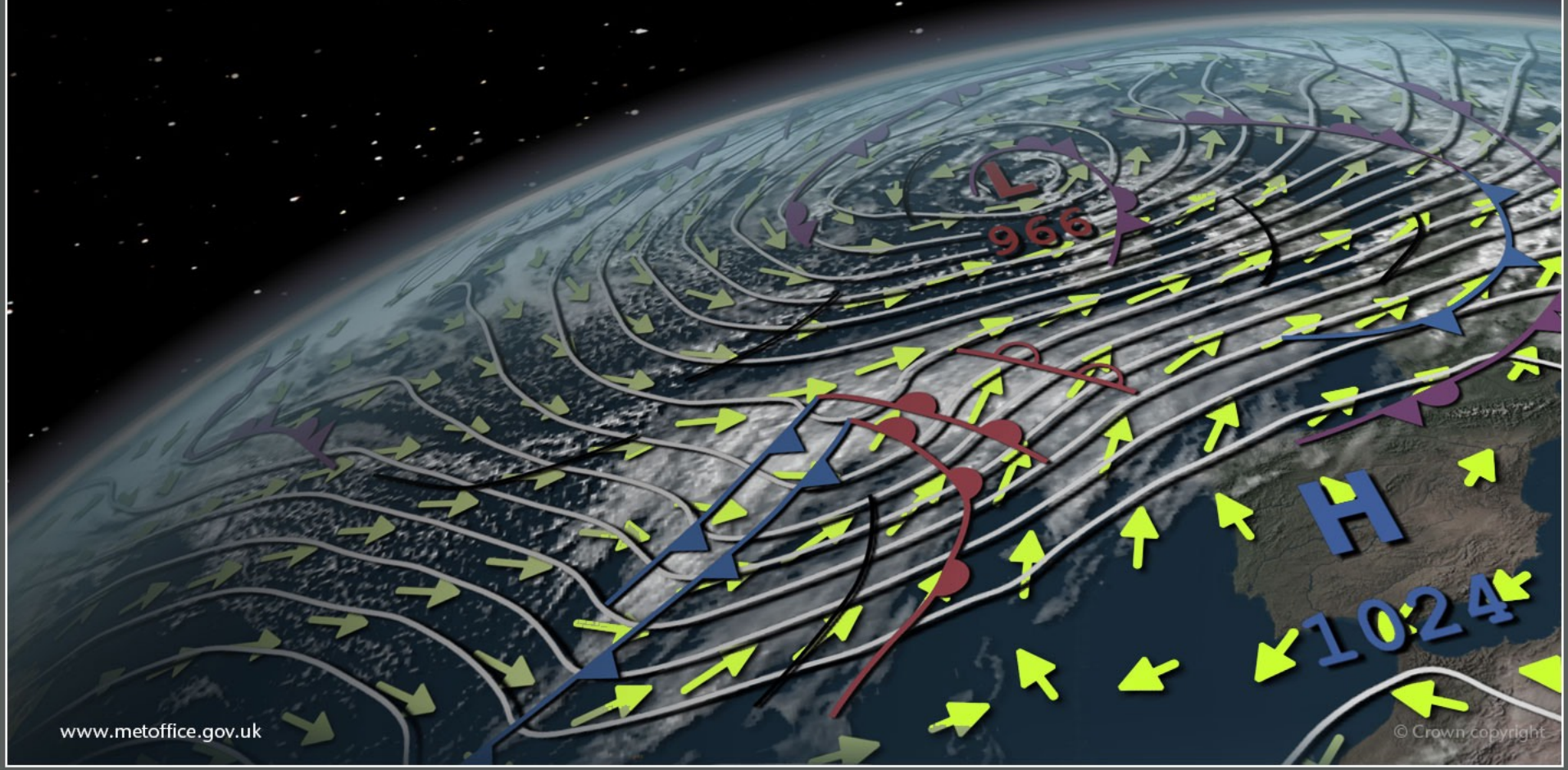
WCRP Carbon Cycle Grand Challenge

Chris Jones

21st November, 2016. Haus Rissen, Hamburg.



Contents

- Back to basics
  - Carbon cycle feedbacks

- Research challenges and how these are changing
  - Carbon cycle under low CO2 pathways
  - Need to understand carbon cycle response to CO2

- Processes
  - Brief discussion on priorities
- Evaluation
  - Emergent constraints, analysis frameworks

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Back to basics

- How do climate feedbacks work?
    - How do they drive research priorities?
- Similarities and differences for the carbon cycle

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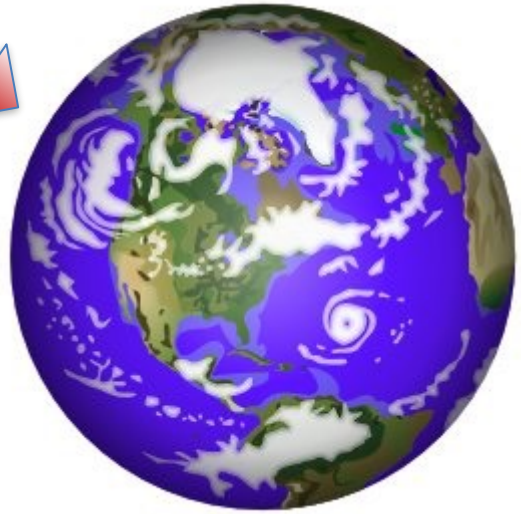
The climate system: Earth's energy budget

Altered top-of-atmosphere energy balance:

- more energy in



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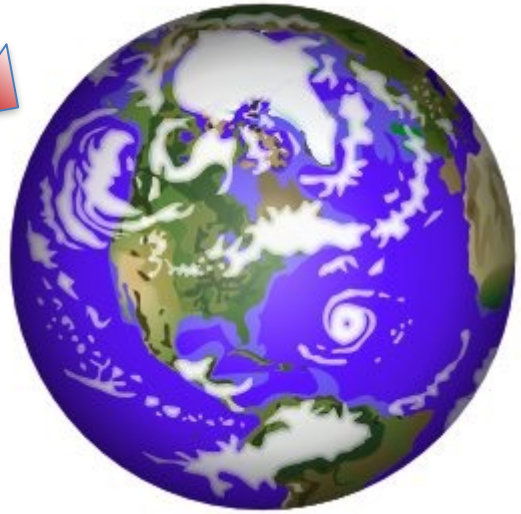

ΔT:

- Earth warms up

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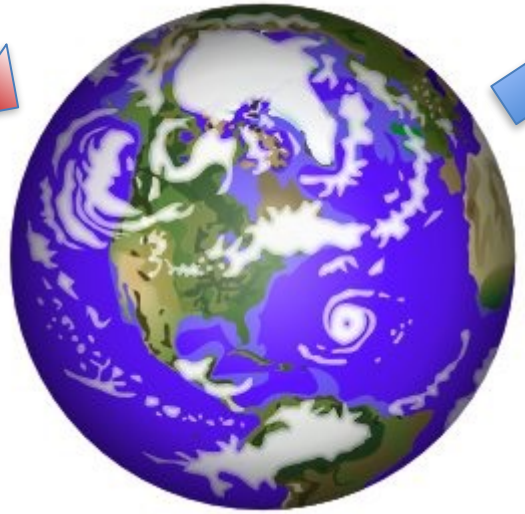

σT^4

ΔT:

- Earth warms up
- More energy out

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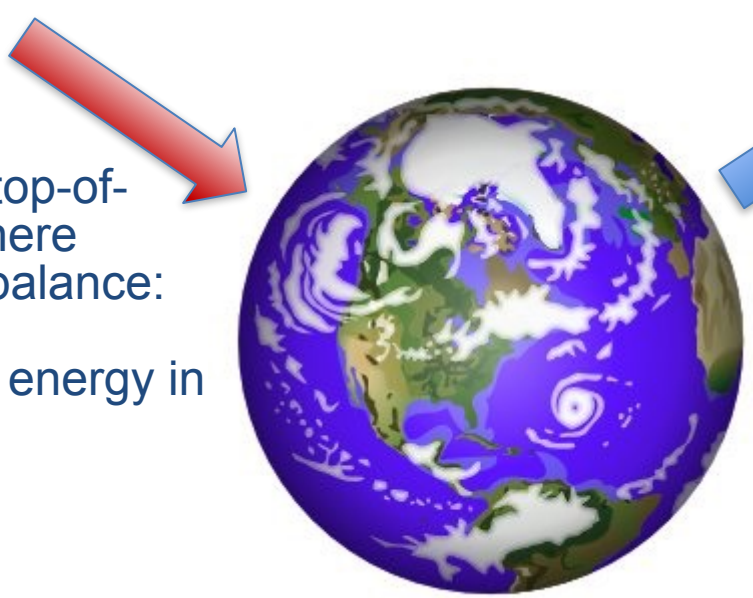
The climate system: Earth's energy budget



Altered top-of-atmosphere energy balance:

