Met Office Hadley Centre

Carbon Cycle results in CMIP6: implications for carbon budgets and next steps

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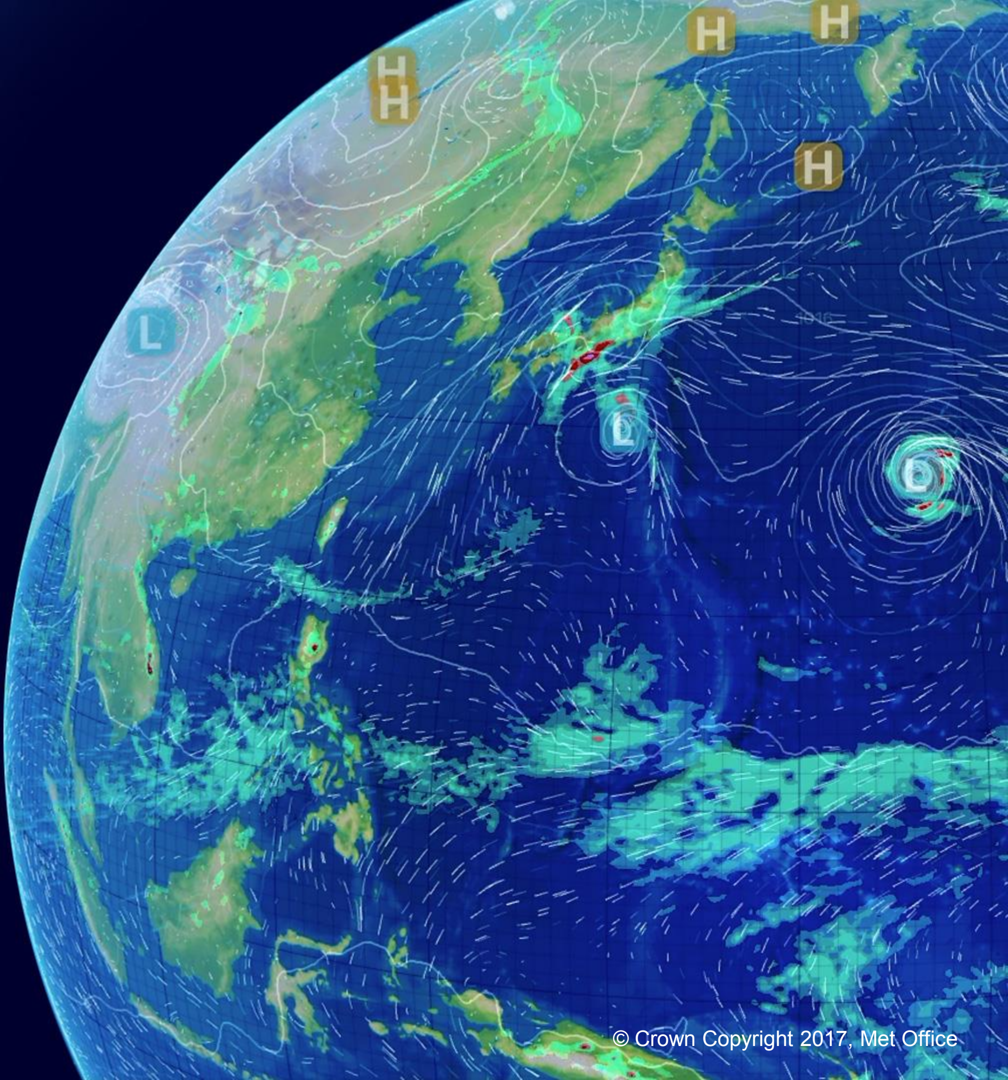
Met Office Hadley Centre

31 Mar. 2020

www.c4mip.net



Contents

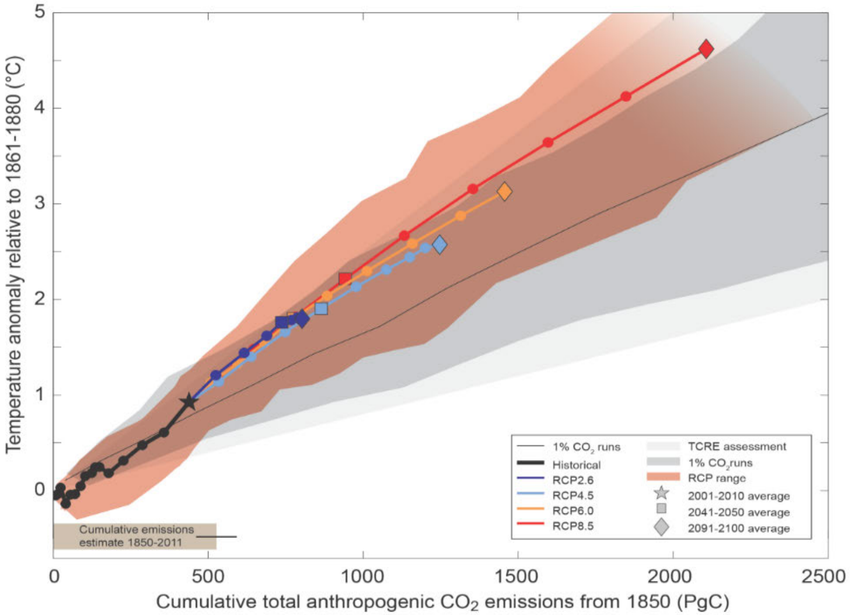
- Carbon cycle background
  - Timeline of carbon cycle intercomparison
  - Framework for carbon budgets
  - Concept of feedback terms and uncertainty

- CMIP6 results
  - C4MIP and ZECMIP
  - Uncertainty – sources and potential for reduction?

- Concluding thoughts
  - CMIP6 successes and failures?
  - Future focus areas

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.

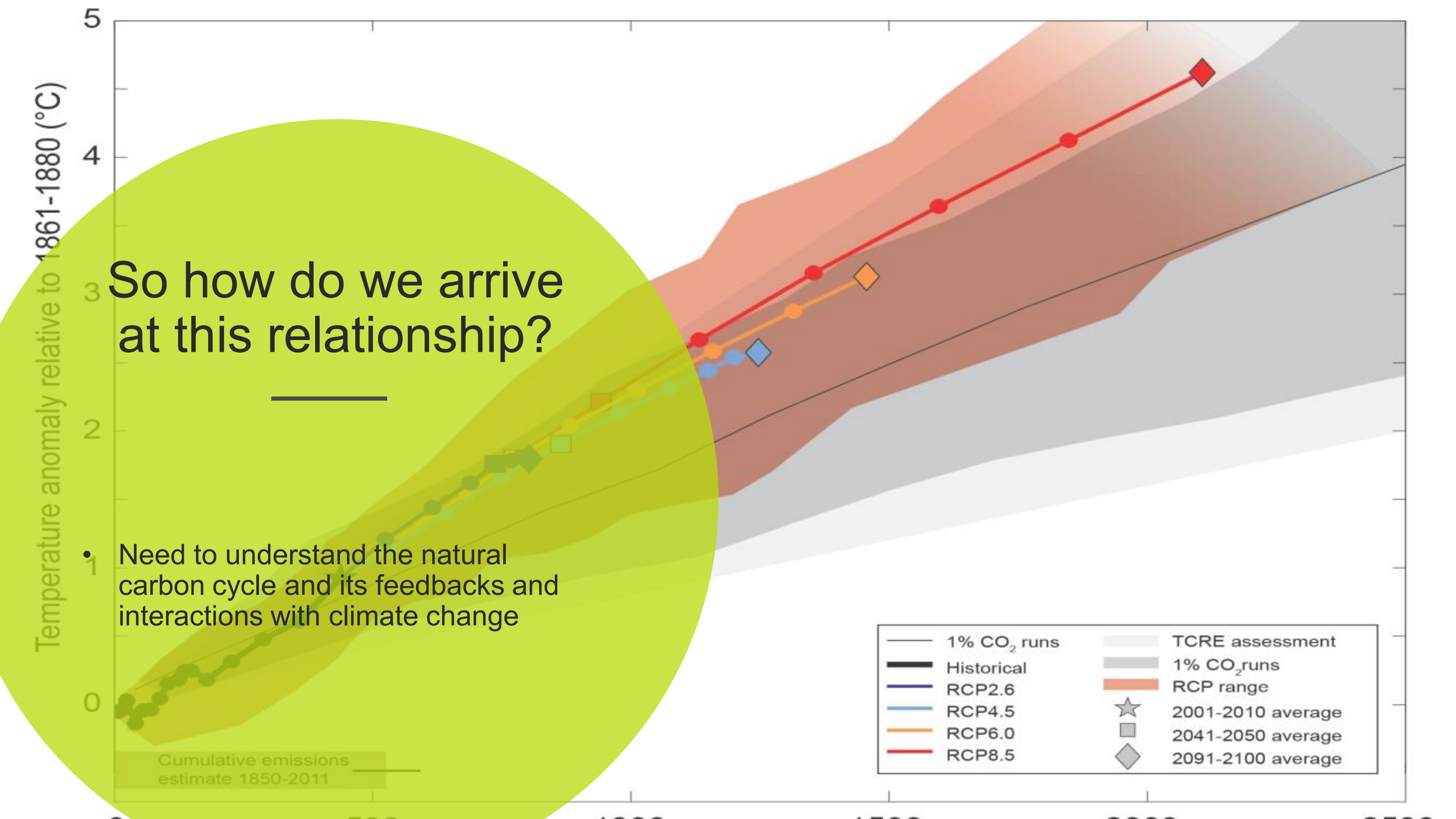


- Allows us to quantify exactly what we must do to meet targets
- Carbon "budget" we can spend
- Quantifying this drew together ***ALL*** of climate science into a single straight line!

TCRE: Transient Climate Response to cumulative carbon Emissions

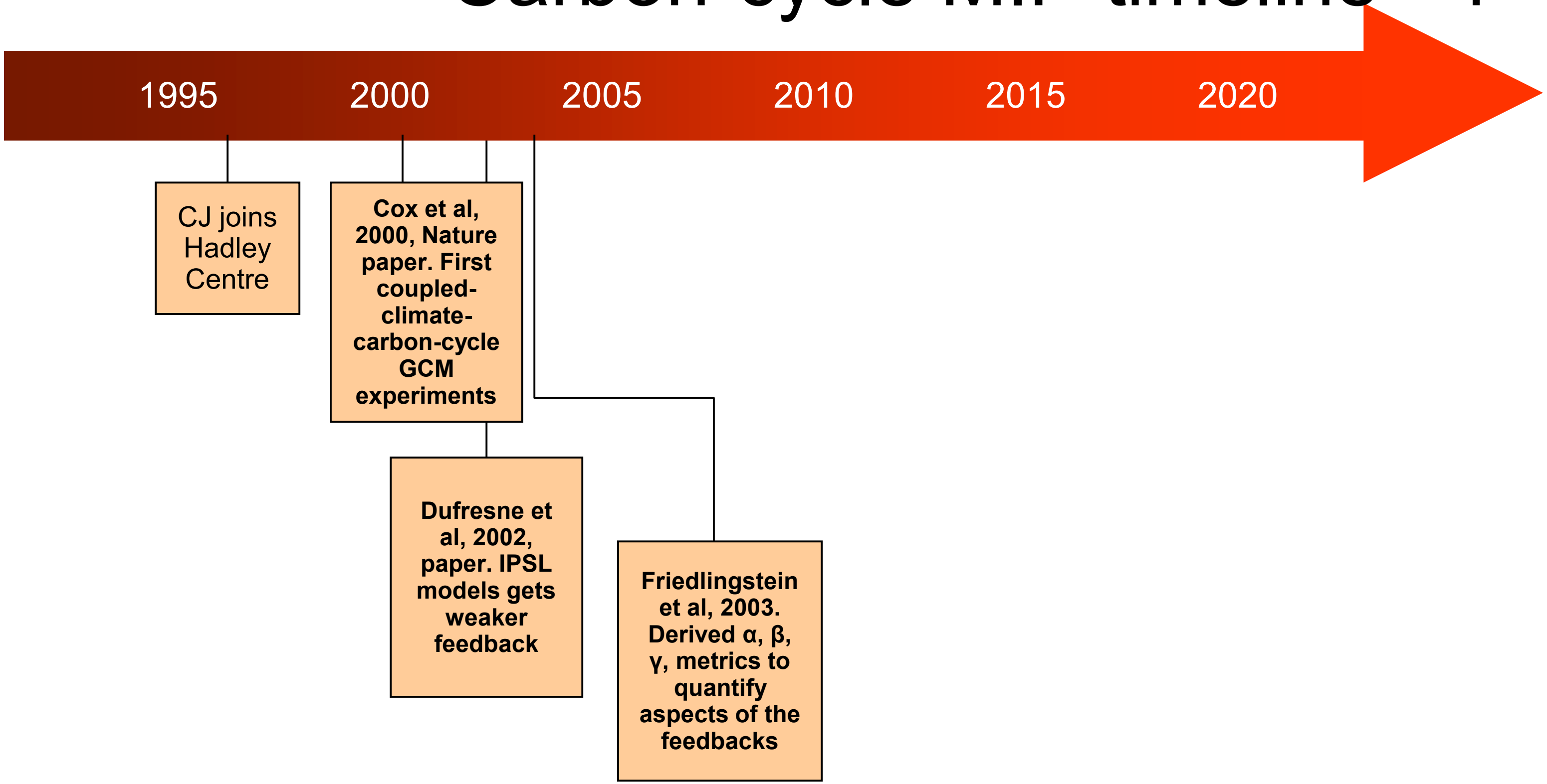
So how do we arrive at this relationship?

- Need to understand the natural carbon cycle and its feedbacks and interactions with climate change



C4MIP history

Carbon-cycle MIP timeline - 1



Carbon-cycle MIP timeline - 1

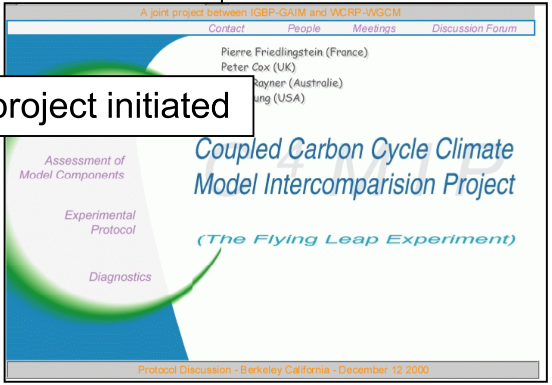
1995 2000 2005 2010 2015 2020

Cox et al.

Dufresne et al.

Friedlingstein et al.

C4MIP project initiated



Friedlingstein et al, 2006. C4MIP paper.

First coupled-climate-carbon-cycle MIP paper.

