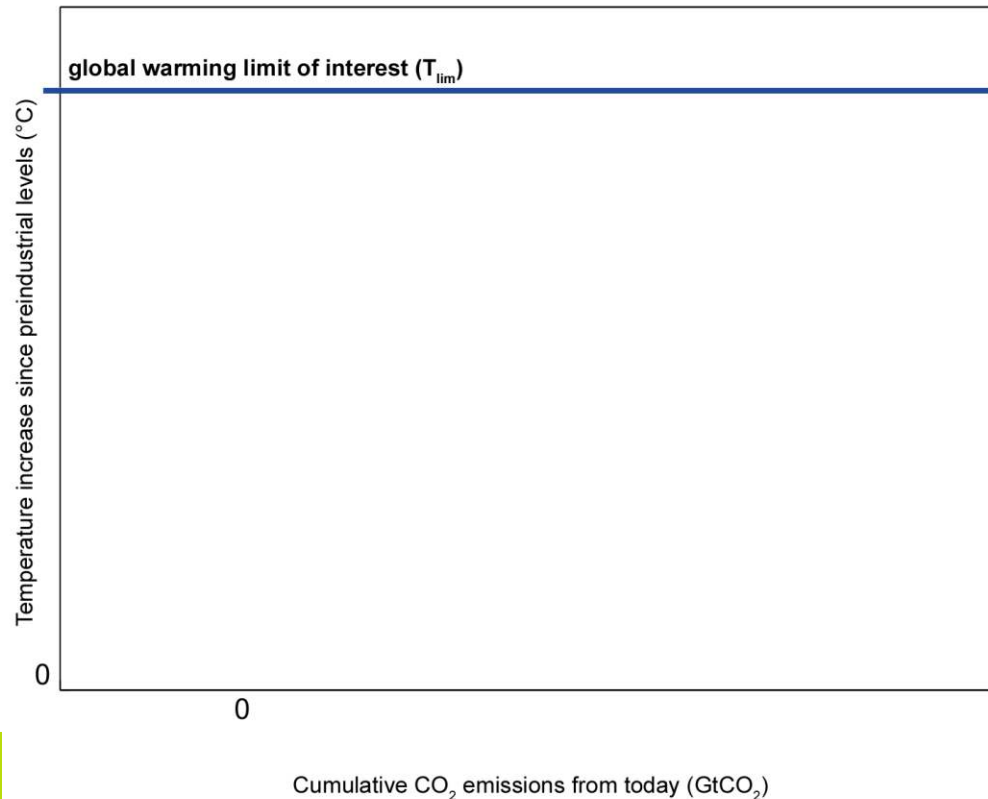- Read off the total budget

- Subtract what's emitted already
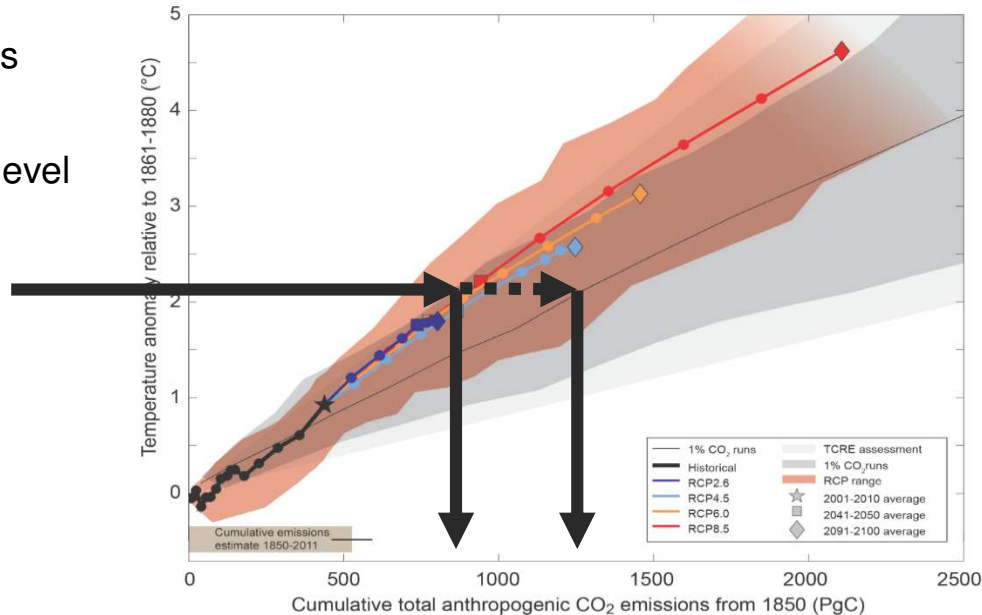


- No account taken of model errors/biases to date

- No account of climate variability

- Non-CO2 hard to consider

- No process understanding of where uncertainty comes from

**TCRE: Transient Climate Response to cumulative carbon Emissions**

Five components:

**Five components:**

- Historical warming to date

**SR15 assessment:**

- Human-induced warming since 1850-1900
- Global Surface Air Temperature (GSAT)
- 0.97°C (+- 0.12°C *likely* range)



*Rogelj et al., 2019*

**Met Office**
**Hadley Centre**

Five components:
- Historical warming to date
- Transient climate response to cumulative emissions of carbon dioxide (TCRE)

SR15 assessment:
- Same as AR5 assessment
- 0.8-2.5°C / 1000 PgC
- Normally distributed uncertainty