- more energy in

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

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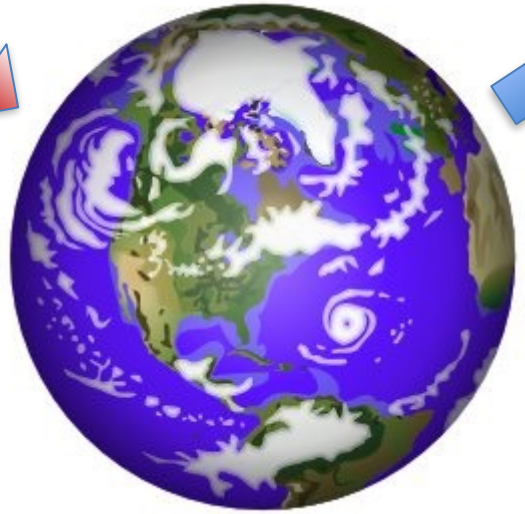
The carbon system: Earth's carbon budget

Anthropogenic emissions:

- more carbon in



To land/ocean sinks

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

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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

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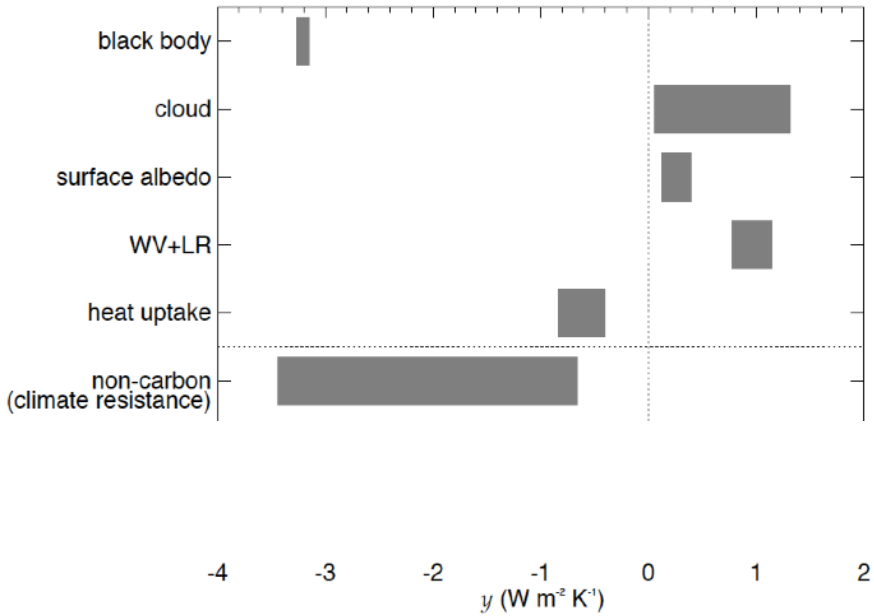
BUT: Fundamental difference in where the uncertainties lie



Gregory et al., 2009, J. Clim.

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The similarities are clear…

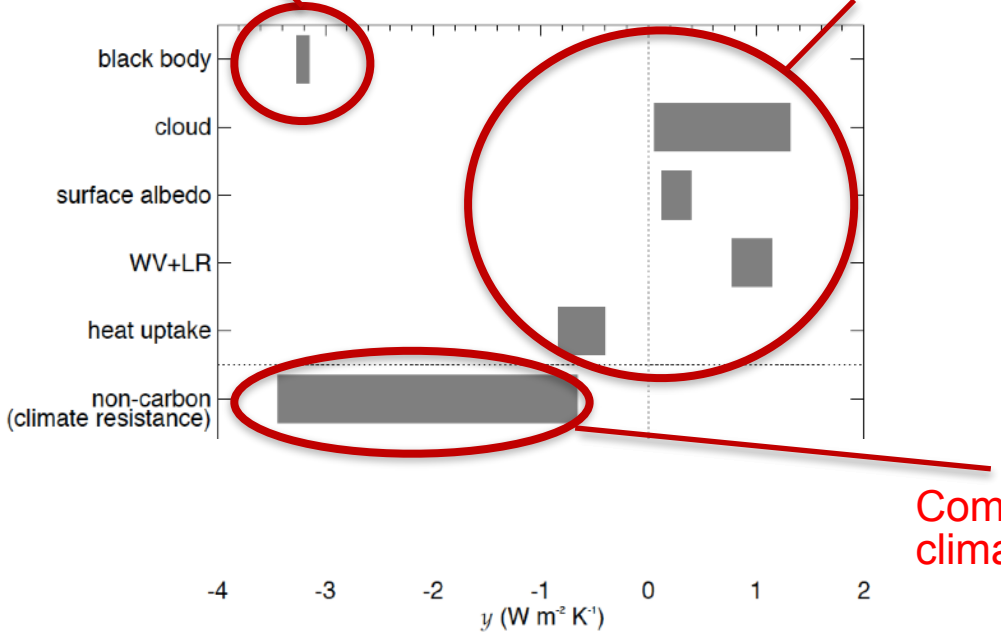
Strong negative response, stabilises the system against the initial perturbation

- Various feedbacks operate to modulate this

BUT: Fundamental difference in where the uncertainties lie

Planck/black-body response: ***extremely*** well known

Physical climate feedbacks – the uncertainties lie here



Combine to give climate sensitivity

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The similarities are clear…

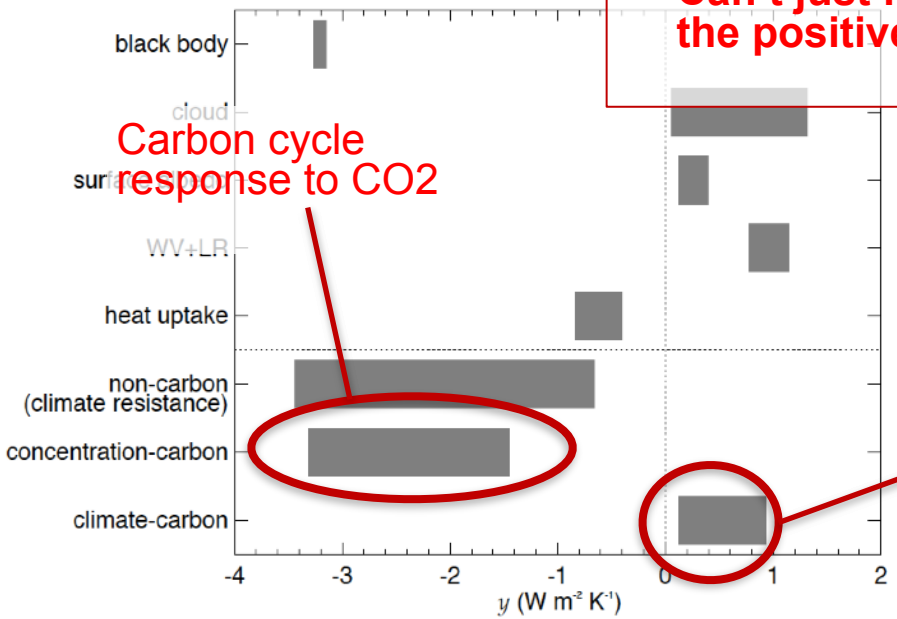
Strong negative response, stabilises the system against the initial perturbation

- Various feedbacks operate to modulate this

BUT: Fundamental difference in where the uncertainties lie

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

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



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The similarities are clear…

Strong negative response, stabilises the system against the initial perturbation

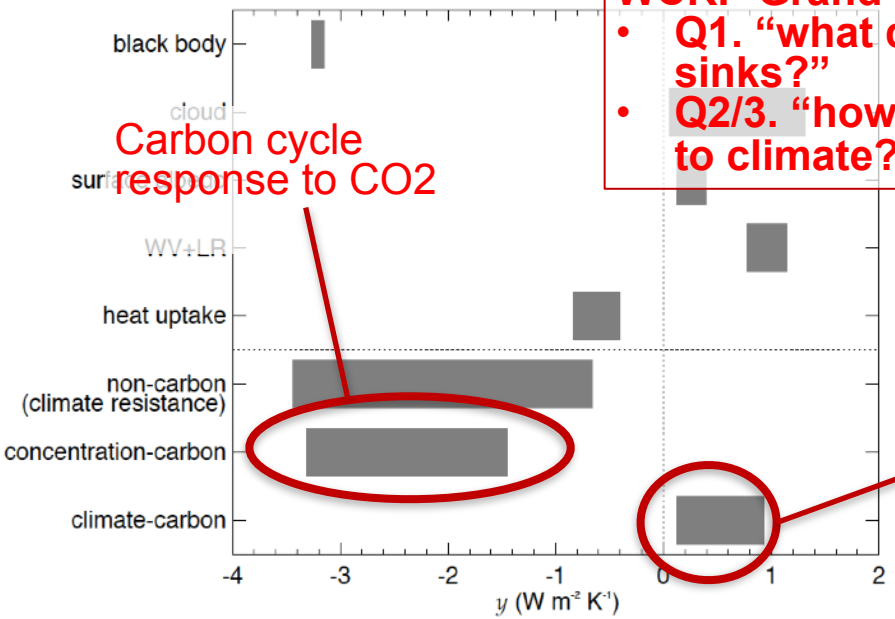
- Various feedbacks operate to modulate this

BUT: Fundamental difference in where the uncertainties lie

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

WCRP Grand Challenge:

- **Q1. "what drives carbon sinks?"**
- **Q2/3. "how do they respond to climate?"**



Carbon cycle response to CO2

Carbon cycle feedbacks with climate

Gregory et al., 2009, J. Clim.