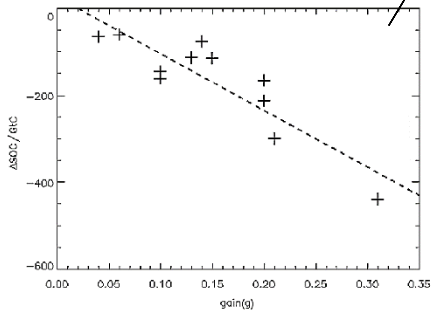
- Stage 1
  - Run lots of models, get lots of (very different) results

Carbon-cycle MIP timeline - 2

1995 2000 2005 2010 2015 2020

Terrestrial uncertainty

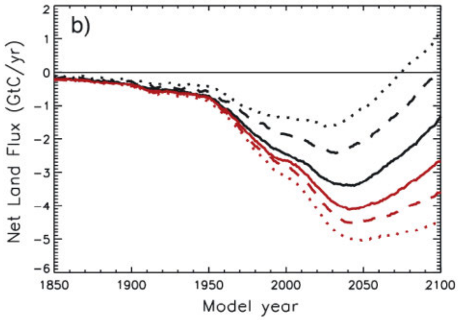
Soil carbon "q10"



e.g. Jones and Falloon, 2009

Matthews et al., 2005, GRL.

NPP control on climate-carbon feedback



Carbon-cycle MIP timeline - 2

1995 2000 2005 2010 2015 2020

Terrestrial uncertainty

Soil carbon "q10"

Matthews et al.

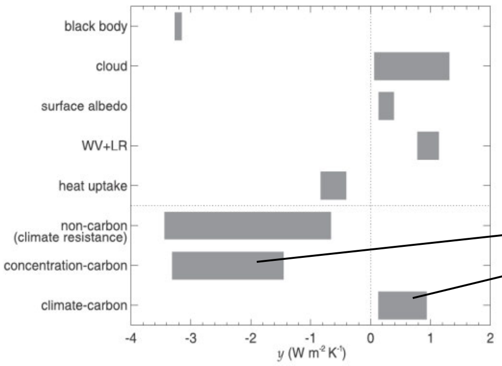
"climate-carbon" feedback dominated thoughts

Gregory et al., 2009, J. Clim.

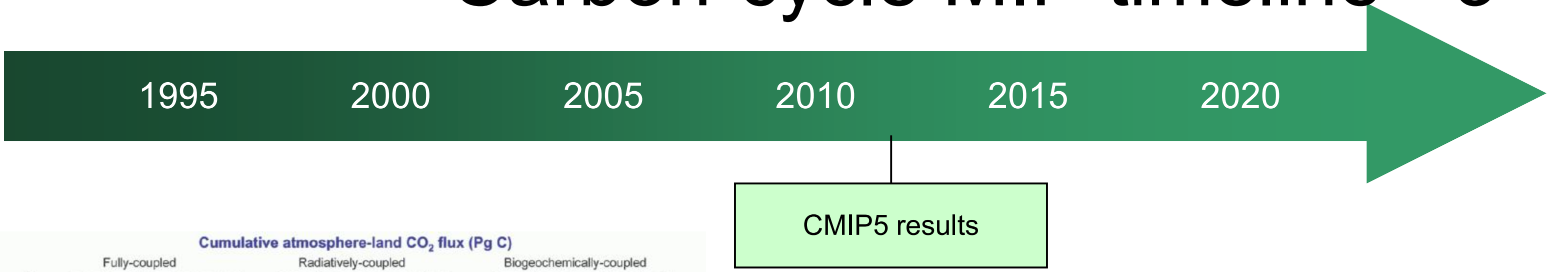
Split into 2 competing feedbacks
-Response to CO2
-Response to climate

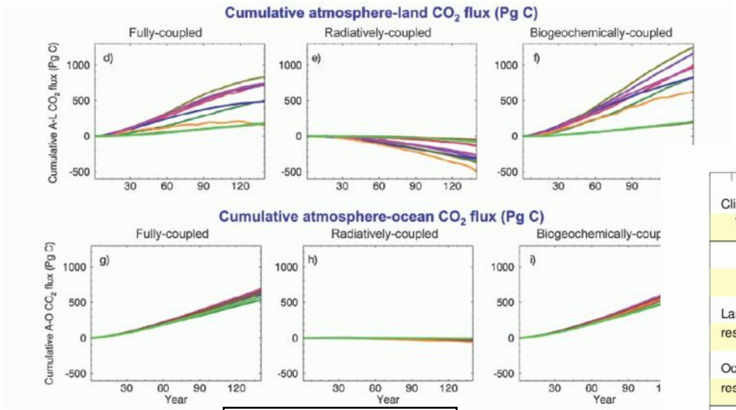
Climate-carbon feedback (+ve) is comparable to cloud feedbacks

Concentration-carbon feedback is bigger (but –ve) and more uncertain



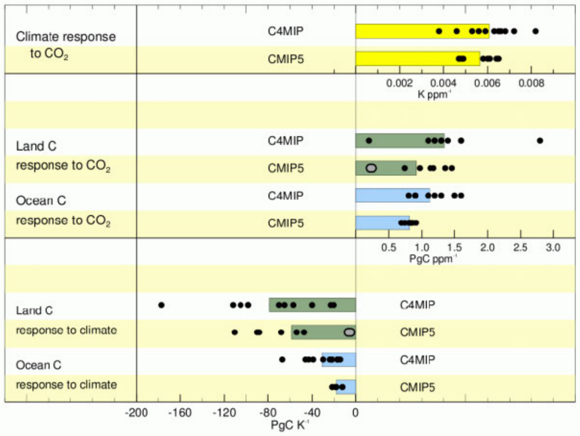
Carbon-cycle MIP timeline - 3



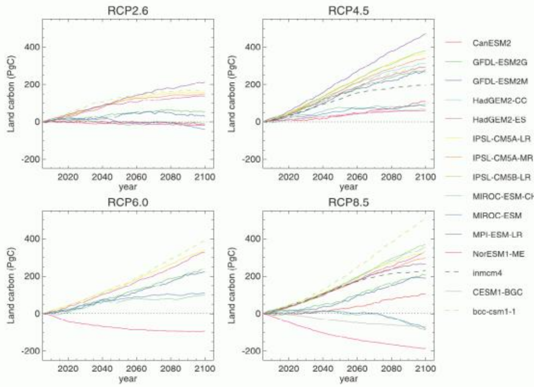


Arora et al., 2013

IPCC AR5, Ch.6



Jones et al., 2013



- Large uncertainty remained – CMIP5 spread no better than C4MIP

Carbon-cycle MIP timeline - 3

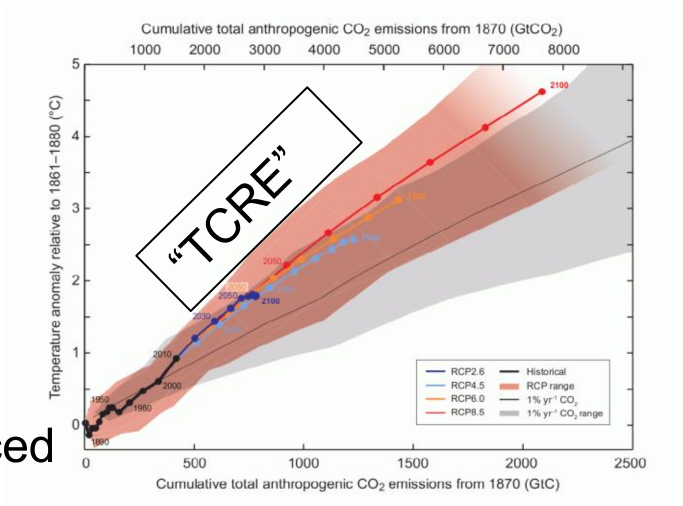
1995 2000 2005 2010 2015 2020

CMIP5 results

SR15

State and rate dependence of feedback factors
Gregory et al., 2009
Schwinger et al., 2014
AR5, Ch.6, table 6.10

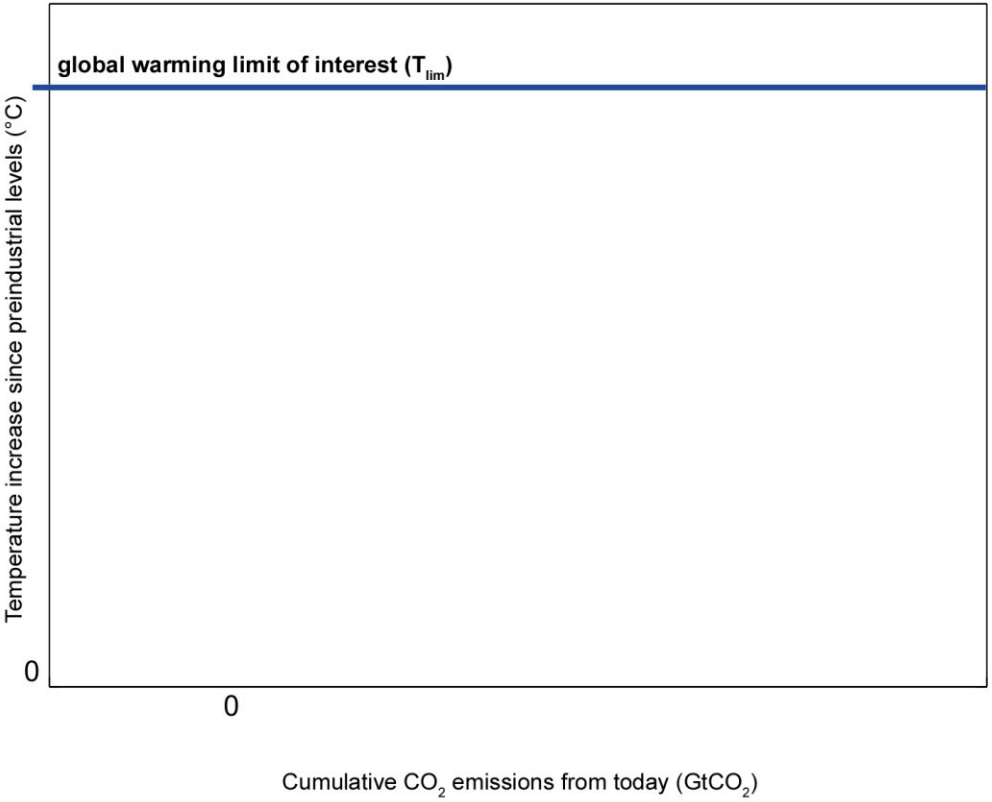
Warming link to cumulative emissions
Allen et al., 2009
Matthews et al., 2009
Gillett et al., 2013
AR5, SPM, Fig SPM.10



- BUT – even though model spread not reduced
  - We’ve learned to use the results better

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

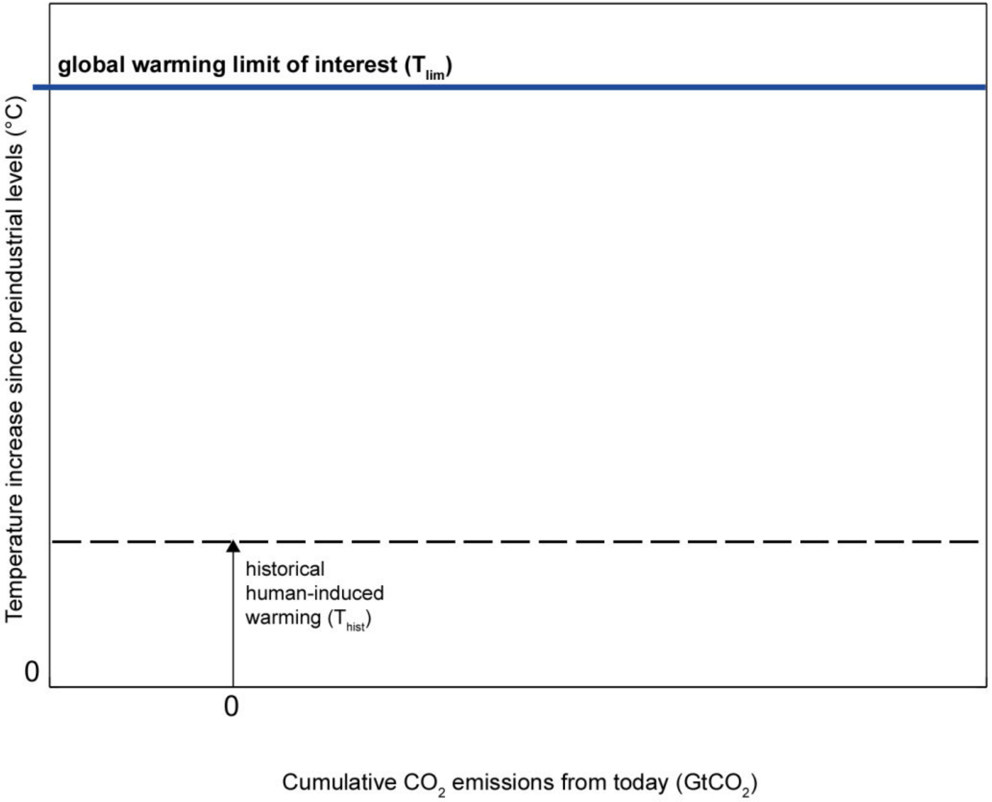
Five components:



Rogelj et al., 2019

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

Five components:
- Historical warming to date



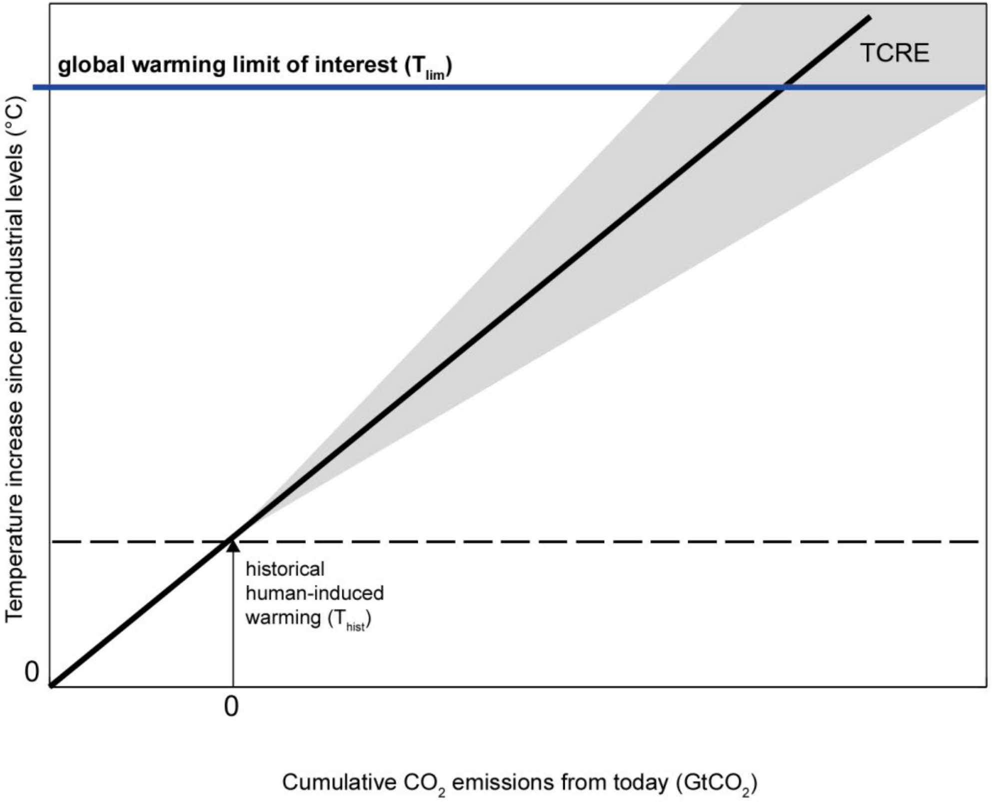
SR15 assessment:
- Human-induced warming since 1850-1900
- Global Surface Air Temperature (GSAT)
- 0.97°C (+- 0.12°C *likely* range)