Rogelj et al., 2019
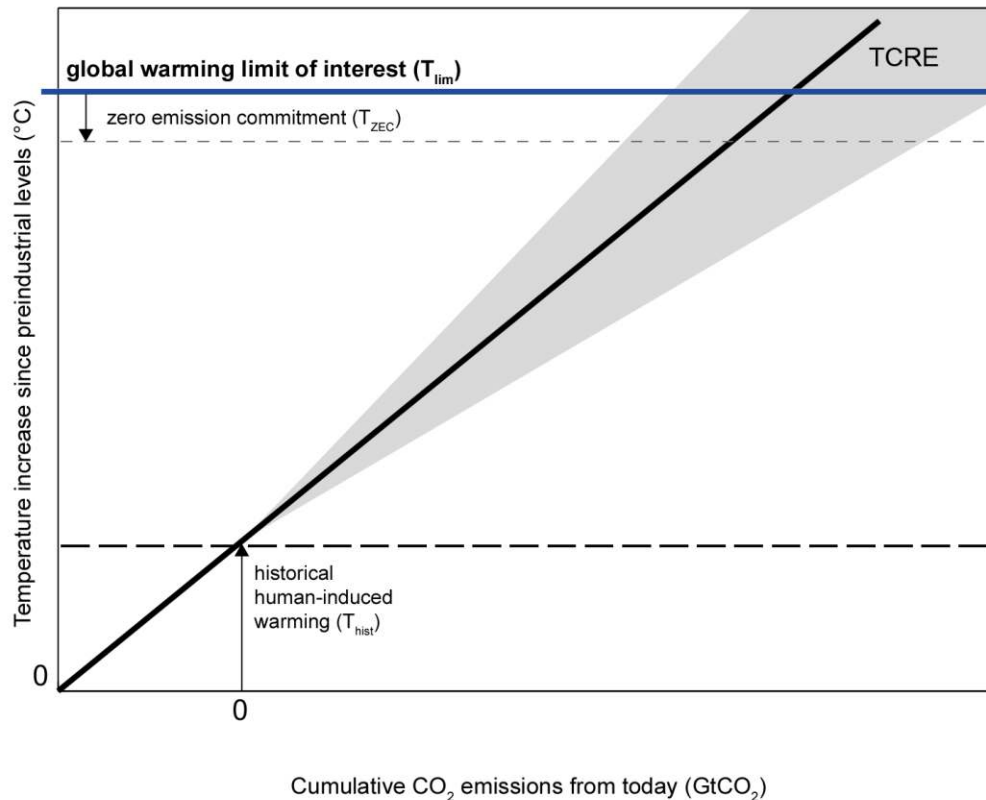
Five components:
- Historical warming to date
- Transient climate response to cumulative emissions of carbon dioxide (TCRE)
- Zero emission commitment (ZEC)

SR15 assessment:
- Same as AR5 assessment
- Zero or negative



*Rogelj et al., 2019*

Five components:
- Historical warming to date
- Transient climate response to cumulative emissions of carbon dioxide (TCRE)
- Zero emission commitment (ZEC)
- Projected future non-$CO_2$ temperature contribution

SR15 assessment:
- Based on SR15 scenario database
- Future non-$CO_2$ warming at time global $CO_2$ emission become net zero
- Estimated with simple climate models MAGICC & FAIR



*Rogelj et al., 2019*

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*Rogelj et al., 2019*



global warming limit of interest ($T_{lim}$)

zero emission commitment ($T_{ZEC}$)

non-$CO_2$ contribution ($T_{nCO2}$)

TCRE

Temperature increase since preindustrial levels (°C)

remaining allowable warming

historical human-induced warming ($T_{hist}$)

0

0
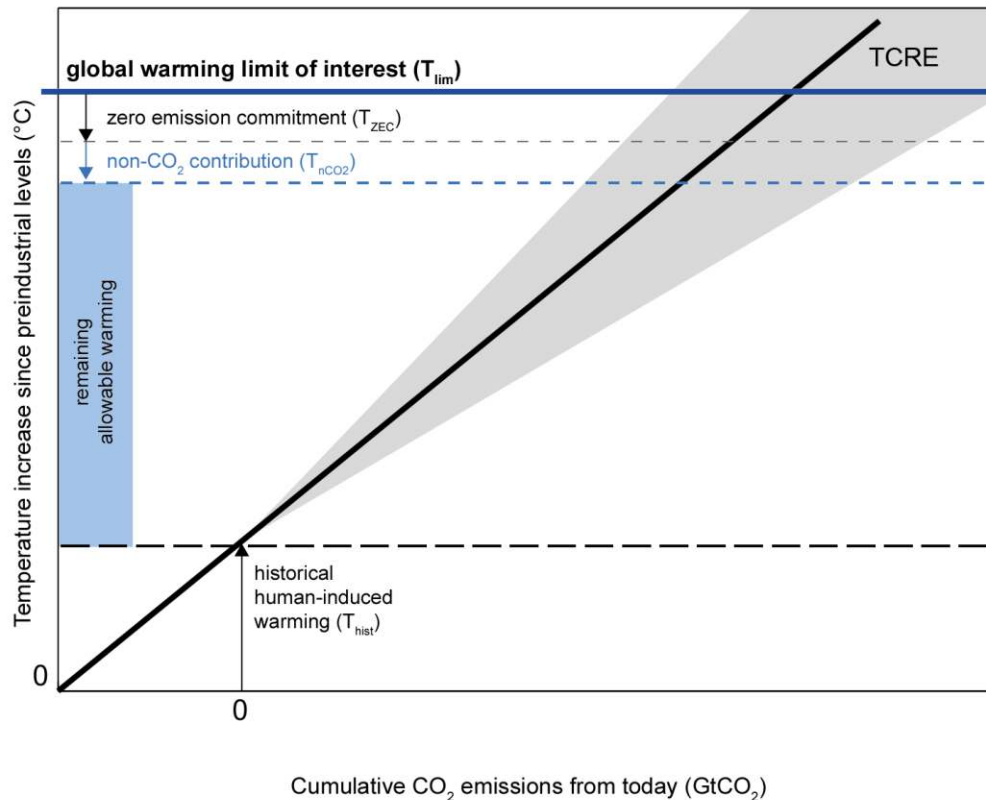
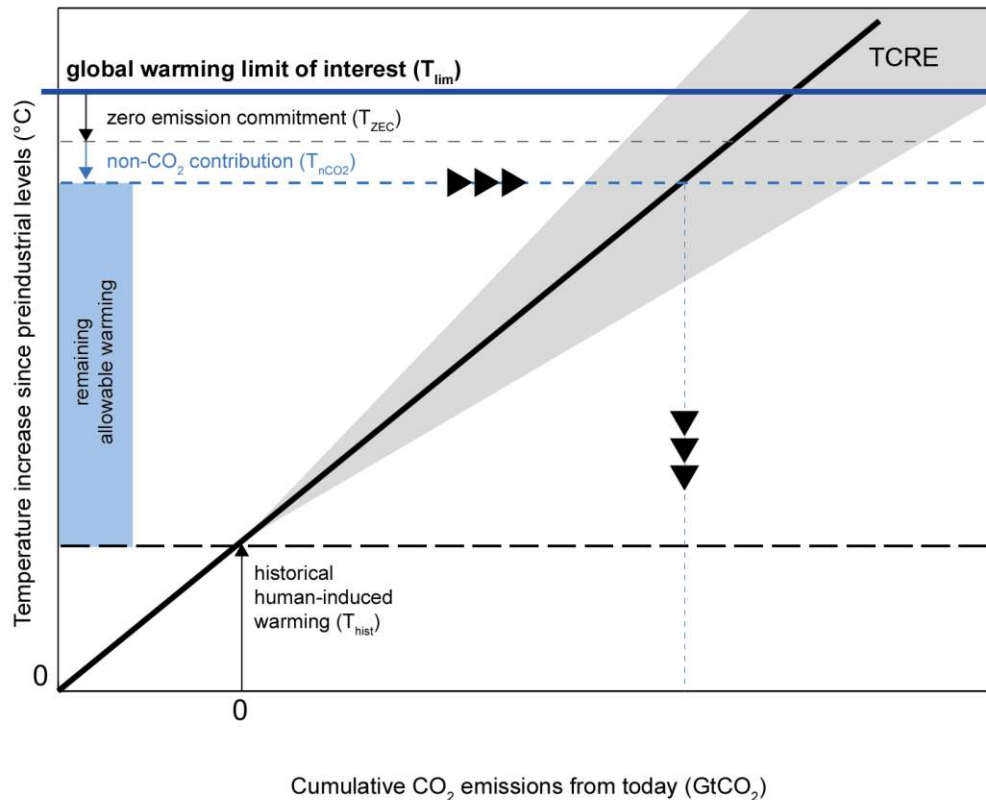Cumulative $CO_2$ emissions from today (Gt$CO_2$)