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Conclusions (1)

- We need to focus research into what drives the sinks (i.e. carbon cycle response to CO2) as well as their response to climate
    - Both magnitude and uncertainty of response to CO2 are bigger than response to climate
    - AND – I'm about to argue – will become increasingly more important in driving future changes

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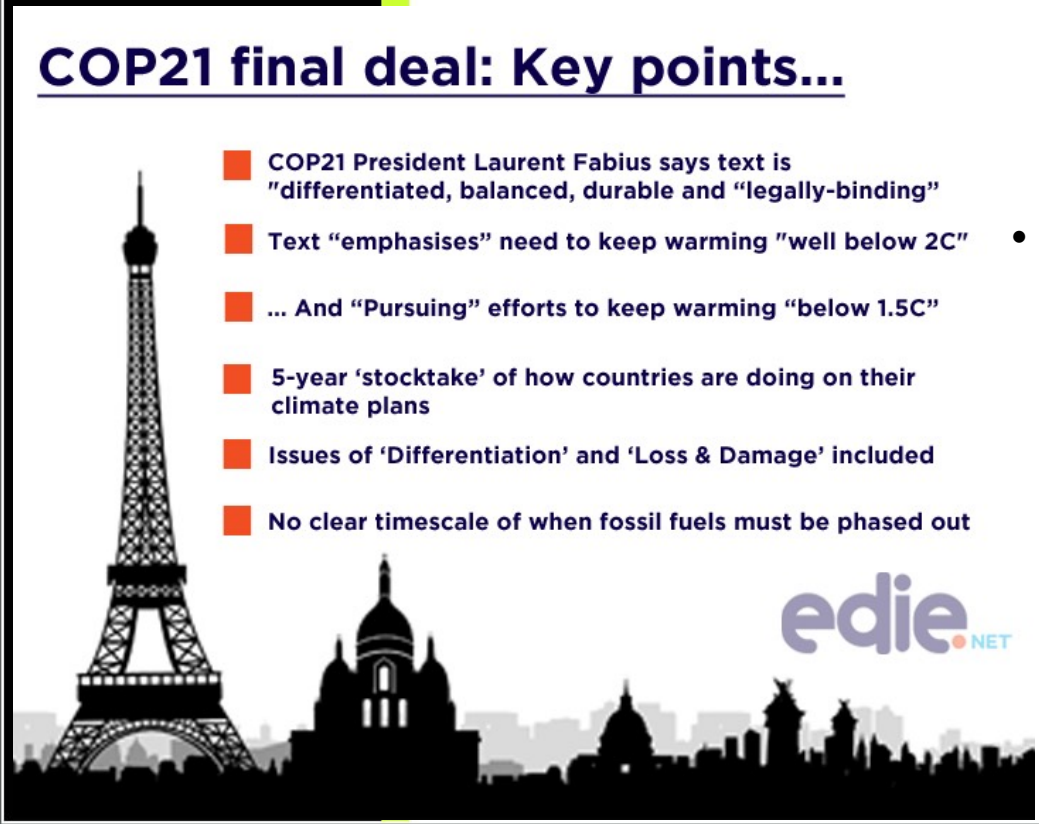
Carbon cycle under low CO_2 pathways

- Paris Agreement
- How does this change carbon cycle research priorities?

COP21: “Paris Agreement”

what does this mean for quantifying carbon budgets?

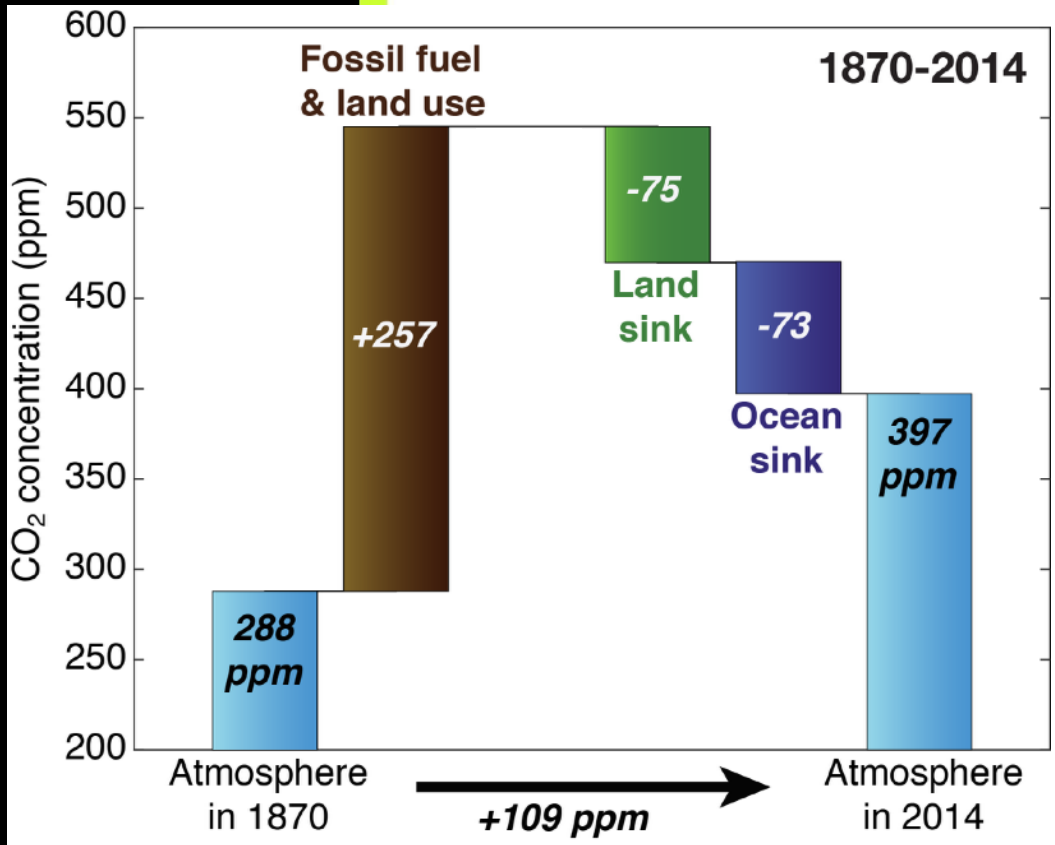
- Ambitious climate targets
- Achieving them will require “negative emissions”



How will carbon cycle respond?

- Carbon cycle simulations in the past have focussed on rapid growth, high-CO_2 scenarios:
  - IS92a, SRES-A2, RCP8.5, 1% per year (up to 1140 ppm)
- Renewed focus on low stabilisation/ overshoot pathways
  - Will carbon sinks respond in the same way as under high emissions?

Historical carbon cycle was easy(ish)



We put some in...

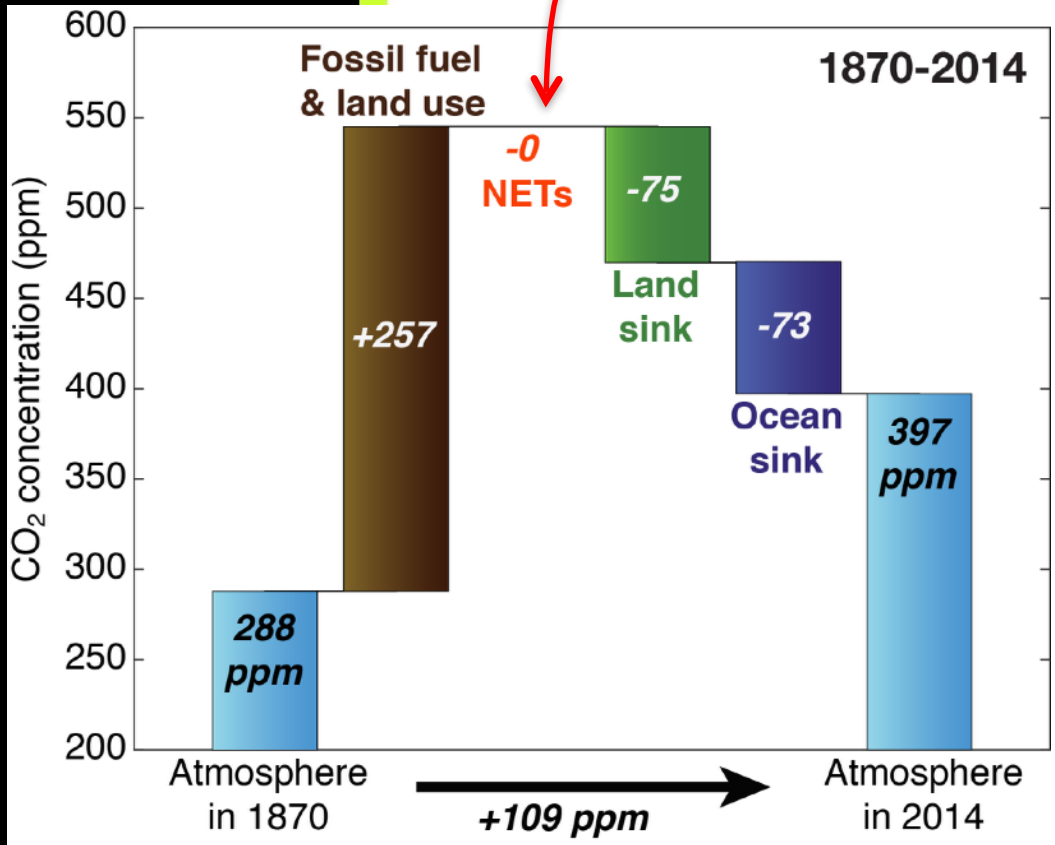
…nature took some out

- in approx constant fraction

Here we use CMIP5 simulations to show how the balance of inputs and removals depends on scenario and changes dynamically over coming decades/centuries