Rogelj et al., 2019

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)

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



Rogelj et al., 2019

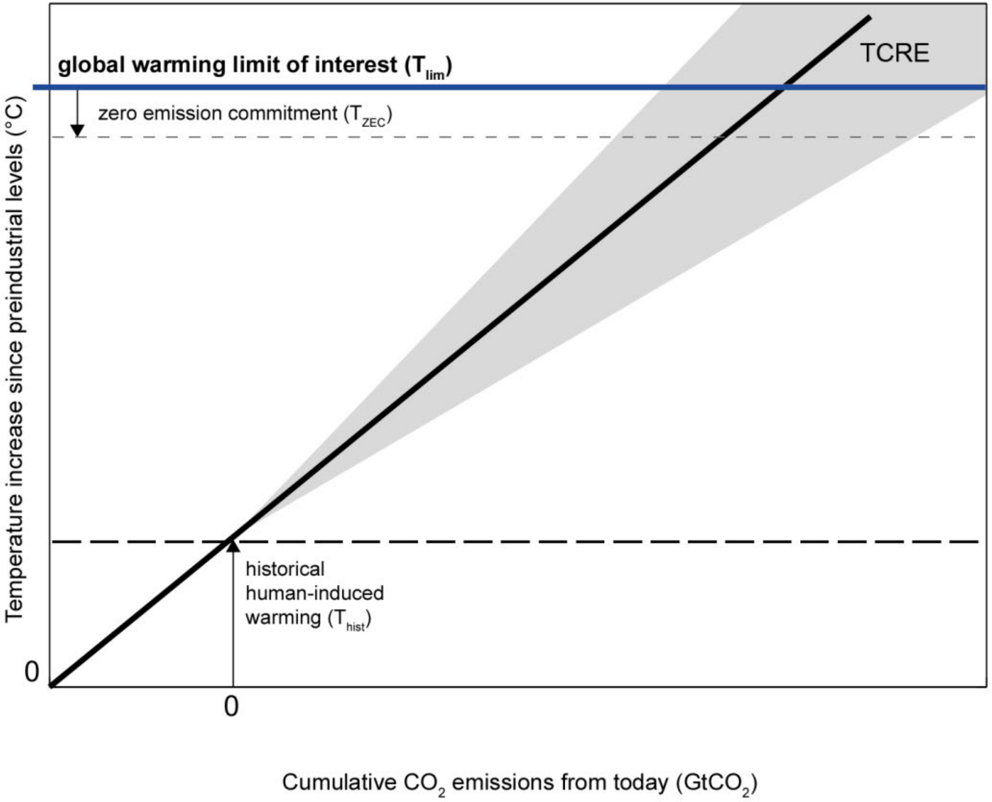
The Remaining Carbon Budget Framework of the IPCC Special Report on Global Warming of 1.5°C

Five components:

- Historical warming to date
- Transient climate response to cumulative emissions of carbon dioxide (TCRE)
- Zero emission commitment (ZEC)

SR15 assessment:

- Same as AR5 assessment
- Zero or negative



Rogelj et al., 2019

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Five components:
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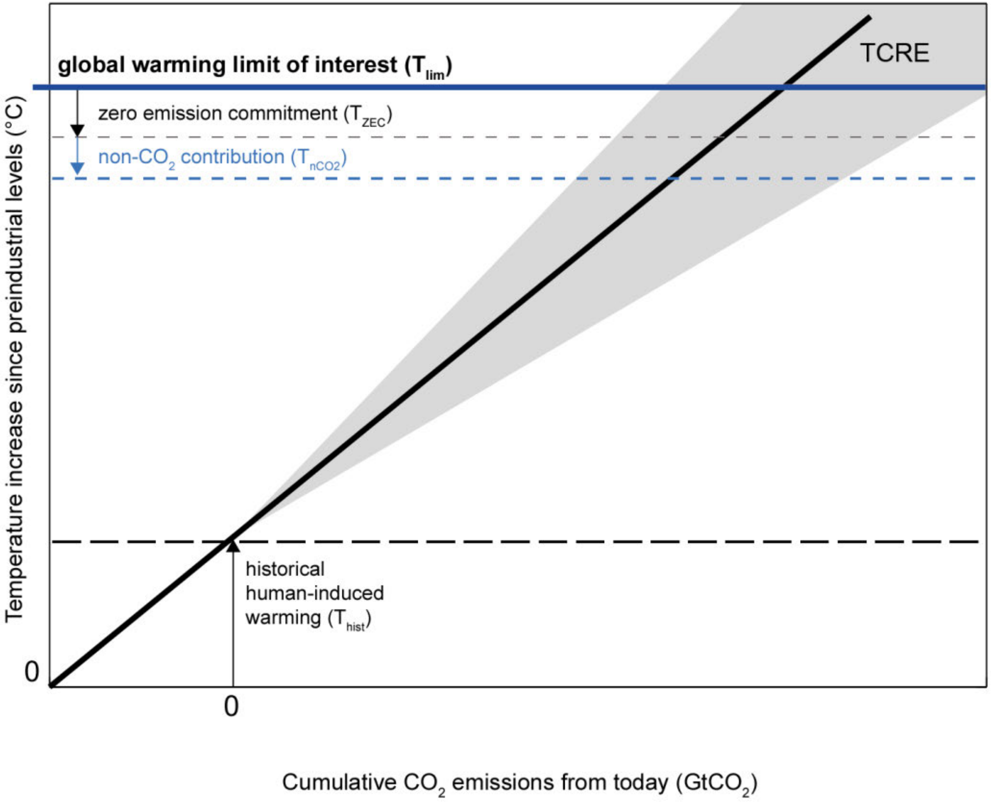
- Projected future non-CO_2 temperature contribution

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



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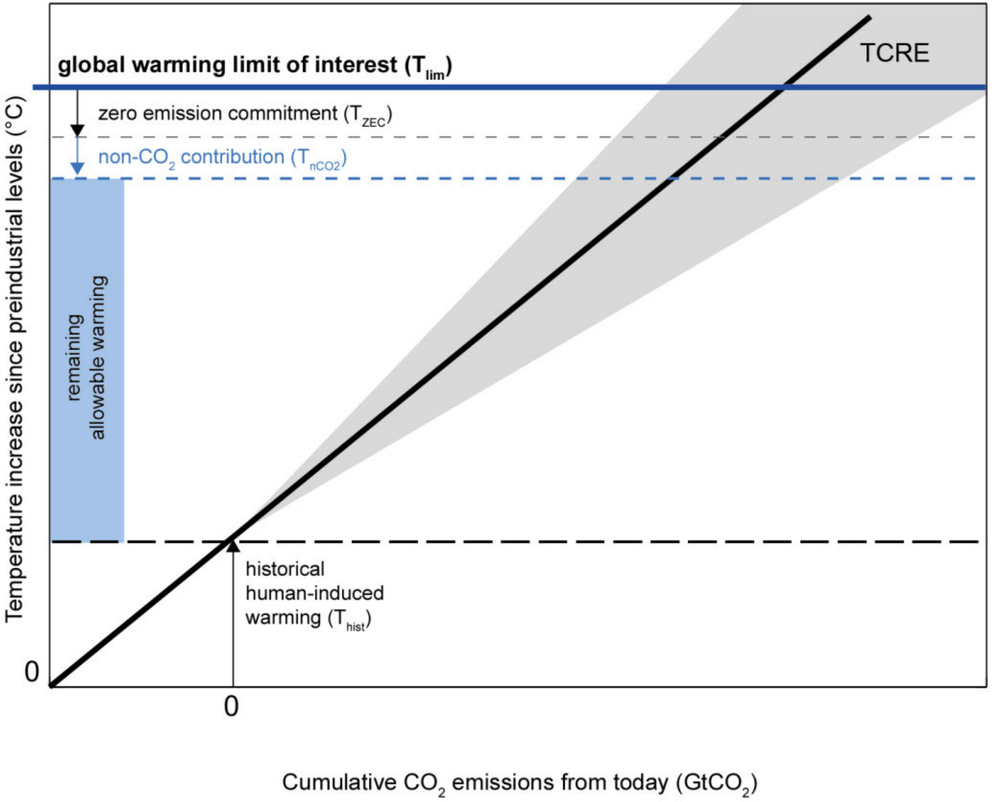

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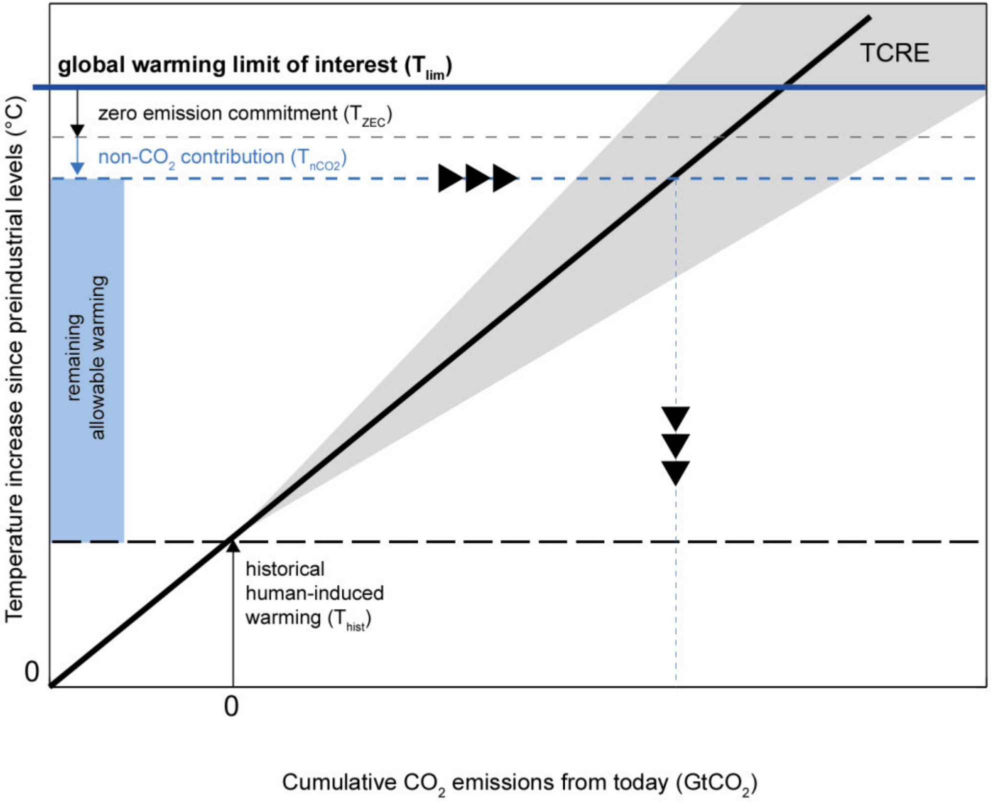

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Five components:
- Historical warming to date
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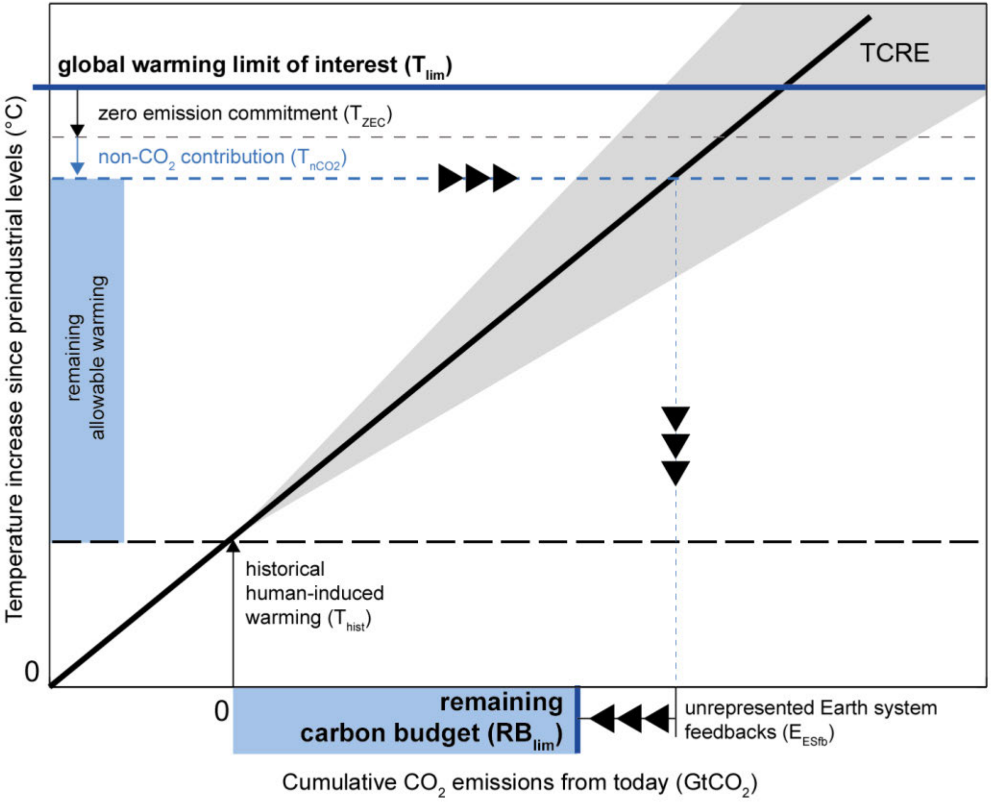
- Projected future non-CO_2 temperature contribution
- Unrepresented Earth system feedbacks

SR15 assessment:
- Permafrost thawing and other unrepresented Earth system feedbacks can contribute to up to 100 $GtCO_2$ until 2100