# The Remaining Carbon Budget Framework of the IPCC Special Report on Global Warming of 1.5°C

Five components:

- Historical warming to date
- Transient climate response to cumulative emissions of carbon dioxide (TCRE)
- Zero emission commitment (ZEC)
- Projected future non-$CO_2$ temperature contribution
- Unrepresented Earth system feedbacks

SR15 assessment:

- Permafrost thawing and other unrepresented Earth system feedbacks can contribute to up to 100 Gt$CO_2$ until 2100



Rogelj et al., 2019
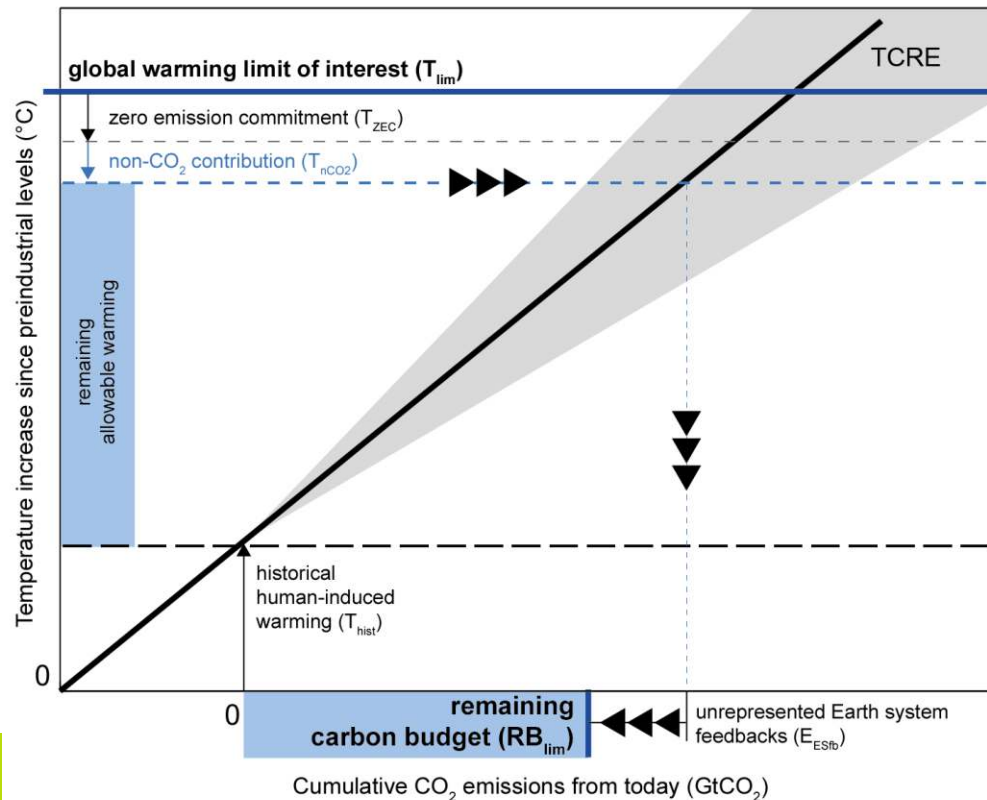
| Additional Warming since 2006–2015 [°C][1] | Approximate Warming since 1850–1900 [°C][1] | Remaining Carbon Budget (Excluding Additional Earth System Feedbacks[5]) [GtCO$_2$ from 1.1.2018][2] | | | Key Uncertainties and Variations[4] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Percentiles 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 | | | | | | |
| 0.4 | | 530 | 350 | 230 | Budgets on the left are reduced by about −100 on centennial time scales | | | | | |
| 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 | | | | | | |

Five components:
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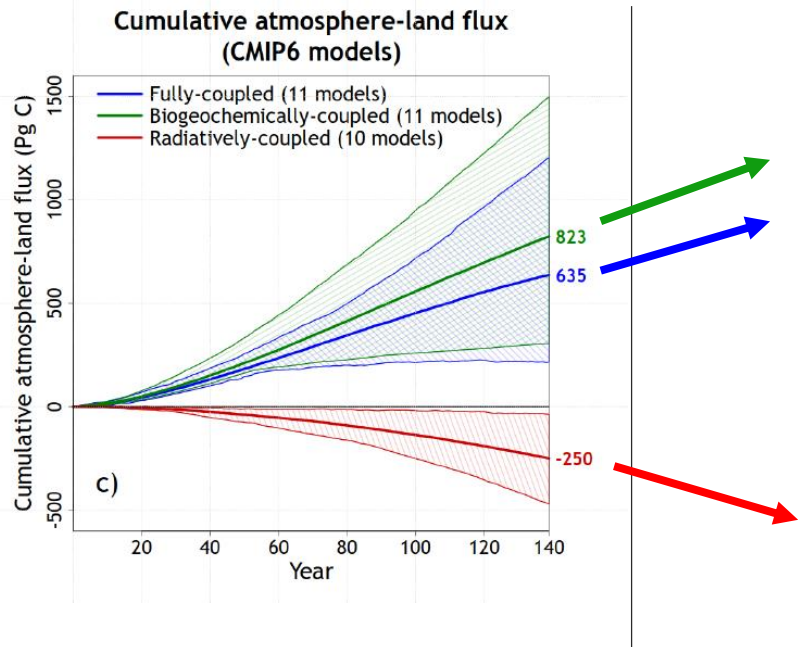  - We continue to burn circa 10 PgC per year…