Historical carbon cycle was easy(ish)

Negative emissions – or carbon dioxide removal



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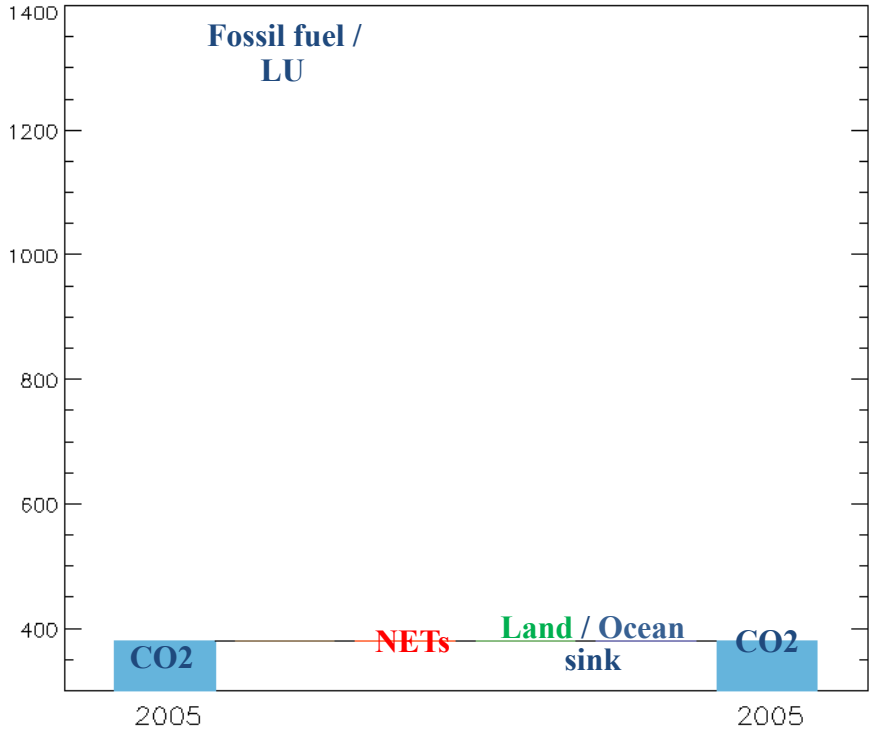
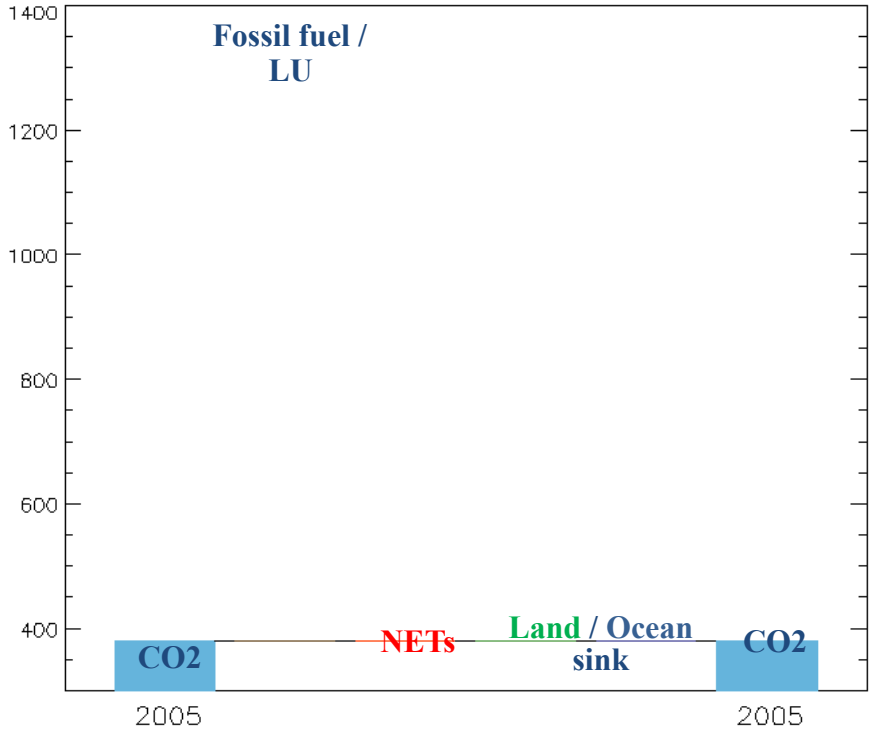
RCP8.5



RCP2.6



Jones et al., 2016, ERL

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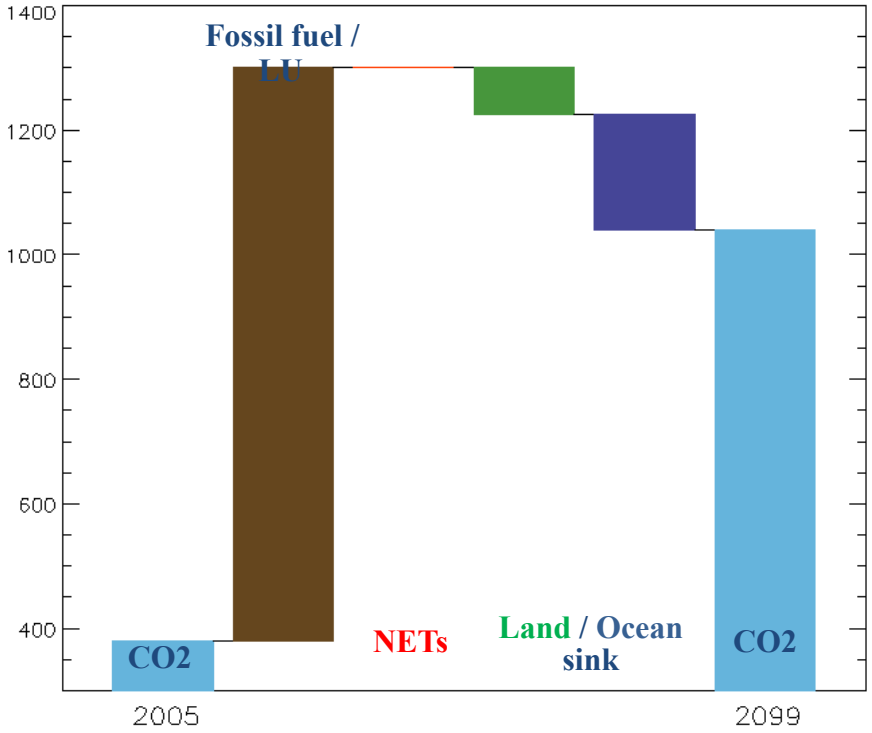