Rogelj et al., 2019

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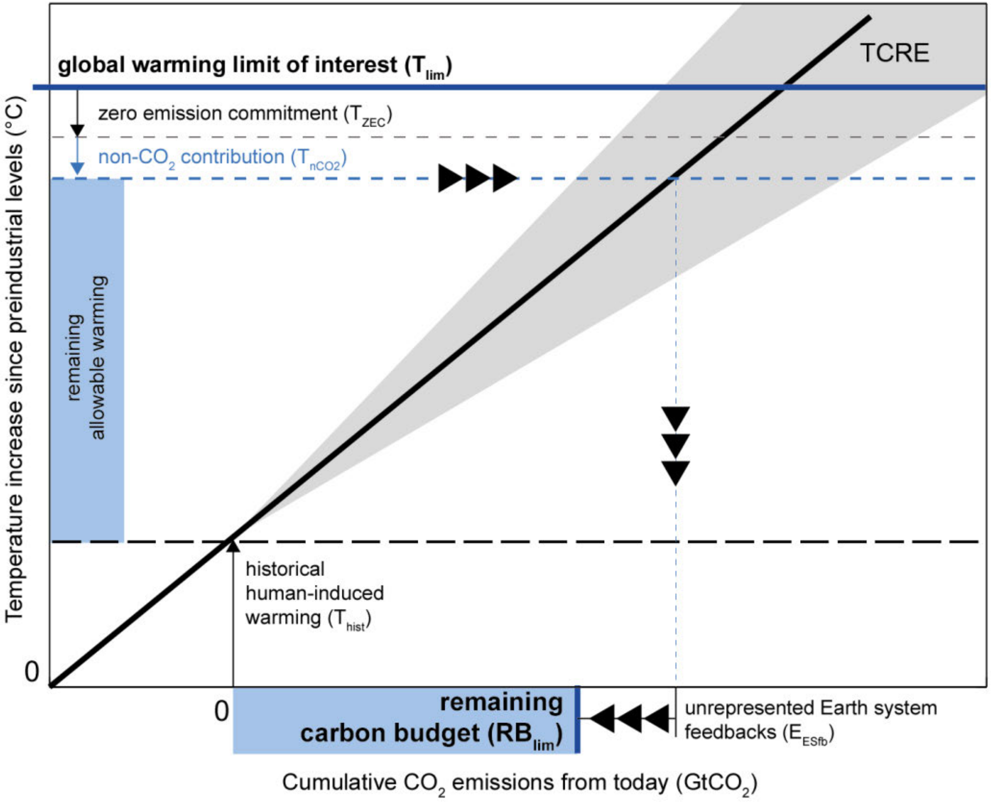
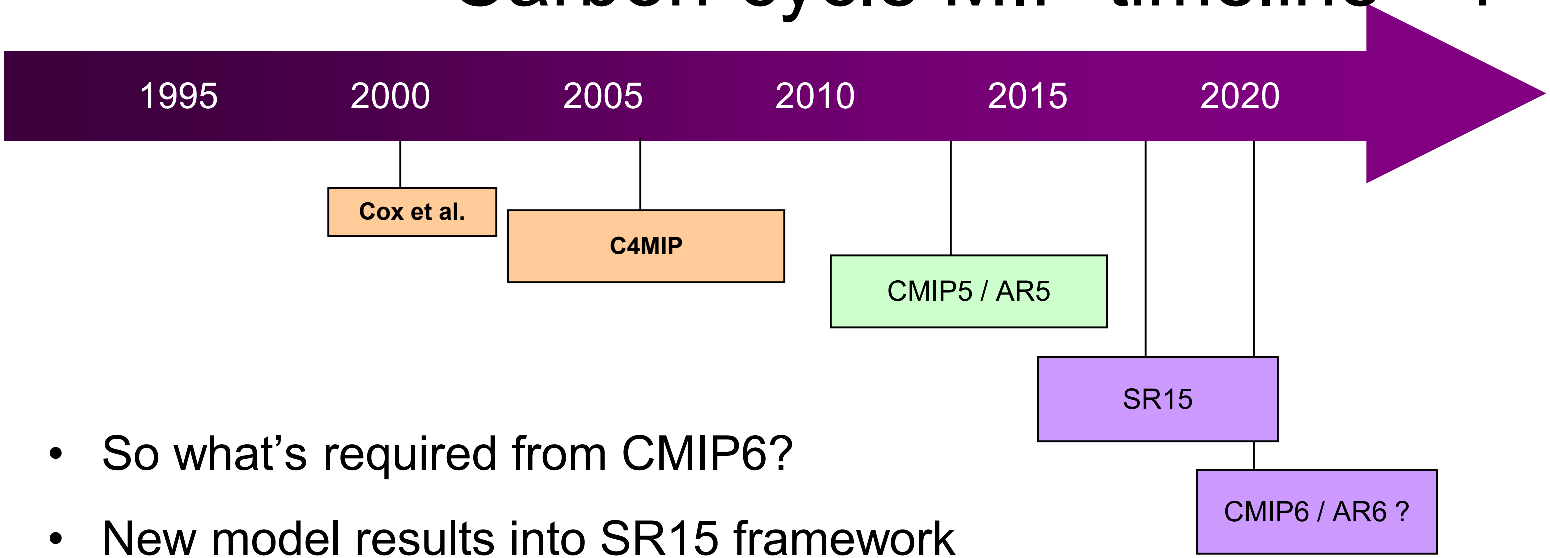


Rogelj et al., 2019

Carbon-cycle MIP timeline - 4



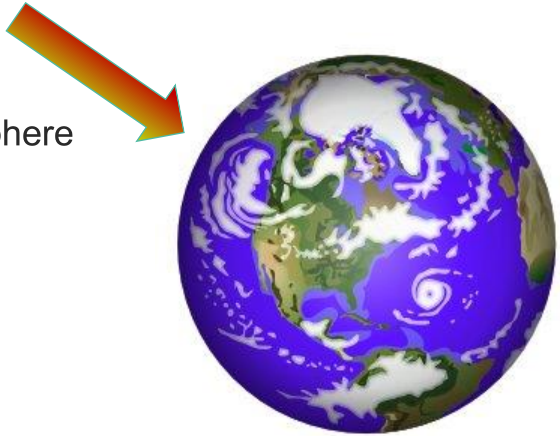
- So what's required from CMIP6?
- New model results into SR15 framework
  - Reduced uncertainty?
  - Improved knowledge on carbon budgets
  - Improved policy advice how to meet targets / avoid impacts

Primer on feedbacks…

The climate system: Earth’s energy budget

Altered top-of-atmosphere energy balance:

- more energy in



The climate system: Earth's energy budget

Altered top-of-atmosphere energy balance:

- more energy in

σT^4

ΔT:

- Earth warms up
- More energy out

The climate system: Earth’s energy budget

Altered top-of-atmosphere energy balance:

- more energy in

σT^4

ΔT:

- Earth warms up
- More energy out

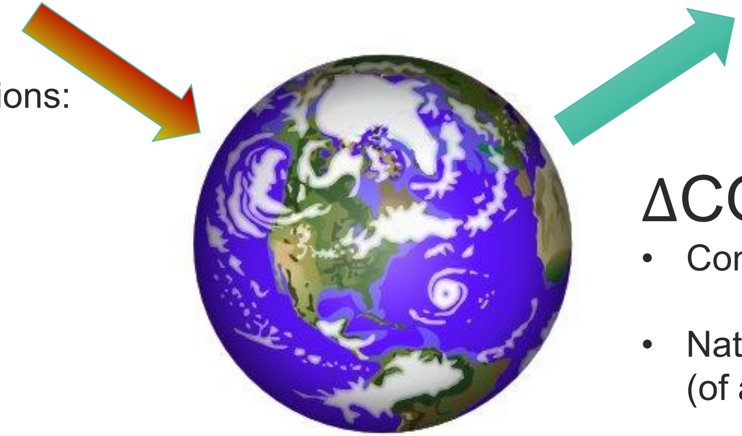
- Strong negative (stabilising) response opposes the initial perturbation
- On top of this get other feedbacks:
    - Clouds, water vapour, ice-albedo, ocean heat…
    - Sum of these is positive/amplifying (from models), but some terms can be globally or locally of either sign

The carbon cycle: Earth’s carbon budget

To land/ocean sinks

Anthropogenic emissions:

- more carbon in



ΔCO_2:

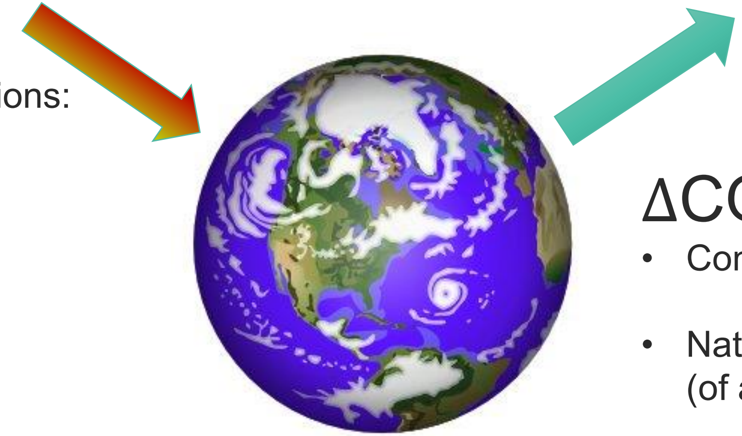
- Concentrations rise
- Natural sinks take carbon out (of atmosphere)

The carbon cycle: Earth's carbon budget

To land/ocean sinks

Anthropogenic emissions:

- more carbon in



ΔCO_2:

- Concentrations rise
- Natural sinks take carbon out (of atmosphere)

- Strong negative (stabilising) response opposes the initial perturbation
- On top of this get other feedbacks:
  - Ocean circulations/solubility, vegetation productivity/mortality, permafrost…
  - Sum of these is positive/amplifying (from models), but some terms can be globally or locally of either sign

The similarities are clear…

Strong negative response, stabilises the system against the initial perturbation

- Various feedbacks operate to modulate this

BUT: …

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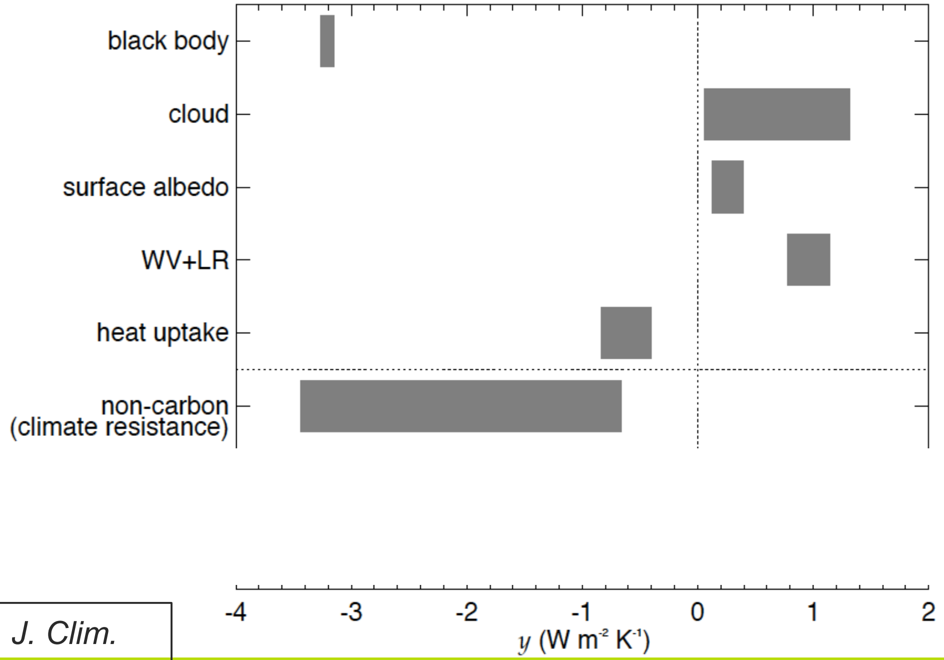
Strong negative response, stabilises the system against the initial perturbation

- Various feedbacks operate to modulate this

BUT: Fundamental difference in where the uncertainties lie



Gregory et al., 2009, J. Clim.

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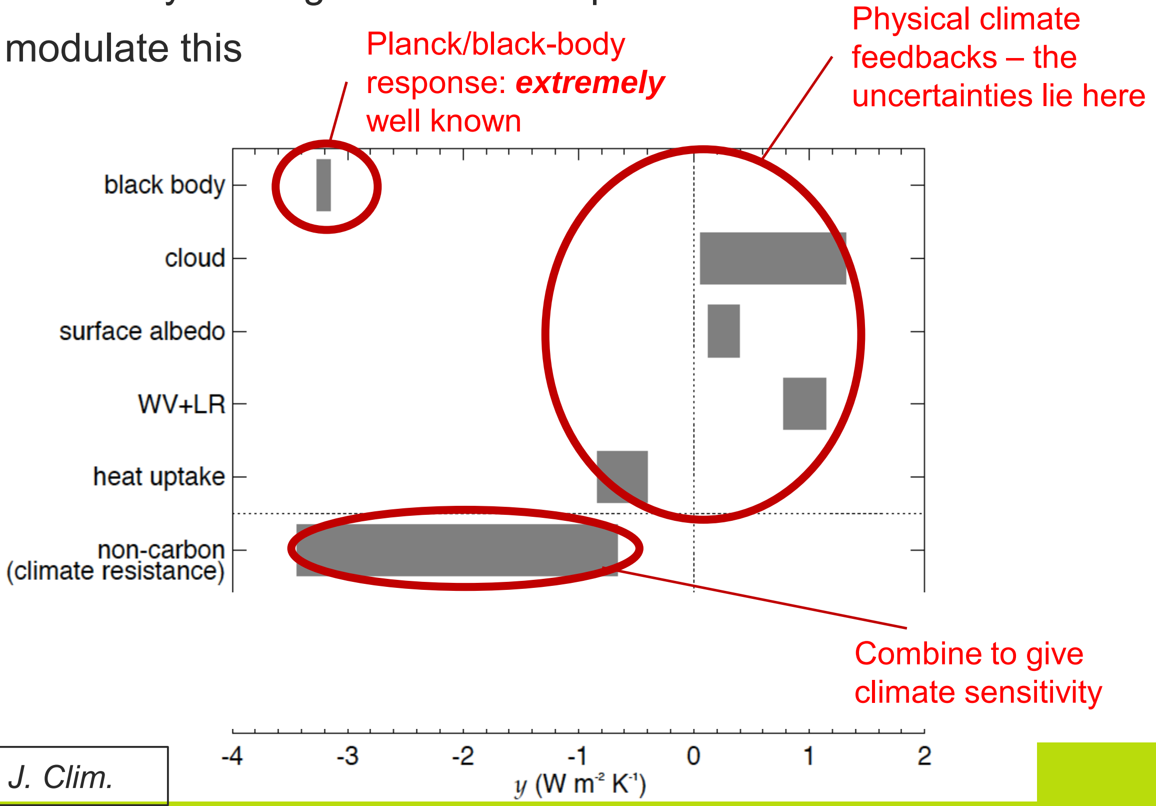

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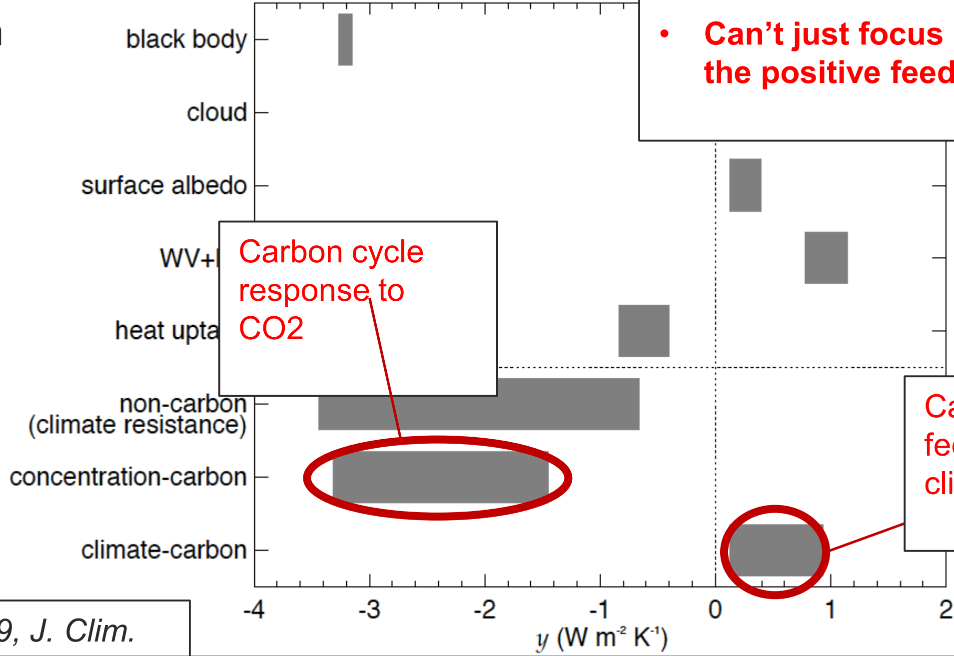


Carbon cycle response to CO2

Carbon cycle feedbacks with climate

Carbon cycle feedbacks – the uncertainties lie **IN BOTH**

- **Can't just focus research on the positive feedbacks**

Gregory et al., 2009, J. Clim.