# C4MIP feedback metrics

- $CO_2$ affects climate:

$$\Delta T = \alpha \Delta C_a$$

$$\Delta C = \beta \Delta C_a + \gamma \Delta T$$

- Carbon affected by $CO_2$ and Climate
- "COU" coupled runs vary both ($CO_2$ and climate)
- "BGC" biogeochemical runs – only vary $CO_2$, to diagnose beta

# C4MIP feedback metrics



Cumulative atmosphere-land flux (CMIP6 models)

- Response to $CO_2$ (BGC)  β

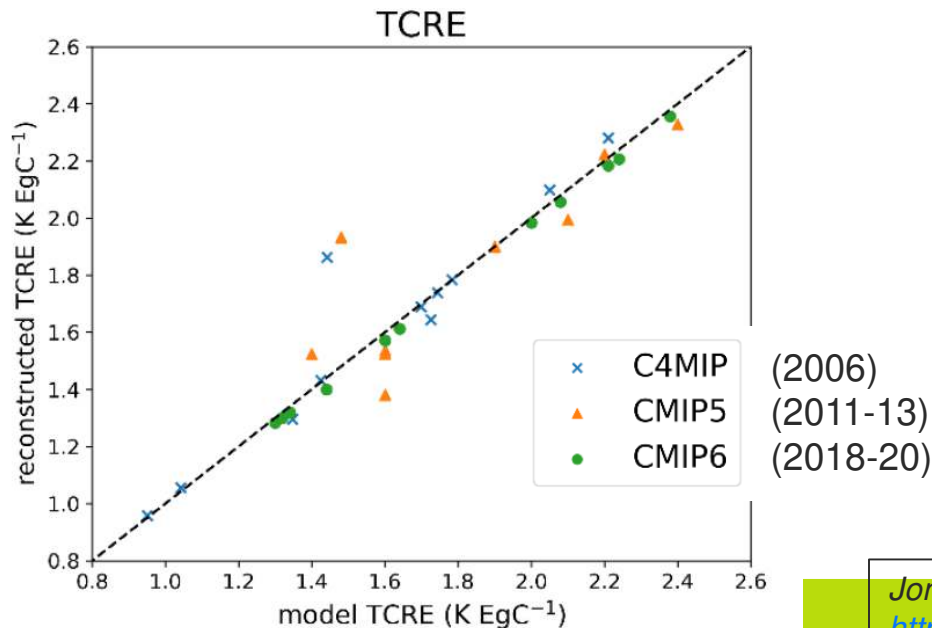- Response to both ($CO_2$ and climate) (COU)

- Response to climate (RAD)  γ

# Using C4MIP metrics

- TCRE can be calculated from the feedback metrics

- Airborne fraction determines how much CO2 stays in atmosphere, and TCRE is climate response to this:  (k = unit conversion, 2.12 PgC/ppm)



$$AF = \frac{k}{k + \beta + \alpha\gamma}$$

$$TCRE = \frac{\alpha}{k + \beta + \alpha\gamma}$$

- Reconstructed quantities fit well

*Jones & Friedlingstein, 2020, ERL*
*https://iopscience.iop.org/article/10.1088/1748-9326/ab858a*

# C4MIP: uncertainty

- This allows propagation of uncertainty from the feedback metrics to the quantity of interest

- **AF** – dominated by beta

- **TCRE** – jointly controlled by beta/alpha

  - CMIP5: approx. 50:50 climate vs carbon cycle
  - CMIP6: move towards control by climate uncertainty



*% variance explained*

*Jones & Friedlingstein, 2020, ERL*
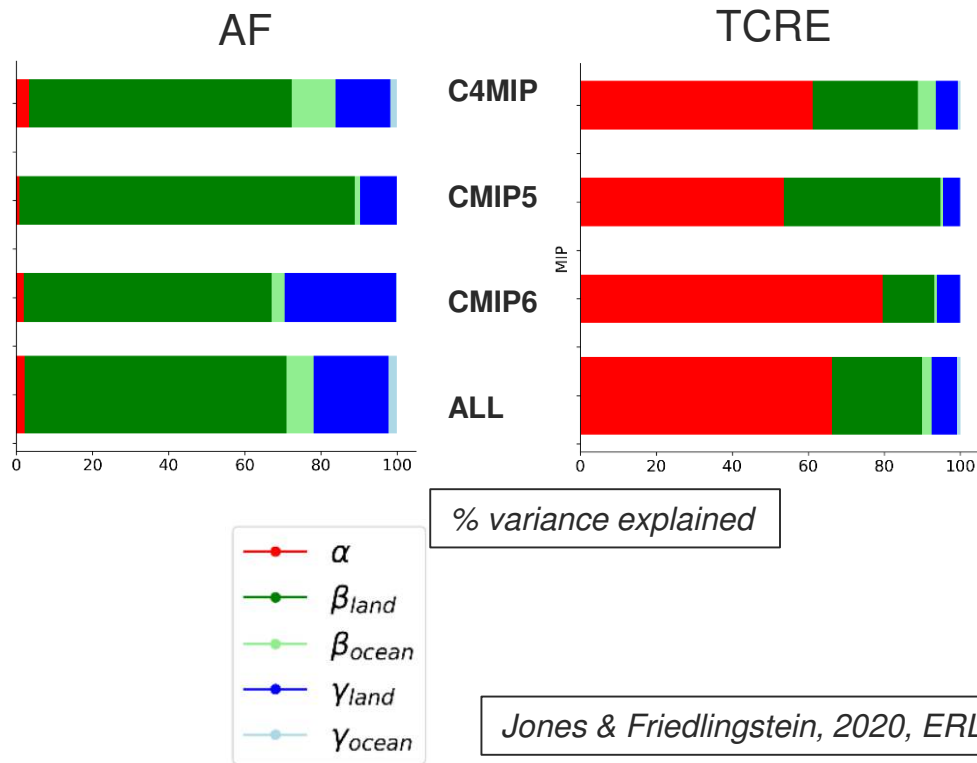
# C4MIP: uncertainty