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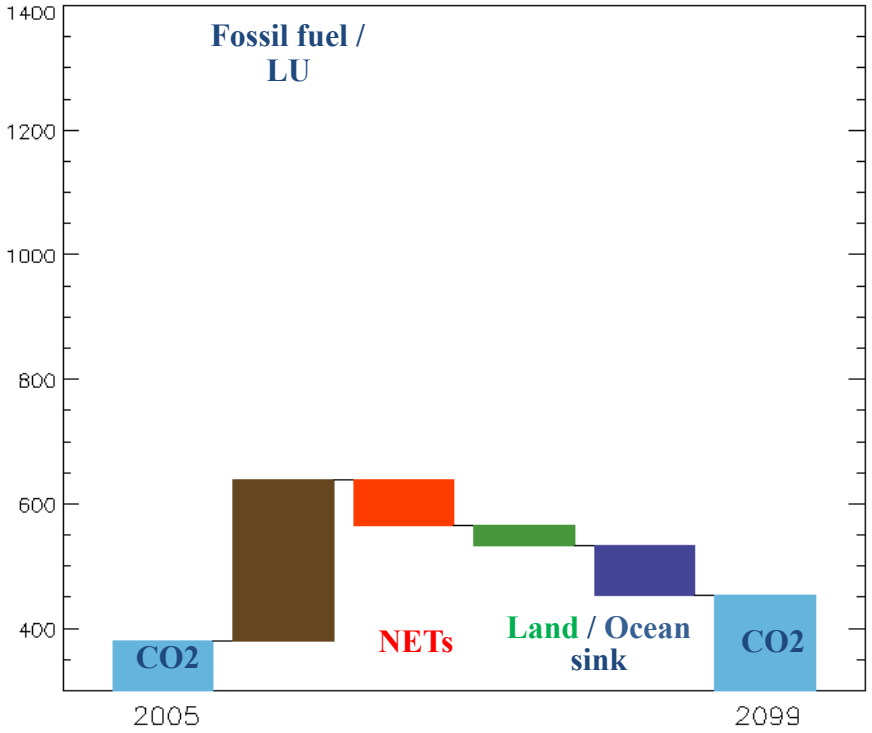
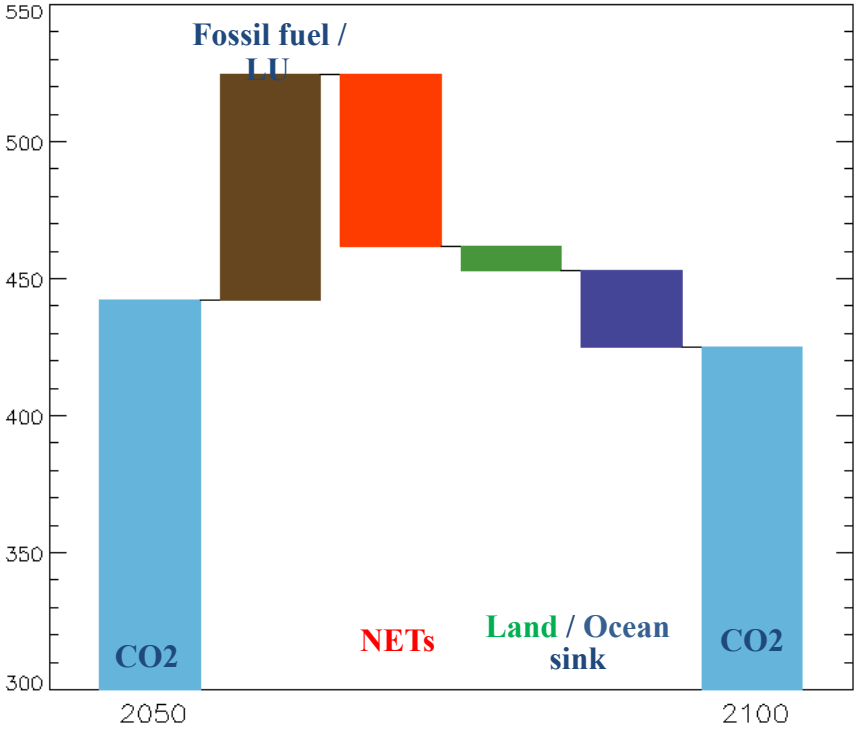
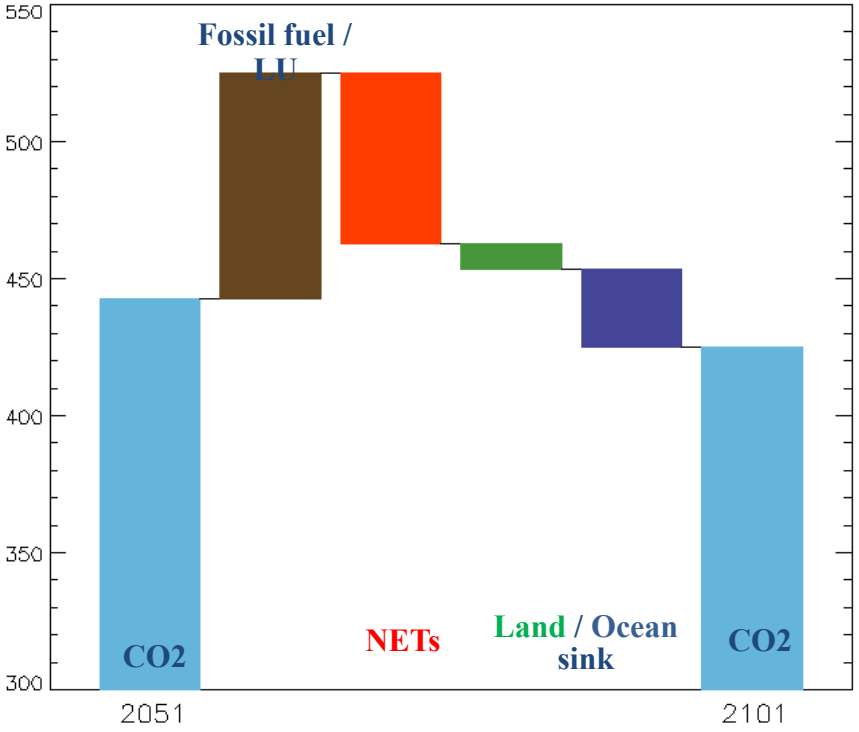


- So RCP2.6 relative to 8.5:
  - Lower fossil fuel emissions
  - More NETs
  - Perhaps not widely appreciated – much smaller land/ocean sinks (in absolute terms, but they're bigger fraction of the emissions)

RCP2.6
second half of 21st century



RCP2.6
50-year moving window



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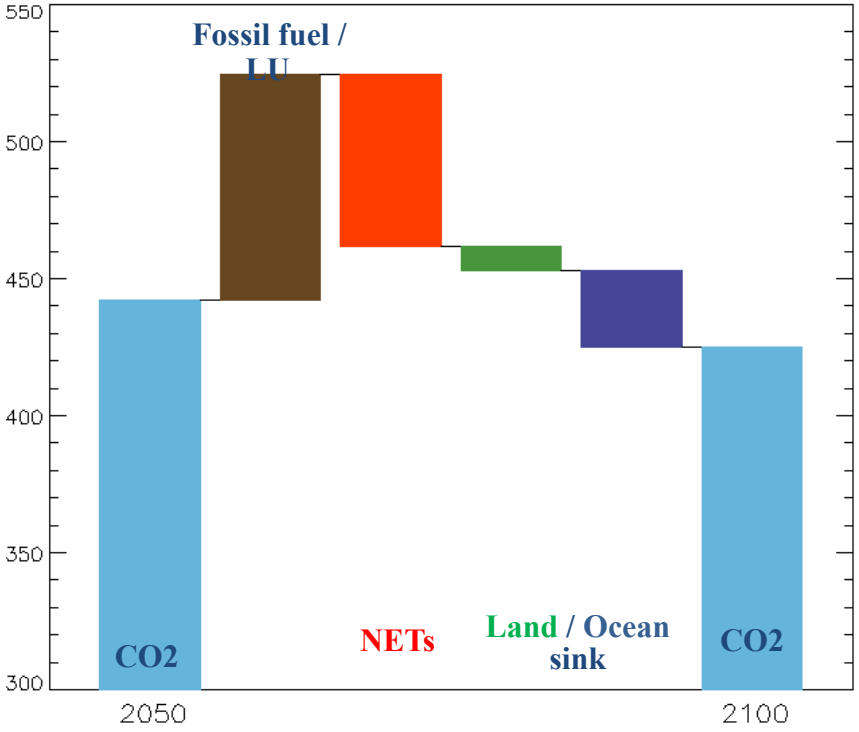

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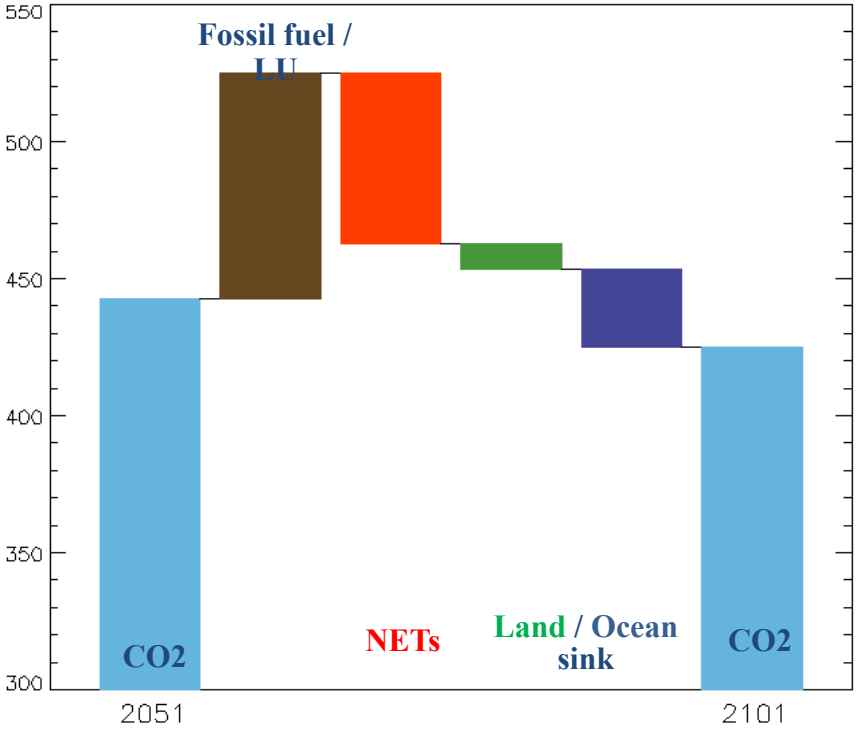