Recap

- C4MIP multi-model analysis dates back to 2006
- large model spread
- need to consider carbon response to CO2 as well as to climate

Results 1.

C4MIP

C4MIP feedback metrics

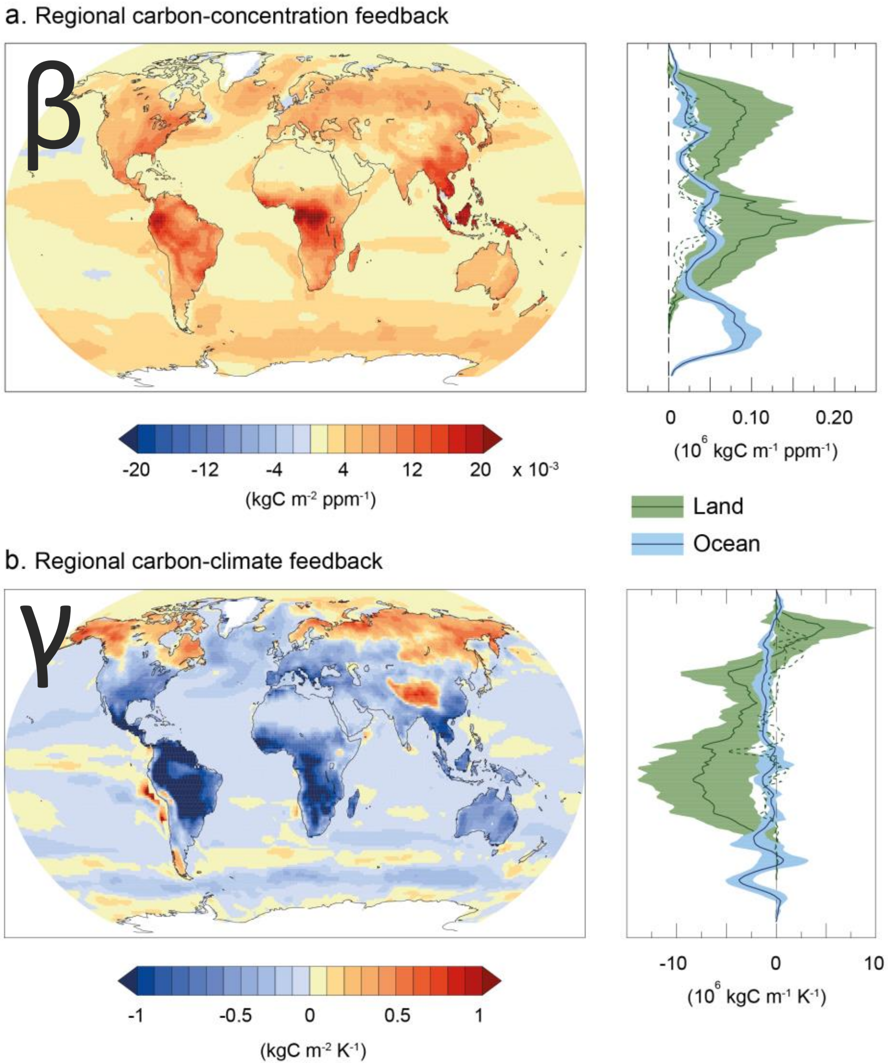
- CO_2 affects climate:

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

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

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

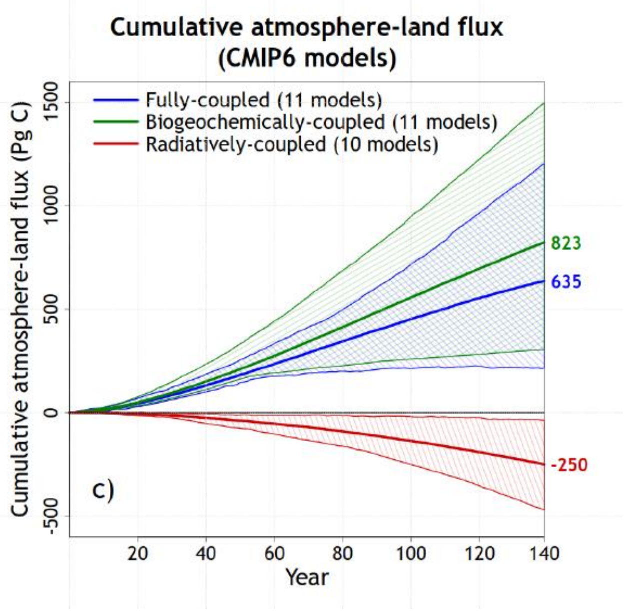
C4MIP feedback metrics



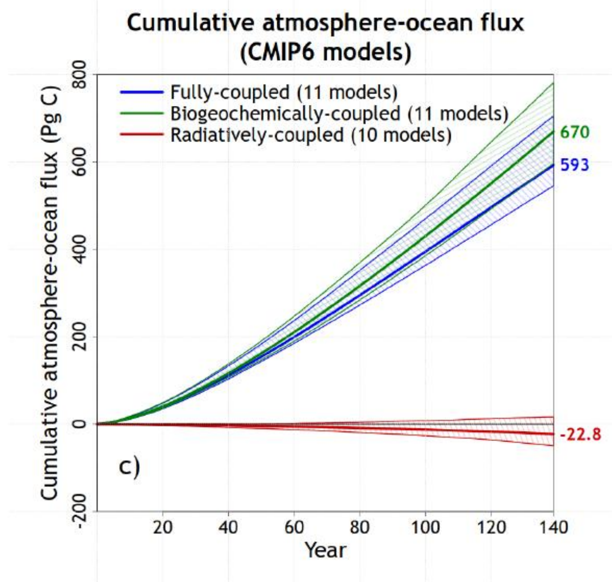
- CO_2 drives natural sinks everywhere
- Climate, globally, reduces sinks
  - Some regional variations

Fig 6.22, IPCC AR5, Ciais et al., 2013

C4MIP feedback metrics



- Land and ocean uptake under 1% CO_2 rise
- Similar overall sinks
- Land stronger dependence on both CO_2 and climate
- Land models much greater spread

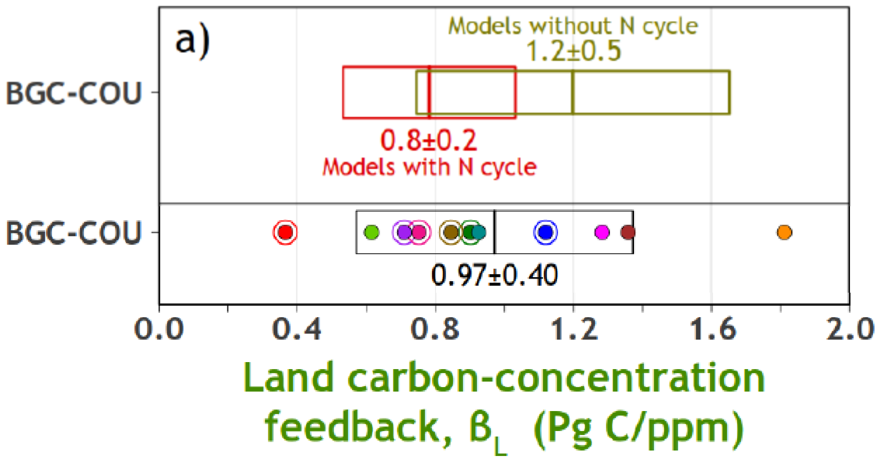


Arora et al., 2020

Met Office Hadley Centre

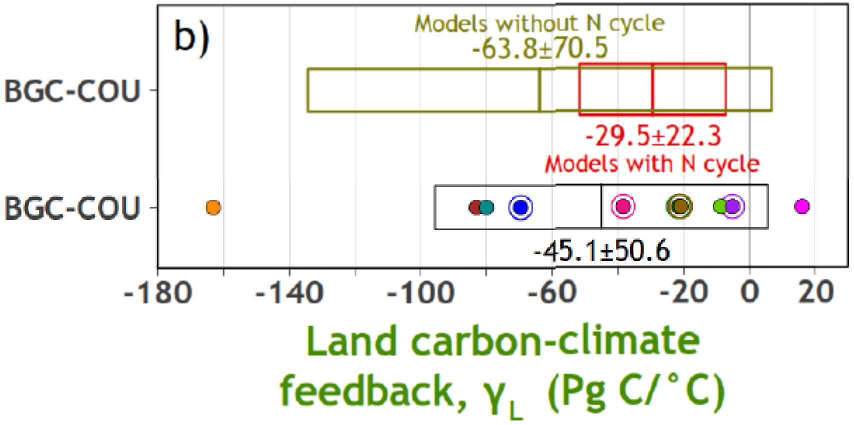
CMIP6 models at $4xCO_2$

- 6 of 11 models include terrestrial N-cycle



Stronger response to climate

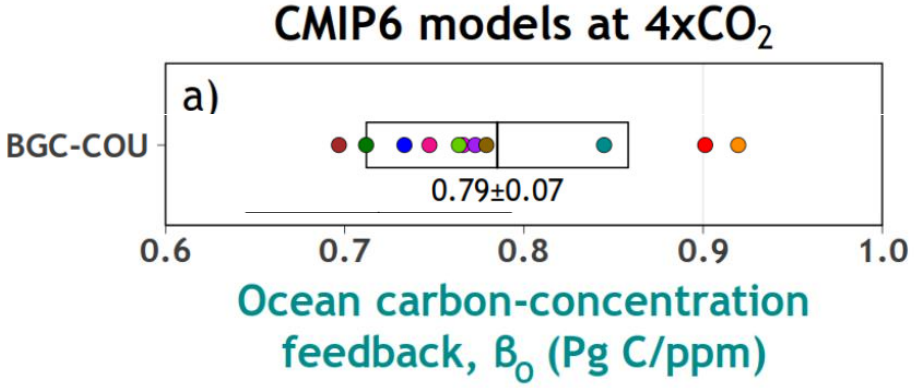
Stronger response to CO_2



- Land beta similar to CMIP5, reduced spread
- Land gamma weaker
- N-cycle models less spread than non-N

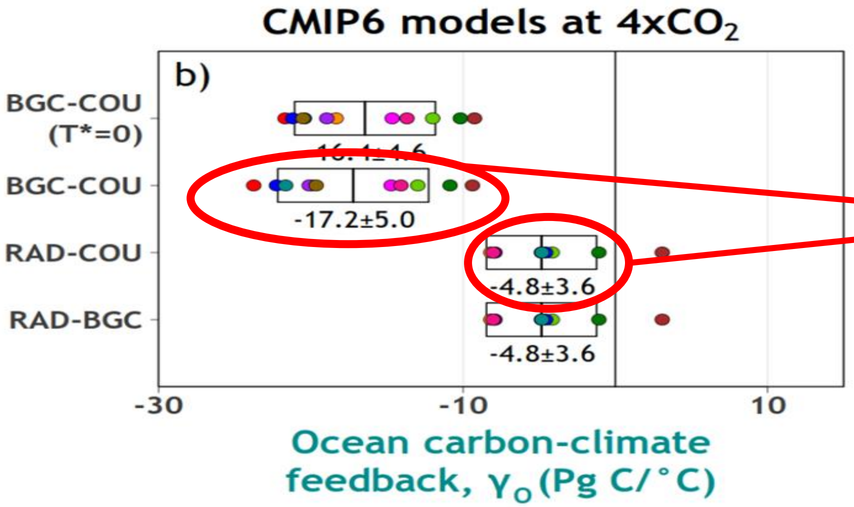
Arora et al., 2020

- Ocean models very similar results to CMIP5



Stronger response to climate

Stronger response to CO_2

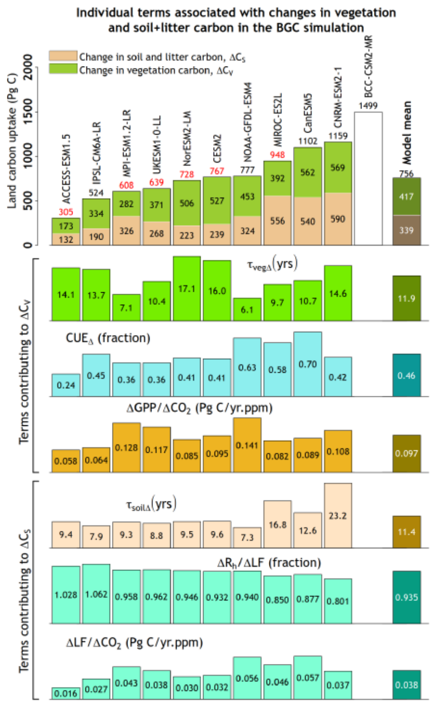


- Explored the sensitivity to methods of calculation
- As recommended by Schwinger 2014, Jones 2016, use COU-BGC

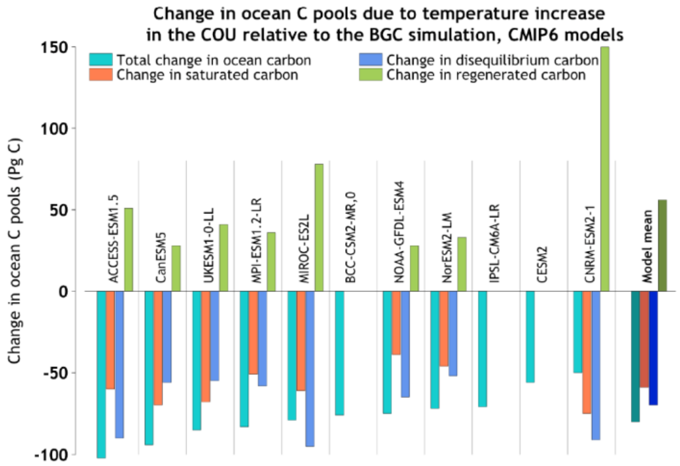
Arora et al., 2020

Met Office Hadley Centre

C4MIP feedback analysis



- Component level breakdown
- Land by veg/soil
  - Then drivers of GPP, allocation, residence time
- Ocean by saturation vs disequilibrium terms
  - And response to warming



- For full details, see: Arora et al. 2020 – in discussion:
  - https://www.biogeosciences-discuss.net/bg-2019-473/

C4MIP historical runs

- Analysis and evaluation just beginning
- Similar to CMIP5: fluxes better than stores?
- Treatment of land-use inconsistent

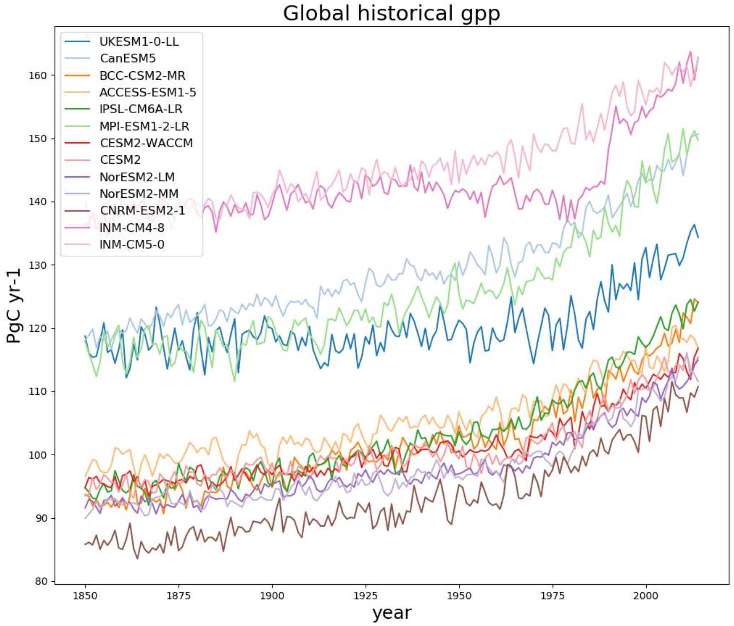
- Beware of changes in carbon stores
  - Hide big differences in baseline state!