- This allows propagation of uncertainty in each term to the quantity of interest



*Jones & Friedlingstein, 2020, ERL*
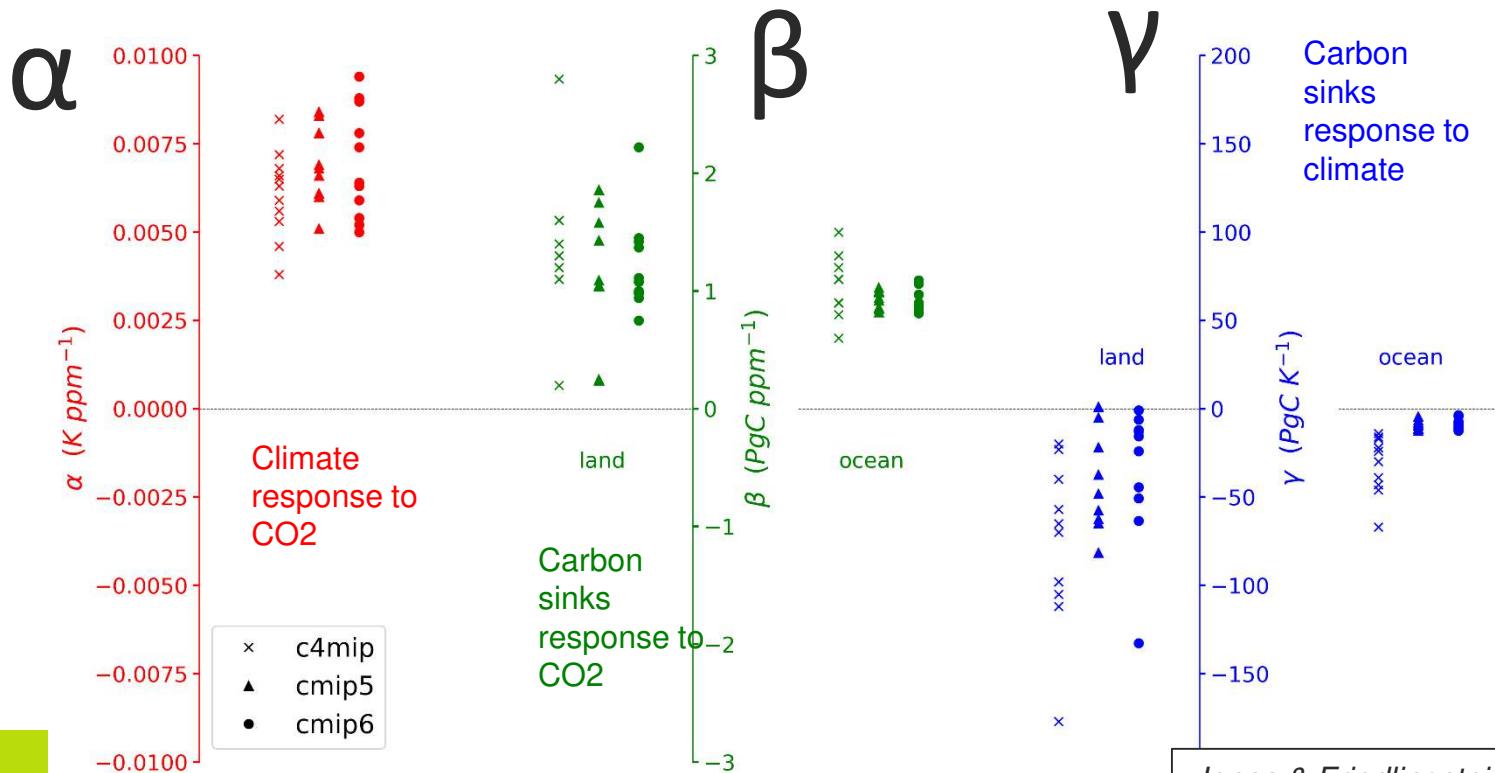
# C4MIP: uncertainty

- Now we can understand how CMIP6 differs from CMIP5

- **AF** – dominated by beta
  - CMIP6 spread <half of CMIP5

- **TCRE** – jointly controlled by beta/alpha

  - CMIP6 and CMIP5 very similar
    - mean and spread
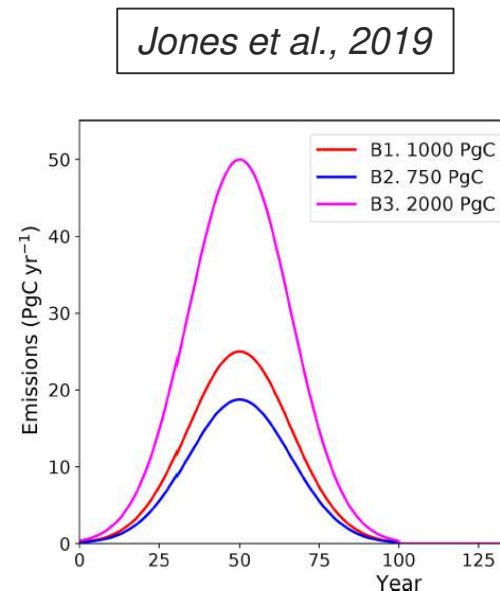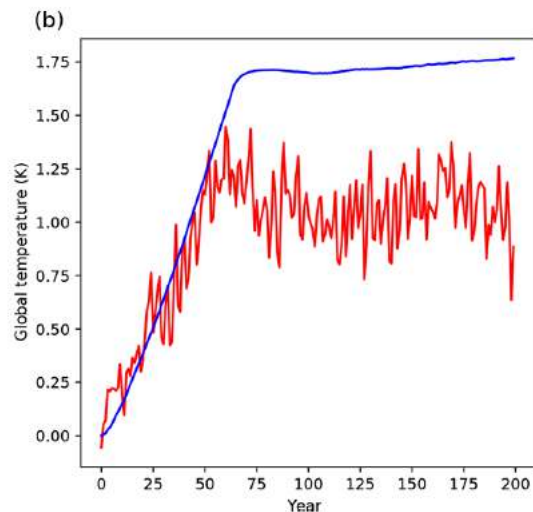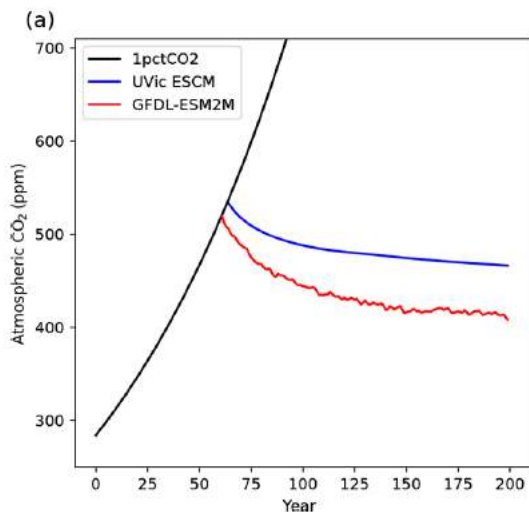  - But due to different combination in CMIP6 than CMIP5