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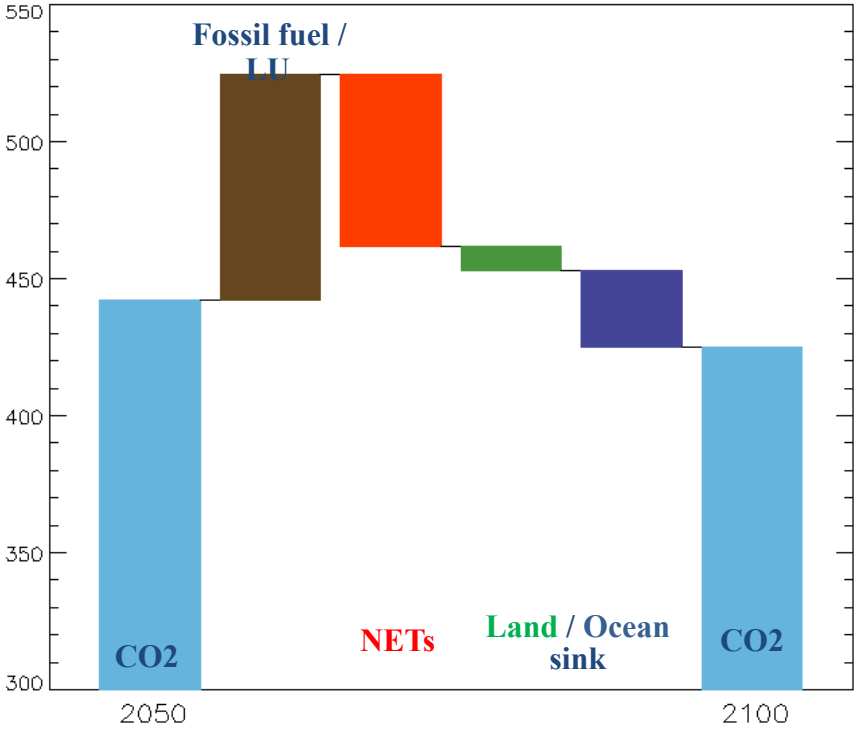
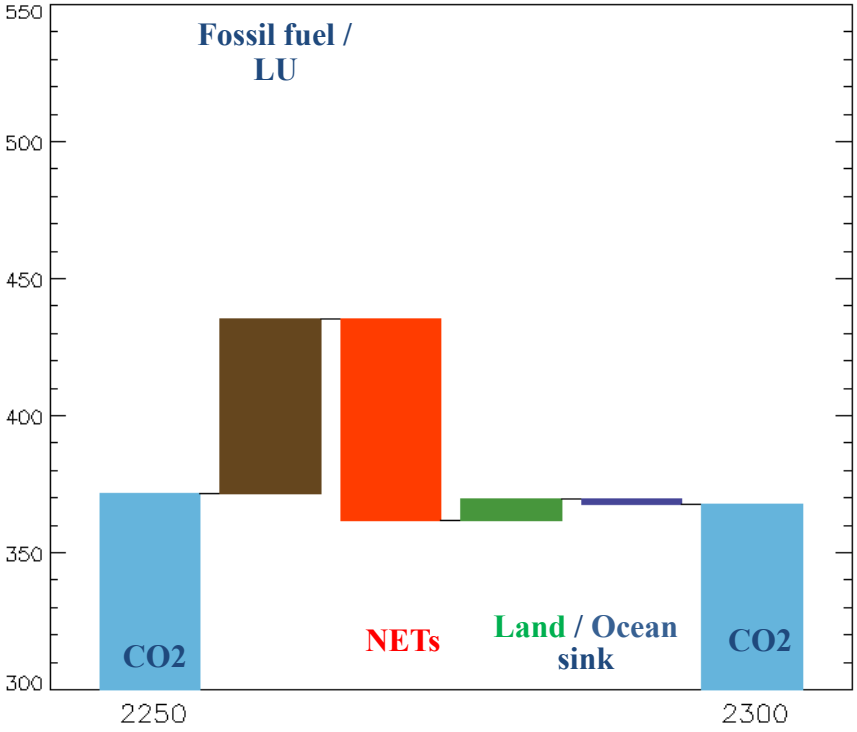
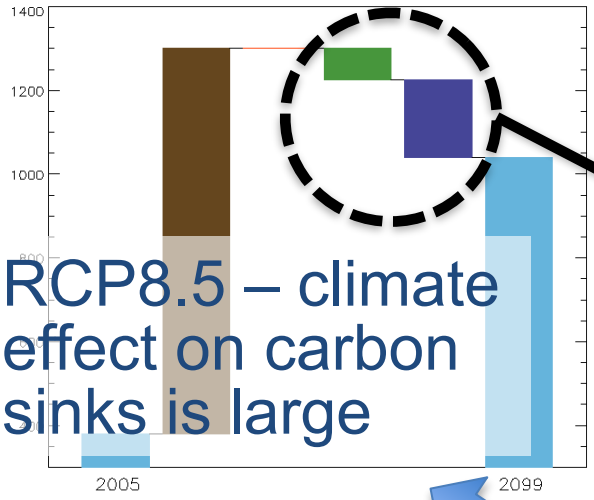


- Human input: positive
- Natural input: negative
- CO_2 decreases ***because of*** natural sinks

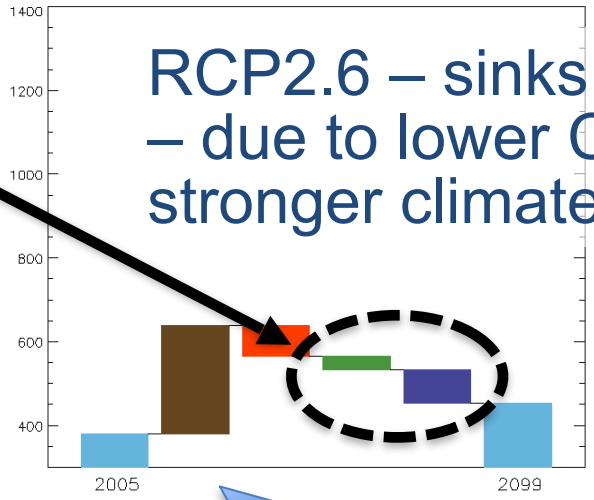
RCP2.6 second half of 23rd century



- Human input: negative
- Natural input: positive
- CO_2 decreases ***despite*** natural sources



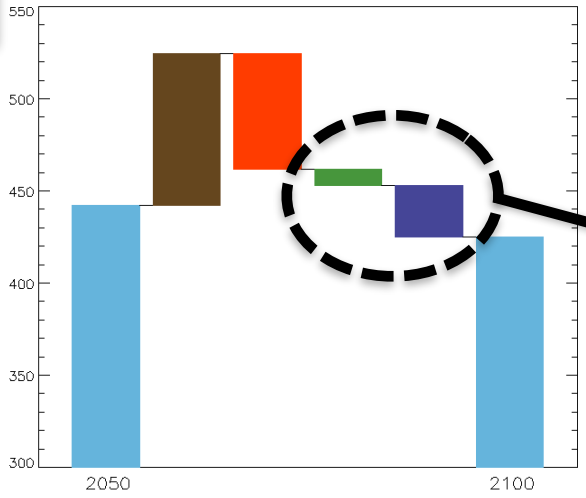
RCP8.5 – climate effect on carbon sinks is large

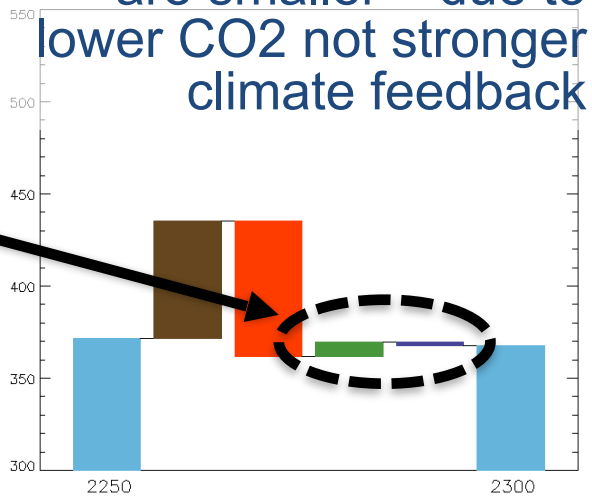


RCP2.6 – sinks are smaller – due to lower CO2 not stronger climate feedback

Between scenarios

Within scenarios





RCP2.6: by 2300 sinks are smaller – due to lower CO2 not stronger climate feedback