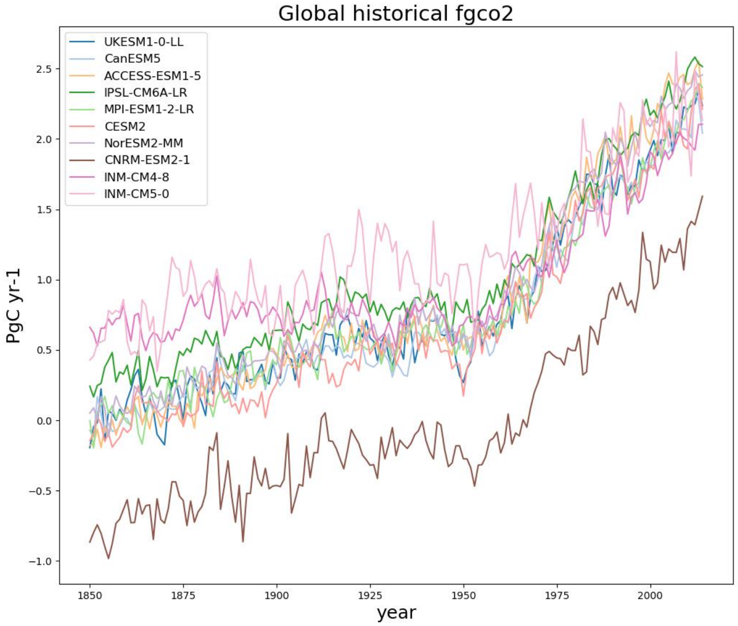
- *<no analysis here – just some results to get you thinking…>*

C4MIP historical runs

- GPP and ocean uptake

- Generally consistent
- Models beginning to include lateral flows…



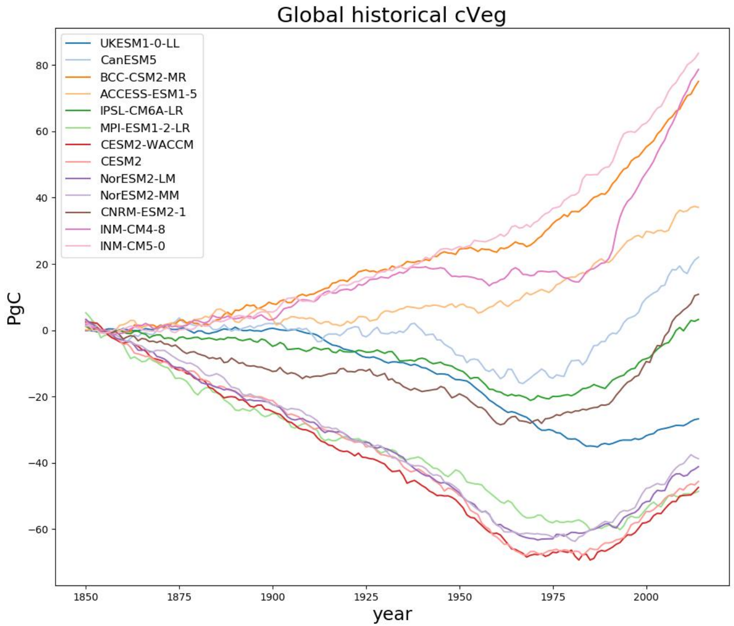


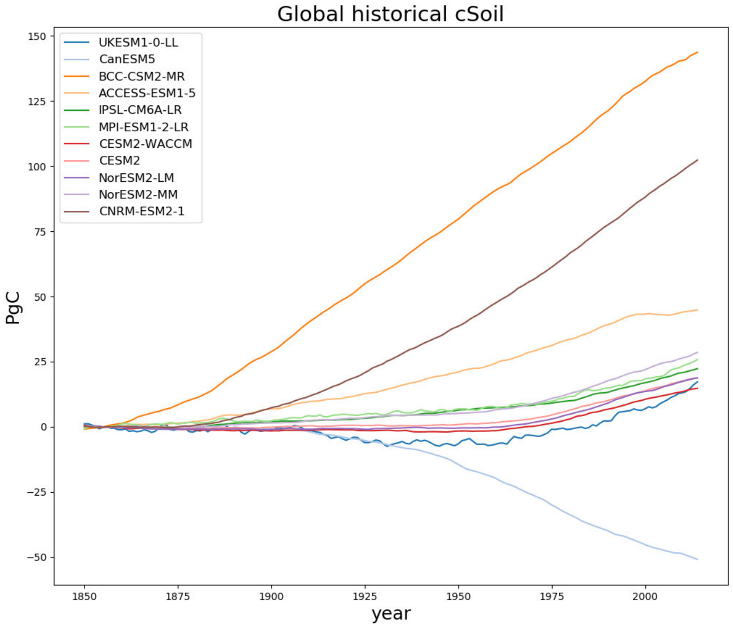
- Within approx. 20% of 120 PgC/yr globally

C4MIP historical runs

- Veg/Soil stores: changes

- 20-30 PgC increase?



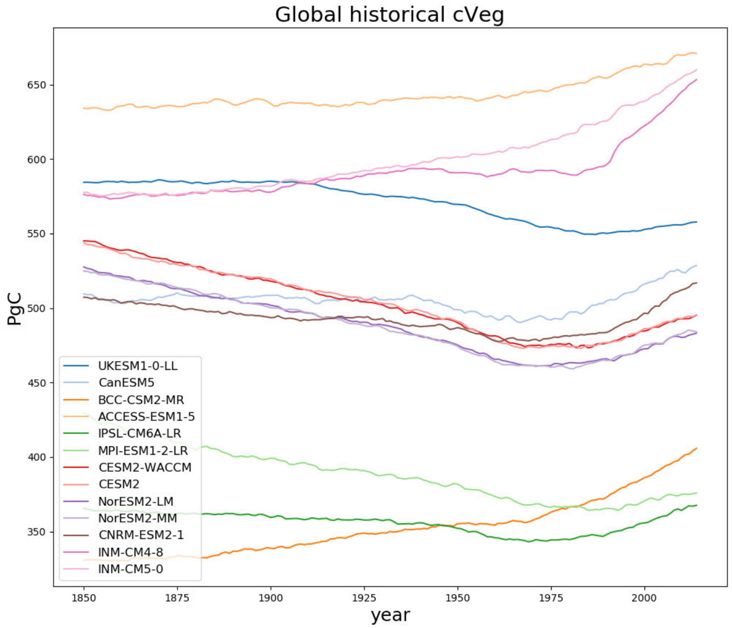


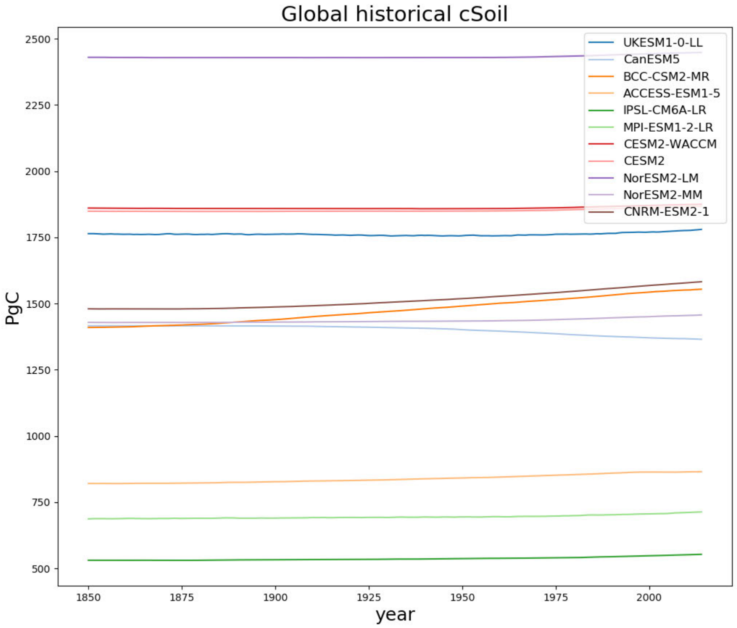
- Cluster into strong/moderate/no effect of land-use?

C4MIP historical runs

- Veg/Soil stores: ***absolutes***

- No correlation between store size and magnitude of change





- Factor 2/5 between veg/soil carbon stores…

Results 2.

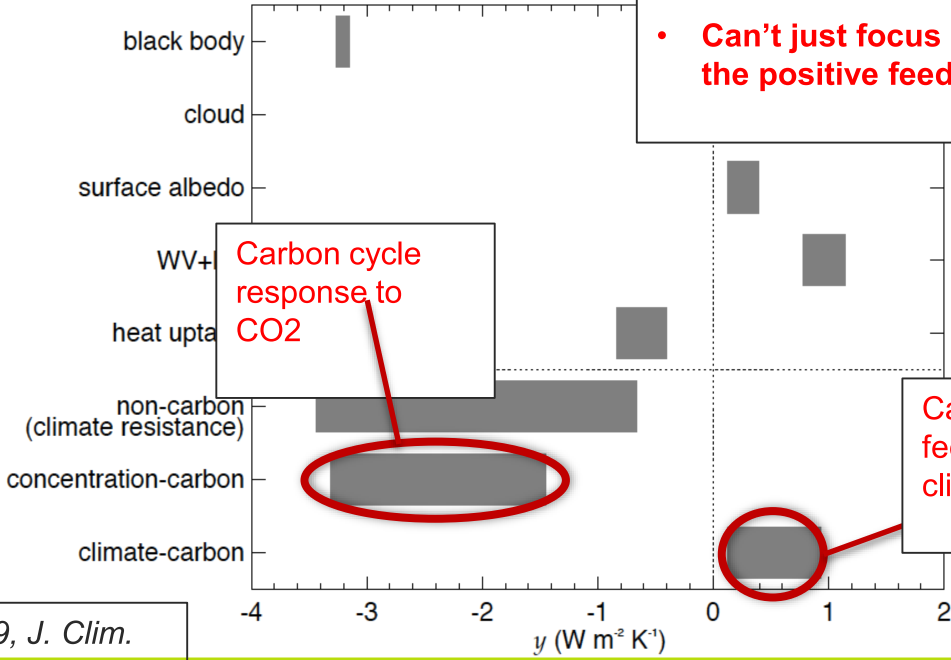
Sources of uncertainty
- changes over MIP generations

C4MIP: uncertainty

- Initial focus on climate feedback gain, “g”
- Over-emphasis on gamma as source of model spread

- So where does the uncertainty come from?

and how has this changed over the generations of C4MIP models?



Carbon cycle feedbacks – the uncertainties lie **IN BOTH**

- **Can’t just focus research on the positive feedbacks**

Gregory et al., 2009, J. Clim.

C4MIP: uncertainty

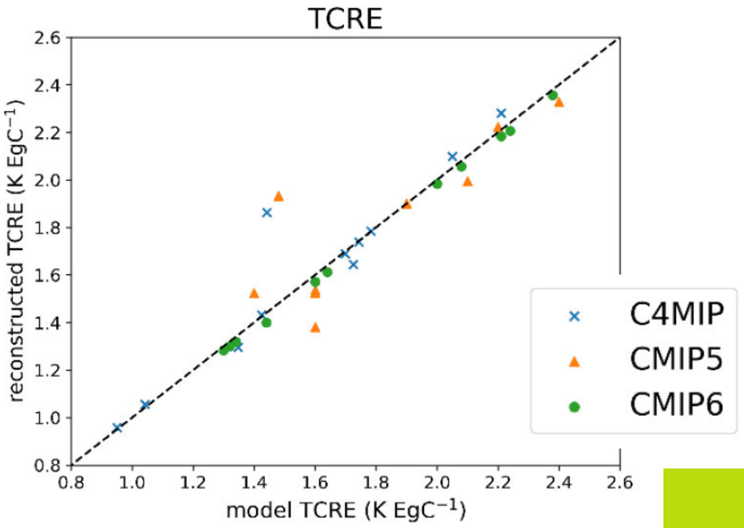
- Gain, g, can be expressed in terms of alpha, beta, gamma metrics:

(k = unit conversion, 2.12 PgC/ppm)

$$g = -\frac{\alpha\gamma}{k+\beta}$$

- But so can air-borne fraction and TCRE:

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



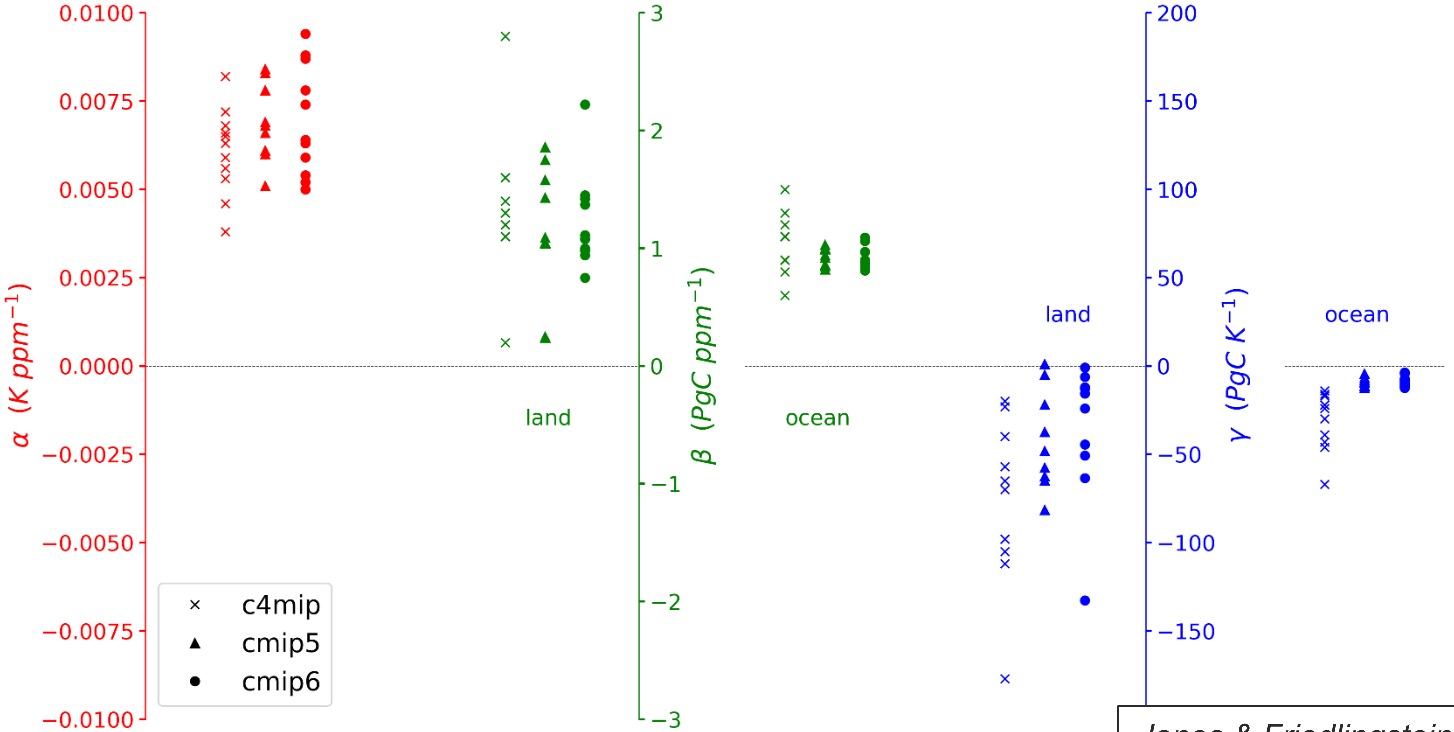
(2006)
(2011-13)
(2018-20)

- Reconstructed quantities fit well
- Jones & Friedlingstein, 2020, ERL

Jones & Friedlingstein, 2020, ERL

C4MIP: uncertainty

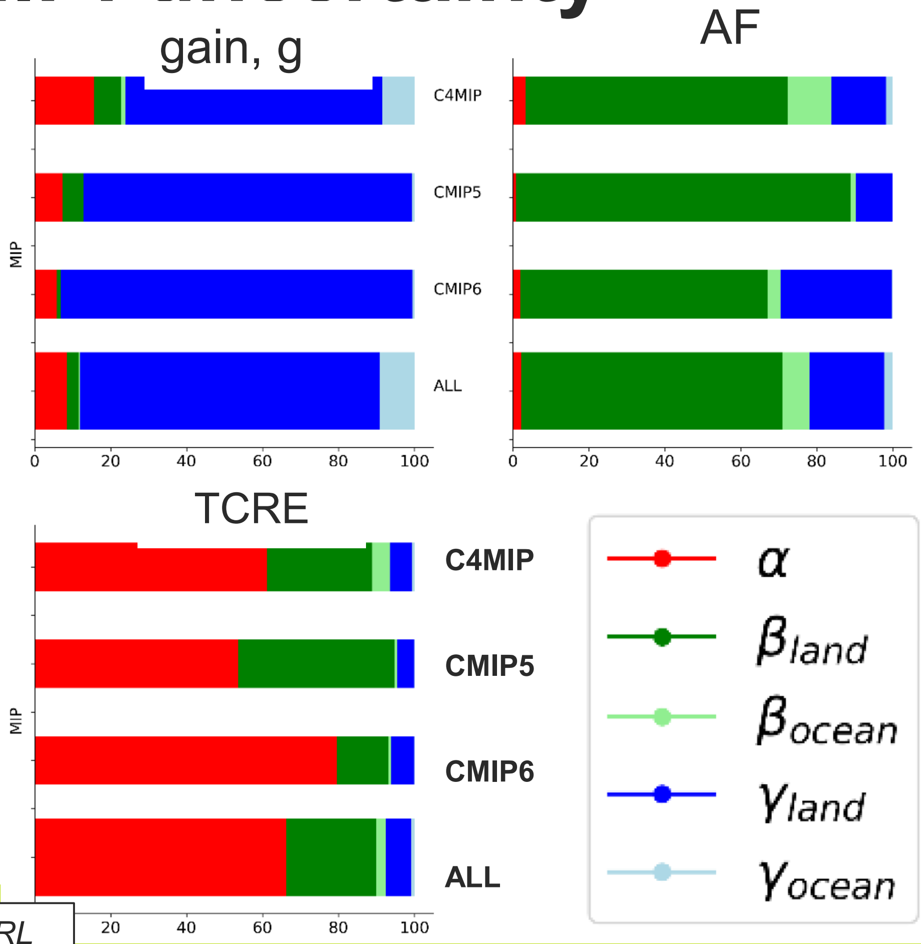
- This allows propagation of uncertainty in each term to the quantity of interest



Jones & Friedlingstein, 2020, ERL

C4MIP: uncertainty

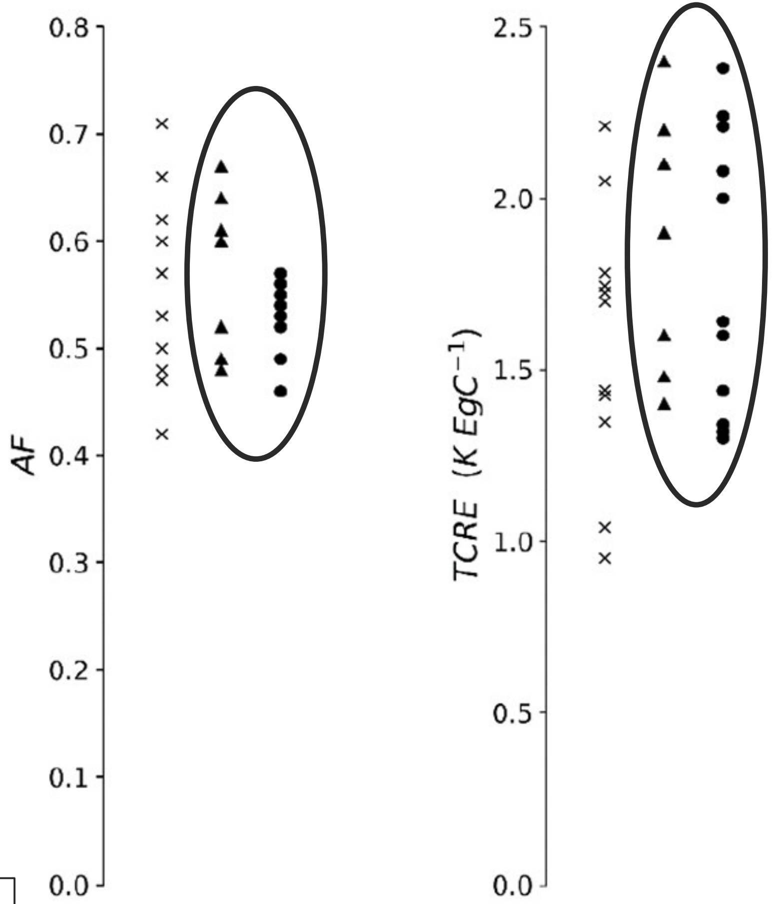
- This allows propagation of uncertainty in each term to the quantity of interest
- **Gain**, as we knew – dominated by gamma
- **AF** – dominated by beta
- **TCRE** – jointly controlled by beta/alpha
  - CMIP5: approx. 50:50 climate vs carbon cycle
  - CMIP6: move towards control by climate uncertainty



Jones & Friedlingstein, 2020, ERL

C4MIP: uncertainty

- **AF** – dominated by beta
  - CMIP6 spread <half of CMIP5
- **TCRE** – jointly controlled by beta/alpha
  - CMIP6 and CMIP5 very similar
    - mean and spread



Jones & Friedlingstein, 2020, ERL

Results 3.

ZECMIP

ZECMIP: “a MIP in a year”

January 2019 – Vancouver carbon budgets workshop

- Hugely successful new MIP – targeted to fill a science gap
- From idea to delivery in less than 12 months.

ZECMIP: “a MIP in a year”

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GMD | Artic

Geosci. Model Dev., 12, 4375–4385, 2019
https://doi.org/10.5194/gmd-12-4375-2019

Model experiment description paper

May/October 2019 – protocol paper submitted/published

The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions

Chris D. Jones[1], Thomas L. Frölicher[2,3], Charles Koven[4], Andrew H. MacDougall[5],

Met Office Hadley Centre

ZECMIP: “a MIP i

- December 2019 – analysis paper
- submitted
- 18 models took part

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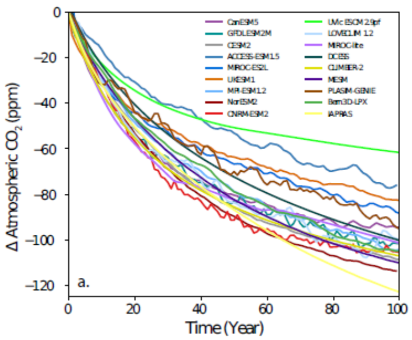
Is there warming in the pipeline? A multi-model analysi emission commitment from CO_2

Andrew H. MacDougall[1], Thomas L. Frölicher[2,3], Chris D. Jones[4], Joeri Rogelj[5,6], H. Damon Matthews[6], Kirsten Zickfeld[7], Vivek K. Arora[8], Noah J. Barrett[1], Victor Brovkin[9], Friedrich A. B Micheal Eby[10], Alexey V. Eliseev[11,12], Tomohiro Hajima[13], Philip B. Holden[14], Aurich Jeltsch-Thömmes[2,3], Charles Koven[15], Laurie Menviel[16], Martine Michou[17], I Akira Oka[18], Jörg Schwinger[19], Roland Séférian[17], Gary Shaffer[20,21], Andrei Sokolov Jerry Tjiputra[19], Andrew Wiltshire[4], and Tilo Ziehn[23]

Model	A1	A2	A3	B1	B2	B3
ACCESS	X	X	X	–	–	–
CanESM5	X	–	X	–	–	–
CESM2	X	–	–	–	–	–
CNRM	X	–	–	–	–	–
GFDL	X	X	X	X	X	X
MIROC-ES2L	X	X	X	–	–	–
MPI-ESM	X	–	–	–	–	–
NorESM2	X	–	–	–	–	–
UKESM	X	X	X	–	–	–
Bern	X	X	X	X	X	X
CLIMBER	X	–	–	–	–	–
DCESS	X	X	X	X	X	X
IAPRAS	X	X	X	X	X	X
LOVECLIM	X	X	–	X	–	–
MESM	X	X	X	X	X	X
MIROC-lite	X	X	X	X	X	X
P. GENIE	X	X	X	X	X	X
UVic	X	X	X	X	X	X

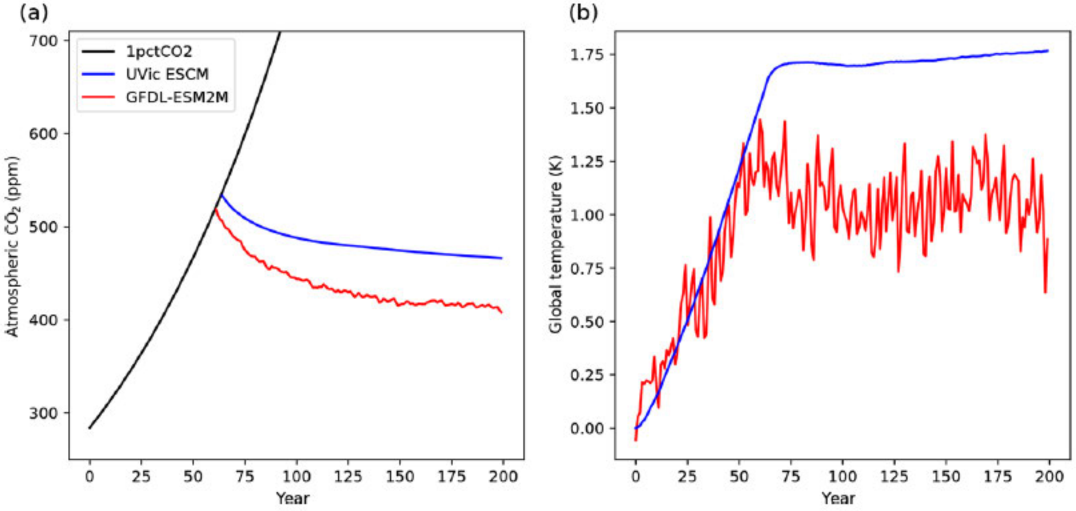


committed climate changes following zero carb emissions

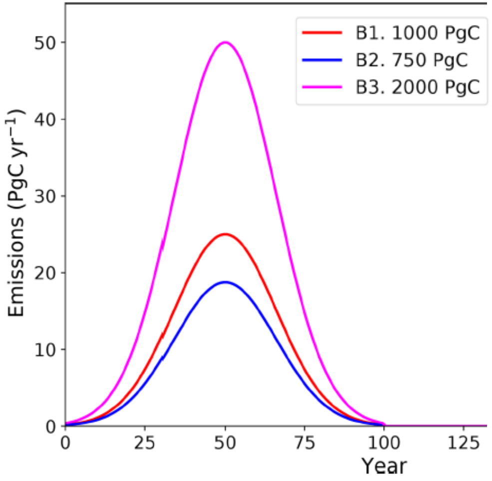
Chris D. Jones[1], Thomas L. Frölicher[2,3], Charles Koven[4], Andrew H. MacDougall[5]

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

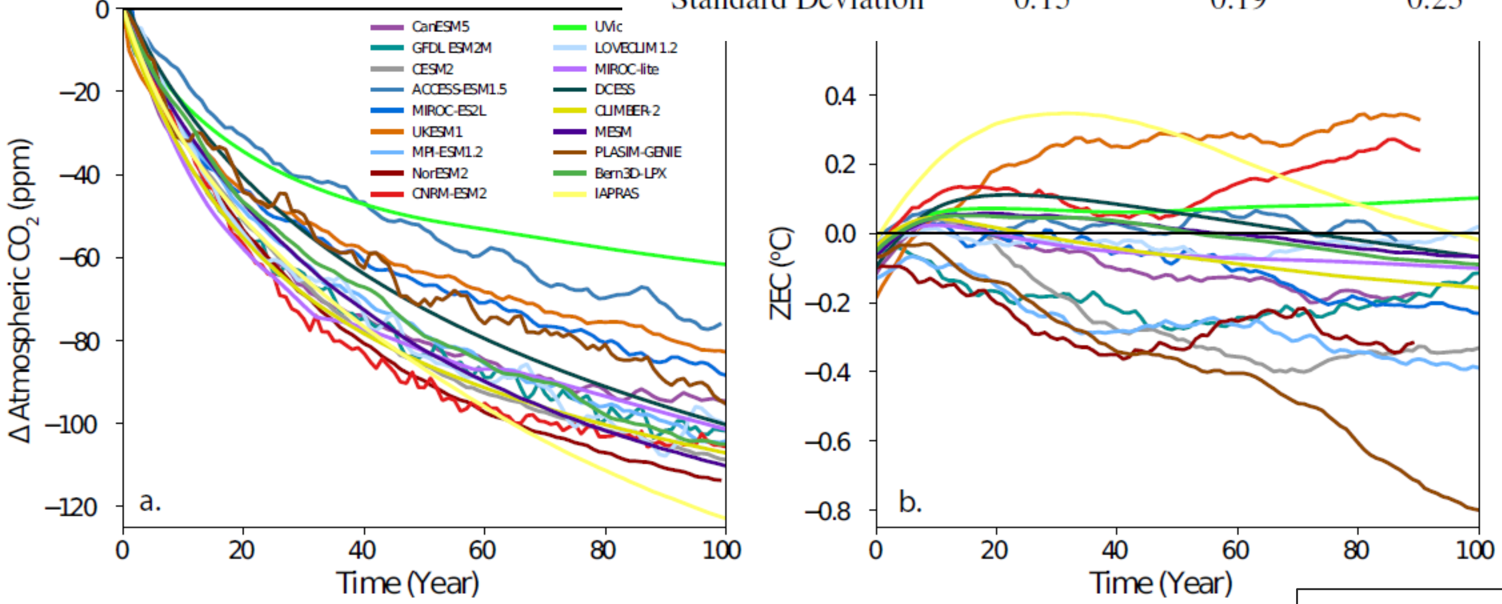


- “A” experiments: sudden stop from 1% trajectory
- “B” experiments: gradual rise and reduce of emissions