*Jones & Friedlingstein, 2020, ERL*
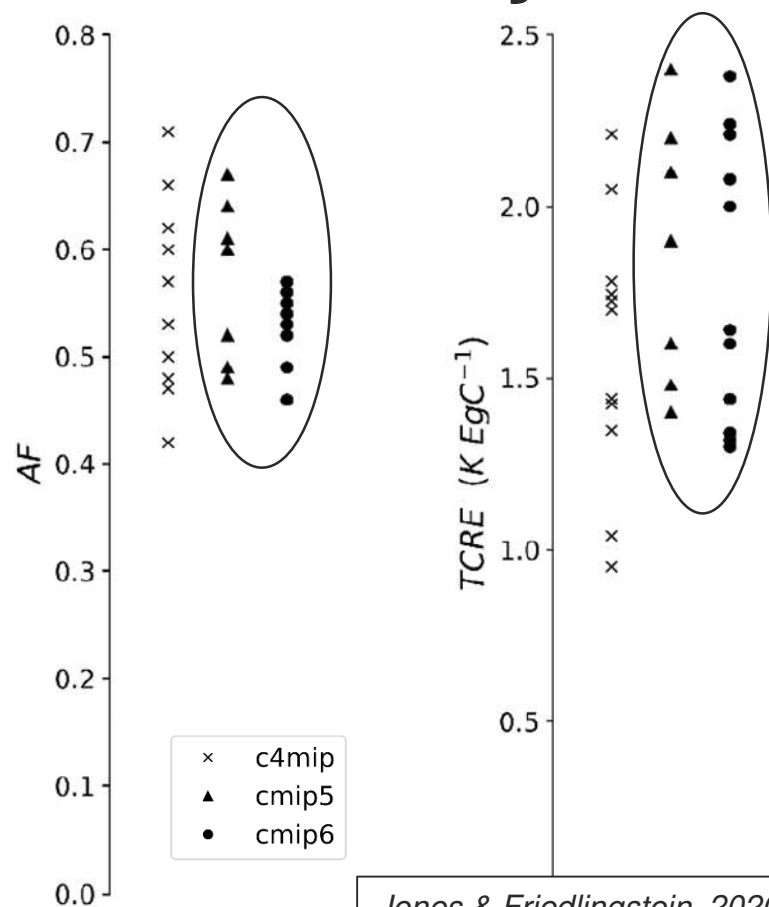
Results 2.

ZECMIP

# ZECMIP: experiments

- How does climate continue to respond following complete cessation of emissions
- (myth: some warming is "locked in", or "in the pipeline")



*Jones et al., 2019*

- "A" experiments: sudden stop from 1% trajectory
- "B" experiments: gradual rise and reduce of emissions

# ZECMIP: results

- All 18 models show rapid initial reduction in $CO_2$ – sinks persist but begin to slow
- Range of warming/cooling spans zero

| Model | $ZEC_{25}$ (°C) | $ZEC_{50}$ (°C) | $ZEC_{90}$ (°C) |
|---|---|---|---|
| Mean | -0.01 | -0.06 | -0.11 |
| Median | -0.01 | -0.05 | -0.08 |
| Standard Deviation | 0.15 | 0.19 | 0.23 |
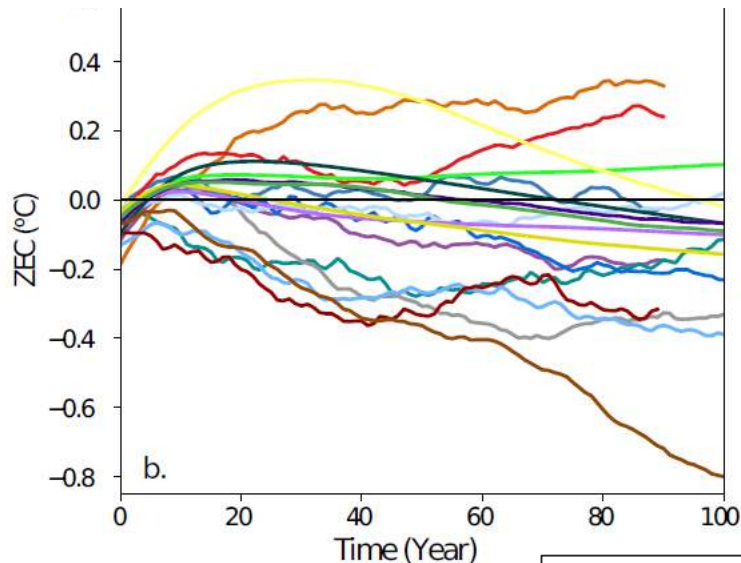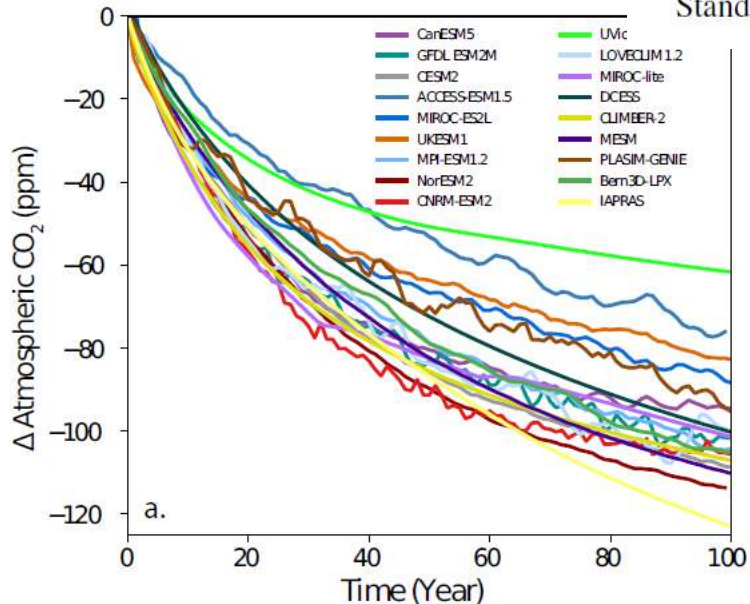