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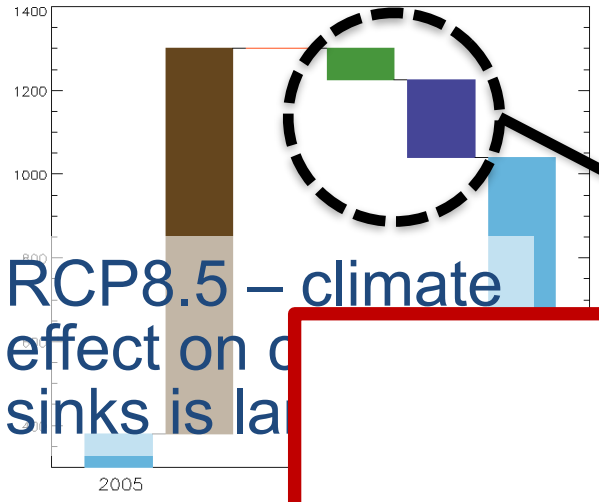
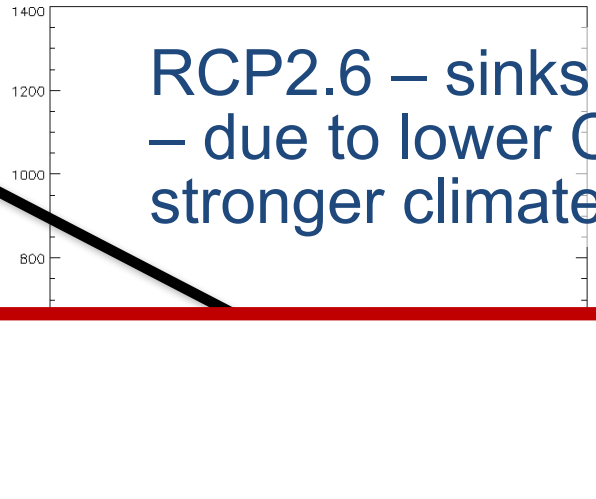


RCP8.5 – climate effect on c
sinks is la



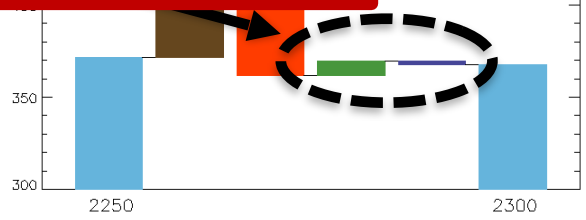
RCP2.6 – sinks are smaller – due to lower CO2 not stronger climate feedback

We need to focus research into what drives the sinks (i.e. carbon cycle response to CO2)

- **especially under low CO2 pathways**

Within sc

300 sinks
– due to
stronger
feedback



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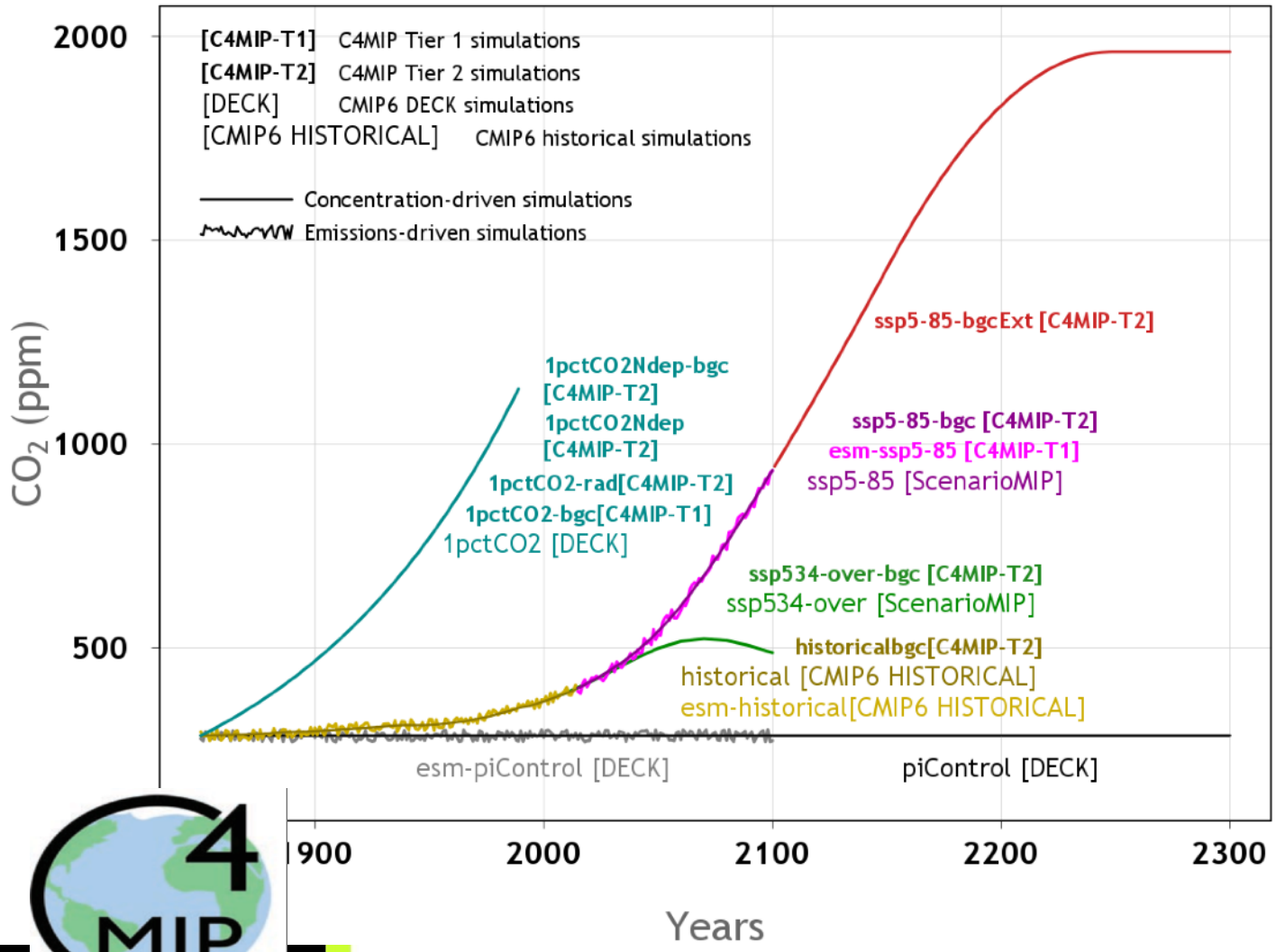
C4MIP simulations in relation to CMIP6 DECK and historical simulations



C⁴MIP simulations build on top of, and require, CMIP6 DECK and historical simulations for its analyses.

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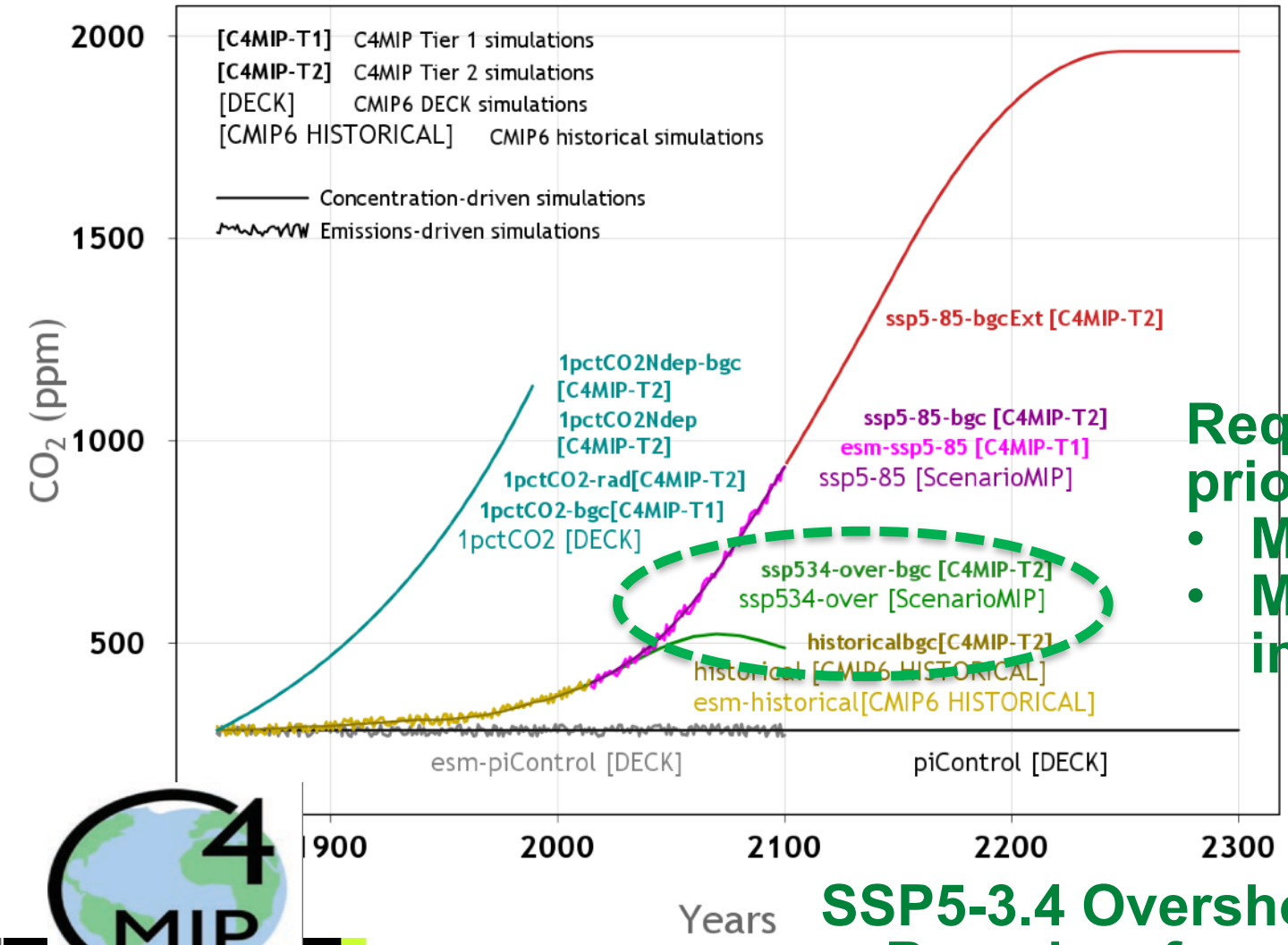
Jones et al., 2016, GMD CMIP special issue
http://www.geosci-model-dev.net/special_issue590.html