ZECMIP: results

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

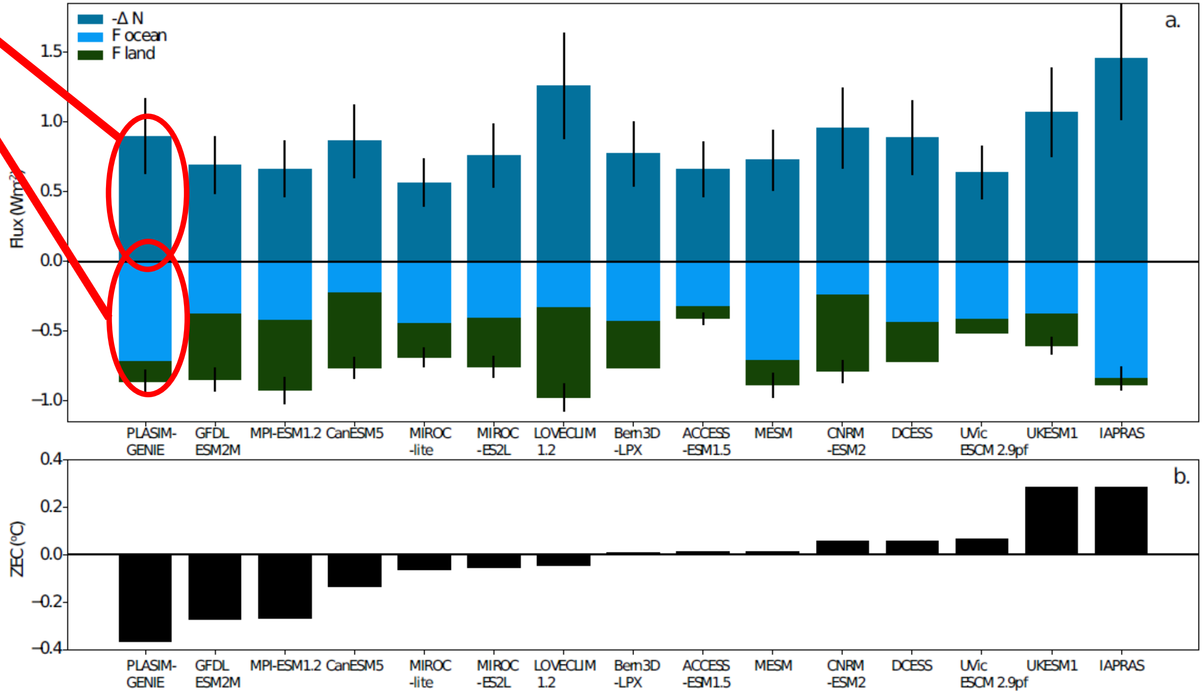
Model	ZEC_{25} (°C)	ZEC_{50} (°C)	ZEC_{90} (°C)
Mean	-0.01	-0.06	-0.11
Median	-0.01	-0.05	-0.08
Standard Deviation	0.15	0.19	0.23



MacDougall et al., 2020

ZECMIP: results

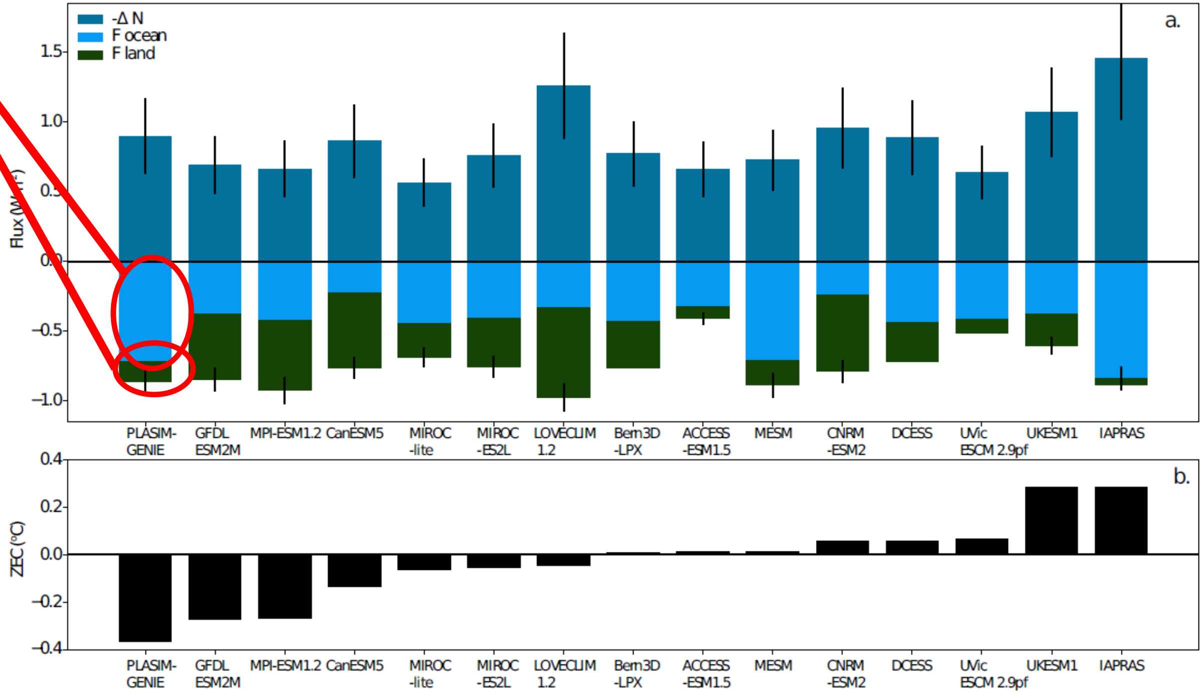
- Heat vs carbon…
- We can diagnose response in terms of balance between CO_2 reduction and ocean heat uptake
- No clear signal why some models have +ve or –ve ZEC
- No correlation with climate sensitivity



MacDougall et al., 2020

ZECMIP: results

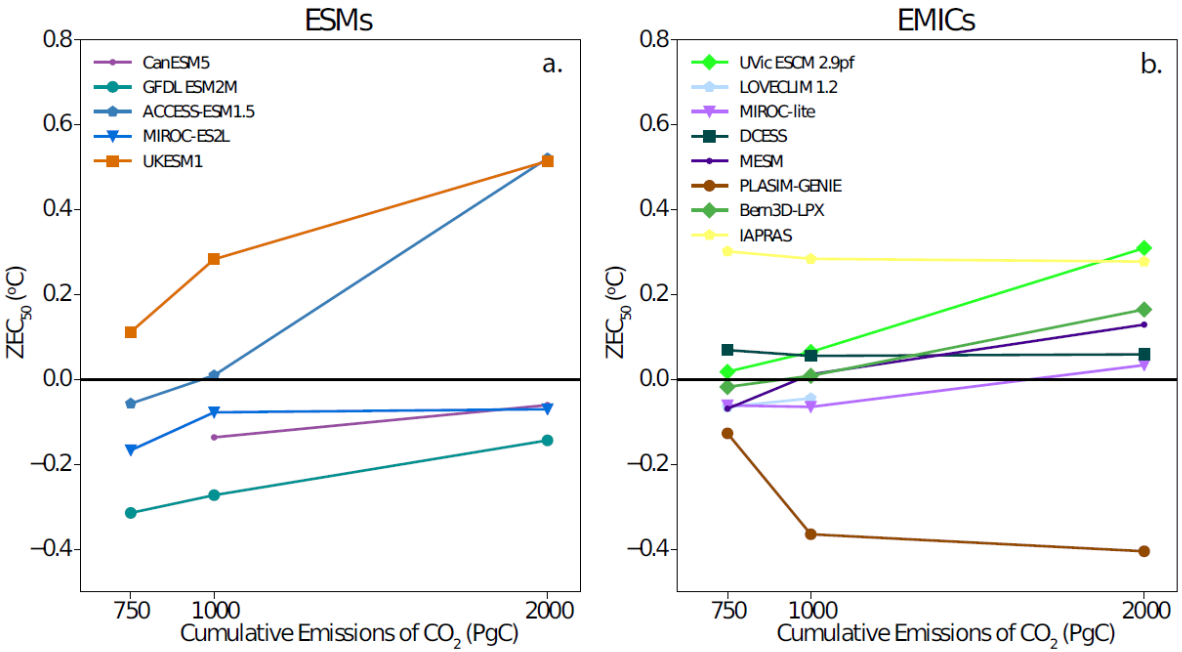
- Land vs ocean…
- We can diagnose response in terms of balance land and ocean carbon sink
- Both just as important (magnitude)
- No clear signal which determines +ve or –ve ZEC



MacDougall et al., 2020

ZECMIP: results

- State-dependence: long-term warming greater after greater emissions



- For full details, see: MacDougall et al. 2020 – in discussion:
  - https://www.biogeosciences-discuss.net/bg-2019-492/

C4MIP / ZECMIP synthesis

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

Met Office Hadley Centre

C4MIP / ZECMIP synthesis

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C4MIP / ZECMIP synthesis

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- 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

C4MIP / ZECMIP synthesis

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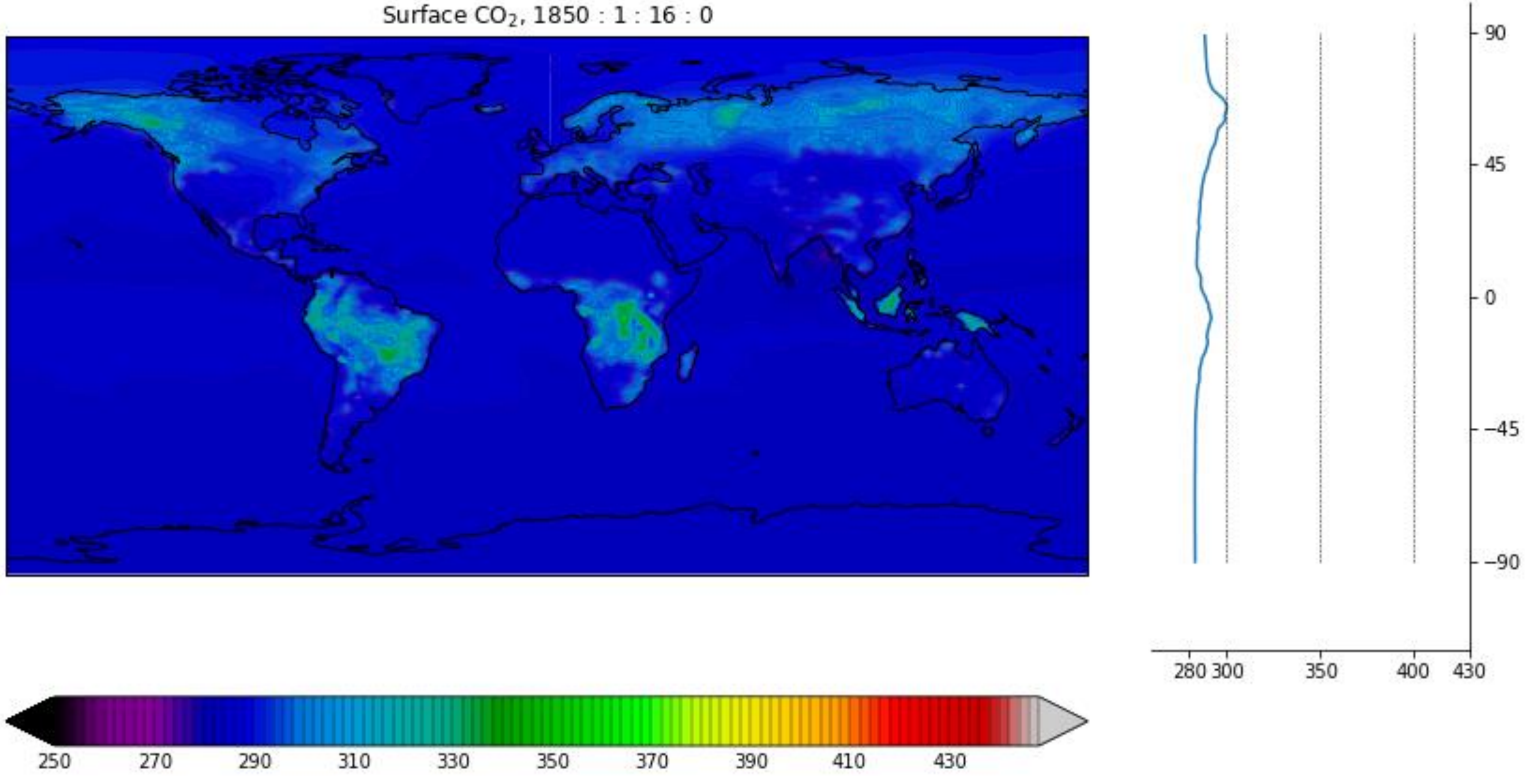
    - N-cycle has reduced spread in land-carbon, leaving greater role for climate response uncertainty

- Missing processes / ES feedbacks
  - Permafrost – still not accounted for in ESMs
  - N-cycle: partially accounted for
    - SR15 framework doesn't allow for this! a work in progress how to account for it

CMIP6 successes and failures?

- CMIP6 has been hugely challenging ✓
  - More complex models, more MIPs, much bigger data request
  - Shorter timelines?
- Carbon stocks? ✗
  - Still rubbish! Community must do more to improve this aspect
- Reduced uncertainty? ≈ ✓
  - Maybe not quantitatively, but better understanding of processes
- Terrestrial N-cycle in 6/11 models ✓
  - Appears to have reduced model spread
  - Needs fuller process-evaluation

  - A reminder of complexity…



Surface CO_2, 1850 : 1 : 16 : 0
90
45
0
−45
−90
280 300
350
400
430
250
270
290
310
330
350
370
390
410
430

Concluding comments

- CMIP6 marks 3rd 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
- Next steps
  - Improved consideration of carbon stocks and residence times
  - Emergent constraints, perhaps regionally, on responses
  - Treatment of mixed-complexity ("partially included processes") in carbon budgets framework

References

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ZECMIP protocol and results

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