*MacDougall et al., 2020*

# C4MIP / ZECMIP synthesis

- So what does all this mean for carbon budgets?
- Three of the five components of SR15 carbon budgets:

# C4MIP / ZECMIP synthesis

- So what does all this mean for carbon budgets?
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- ZEC ≈ 0
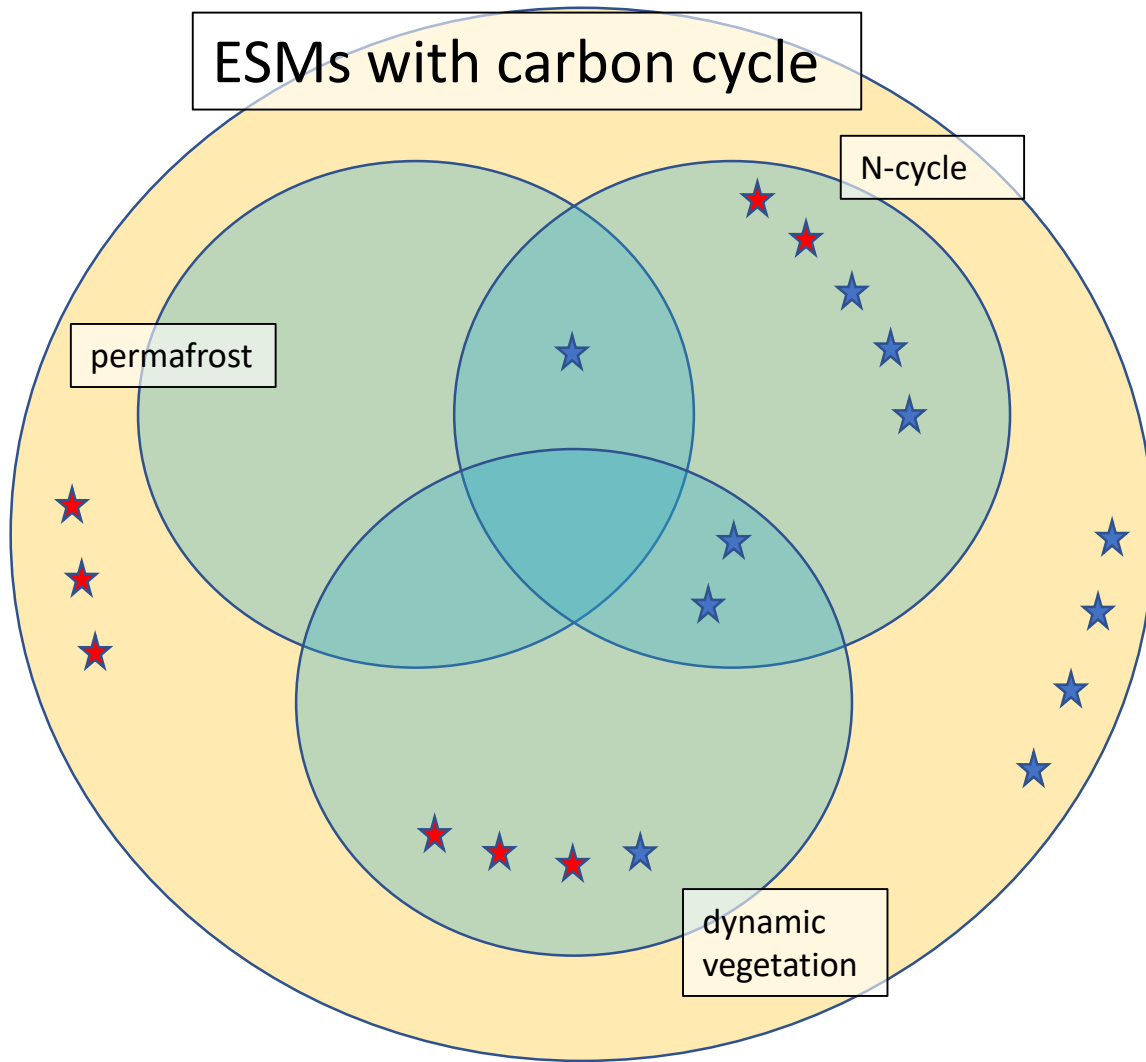  - No change to our assumption, but now we can justify it

# C4MIP / ZECMIP synthesis

- So what does all this mean for carbon budgets?
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- ZEC ≈ 0
  - No change to our assumption, but now we can justify it

- TCRE
  - No change in TCRE magnitude or spread since CMIP5
  - BUT: change in _*source*_ of uncertainty
    - N-cycle has reduced spread in land-carbon, leaving greater role for climate response uncertainty
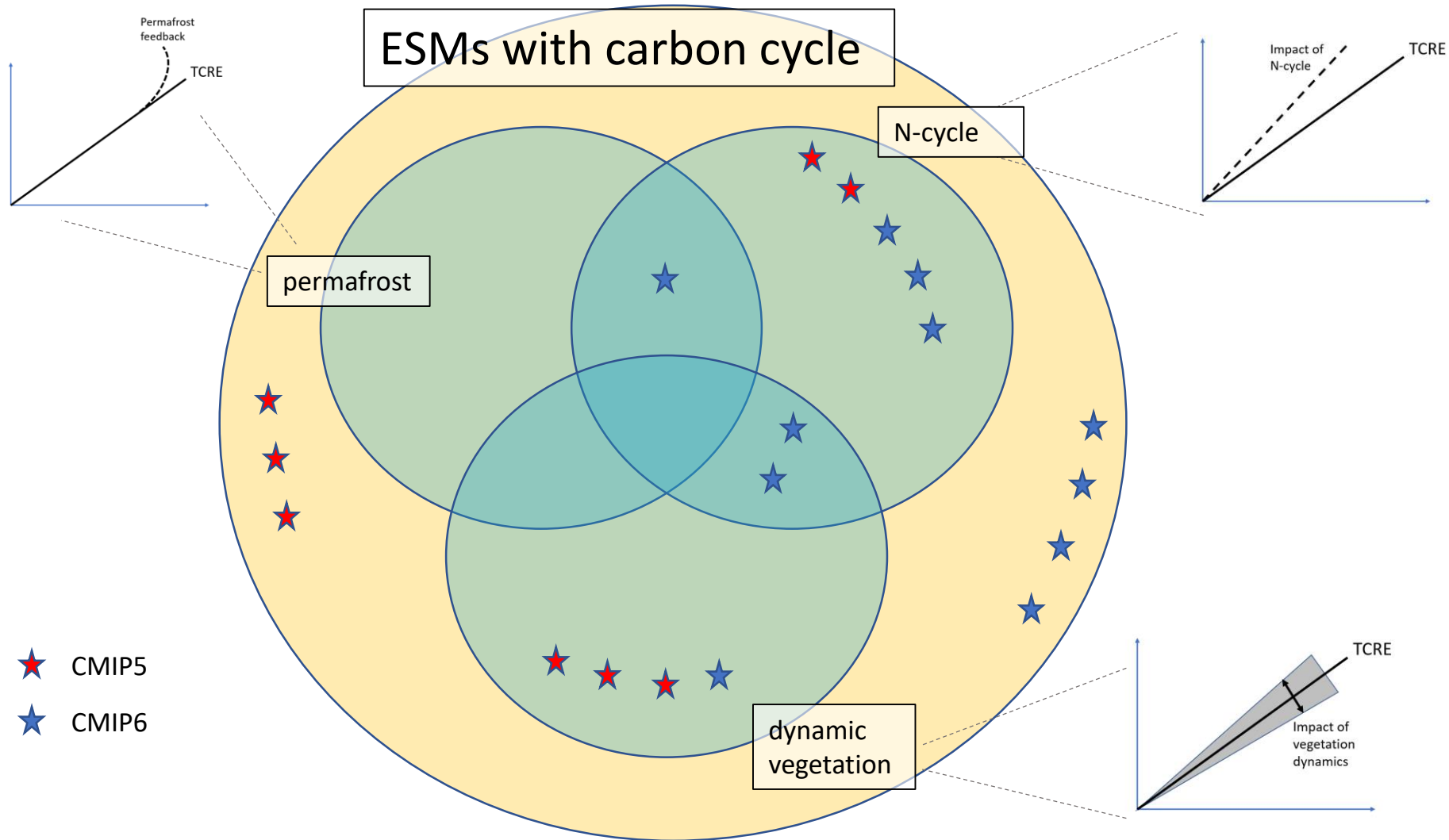
# Next steps?

- SR15 framework includes adjustment for "un-represented processes"
  - But no treatment of mixed-complexity ("partially included processes") in carbon budgets framework
  - What to do if half models have N-cycle and half don't?

  - Can we do model-by-model adjustment for which processes it includes?
  - Role of emergent constraints?

ESMs with carbon cycle

N-cycle

permafrost

dynamic
vegetation

★ CMIP5

★ CMIP6

ESMs with carbon cycle

Permafrost feedback / TCRE

Impact of N-cycle / TCRE

permafrost

N-cycle

dynamic vegetation

Impact of vegetation dynamics / TCRE

★ CMIP5

★ CMIP6

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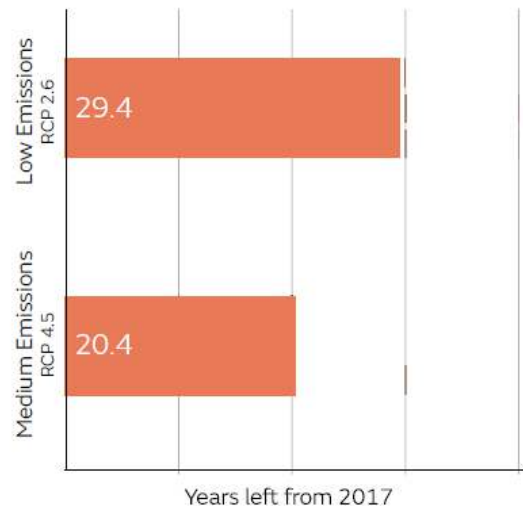# We're not solving a problem in a static world…

- In 7 years since AR5 world has emitted 67 PgC (fossil fuel) out of 440 since 1850
- i.e. +15%

- Significant fraction of remaining budget…

**To stay within 2 °C** using IPCC carbon budget estimates

How much carbon can we emit?
Gt CO2

Carbon budget we have left 768

Carbon spent 2075
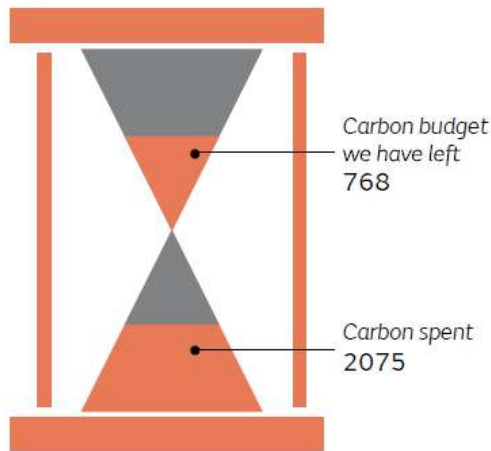
From 2017, how long do we have left to emit?

Low Emissions RCP 2.6: 29.4

Medium Emissions RCP 4.5: 20.4

Years left from 2017

# Concluding comments

- CMIP6 marks 3$^{rd}$ generation of coupled climate-carbon cycle ESMs

- Headline numbers not hugely different from CMIP5…

- BUT – there has been progress
  - Confirmation of ZEC=0, and understanding of mechanisms
  - Increased complexity (N-cycle) in land models has led to reduced spread of response
  - TCRE uncertainty now more controlled by climate sensitivity than carbon cycle feedbacks


- Carbon budgets
  - New framework since AR5          ☺
  - New models since AR5              ☺
  - New emissions since AR5          ☹

Questions and Answers