C4MIP simulations in relation to CMIP6 DECK and historical simulations



Request to prioritise this one:

- **Most relevant?**
- **Most interesting?**

SSP5-3.4 Overshoot

- **Branches from 8.5 at 2040**
- **Extension to 2300**

Jones et al., 2016, GMD CMIP special issue
http://www.geosci-model-dev.net/special_issue590.html

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Conclusions (2)

- All previous feedback analyses focus on high CO2 monotonic increase scenarios
  - Policy focus on low CO2 stablisation or peak-and-decline
  - Balance of sources and sinks may change dramatically
    - Between and within scenarios
    - [*aside – need also to ensure simple models/ IAMs are calibrated robustly for these scenarios*]

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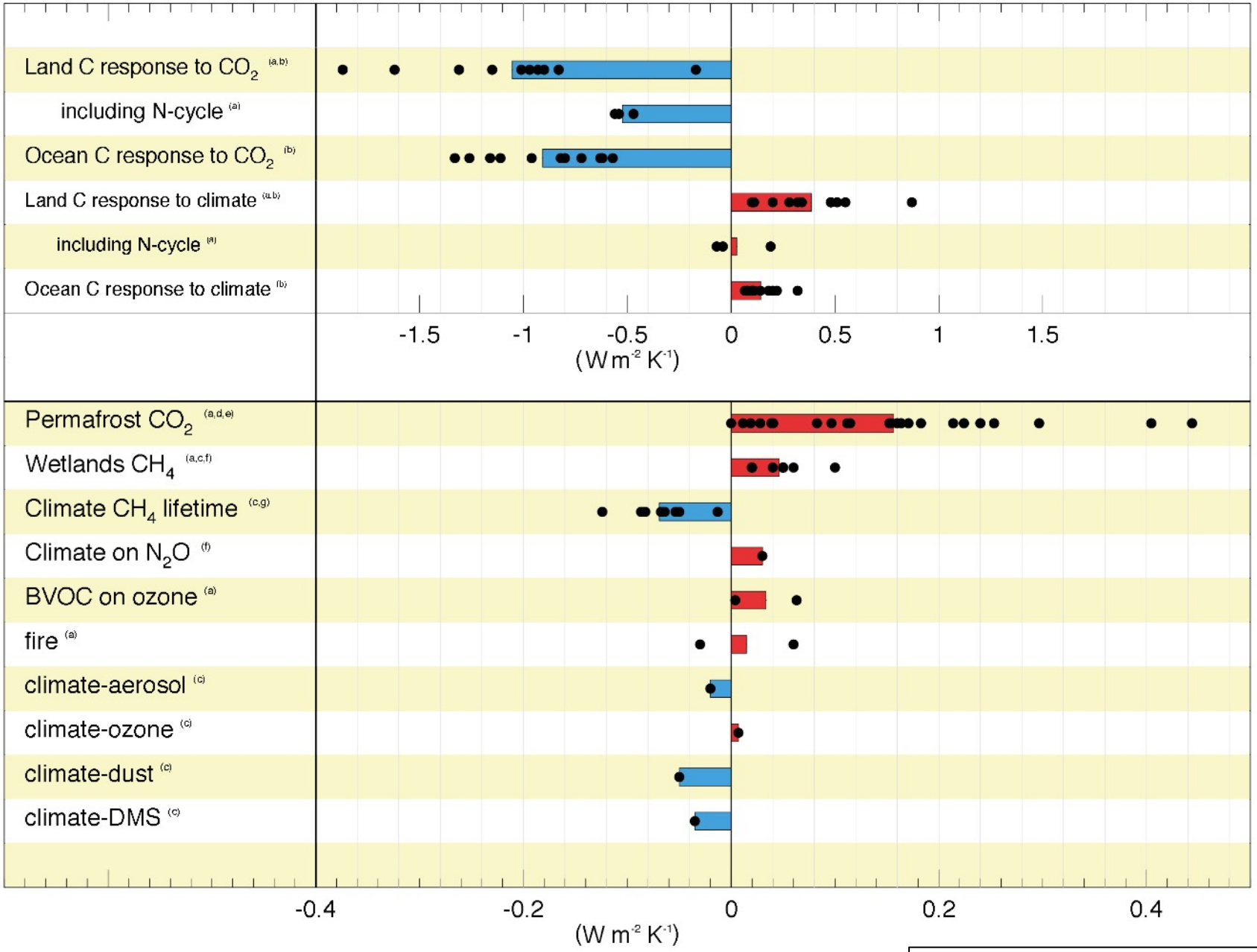
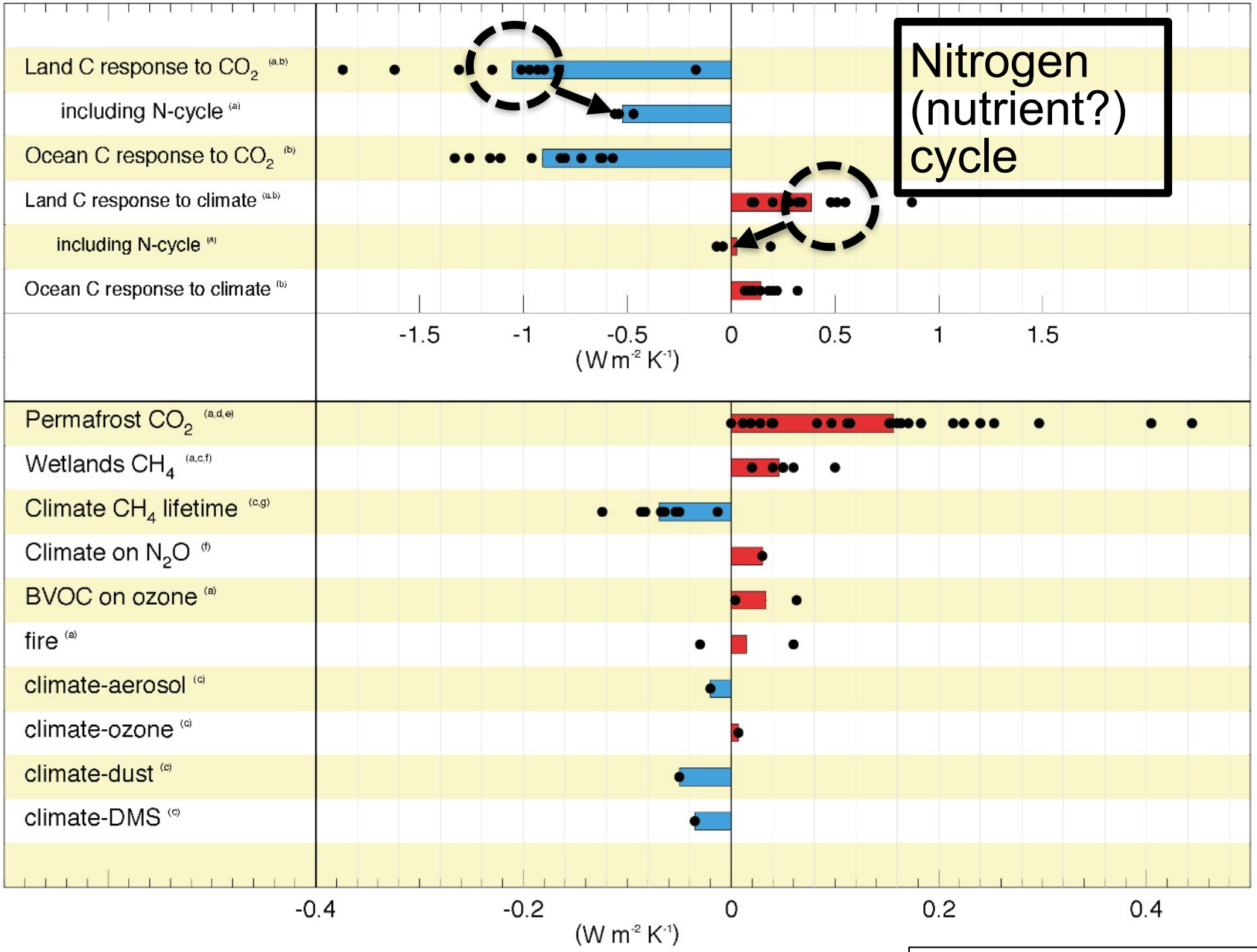
Process improvements?

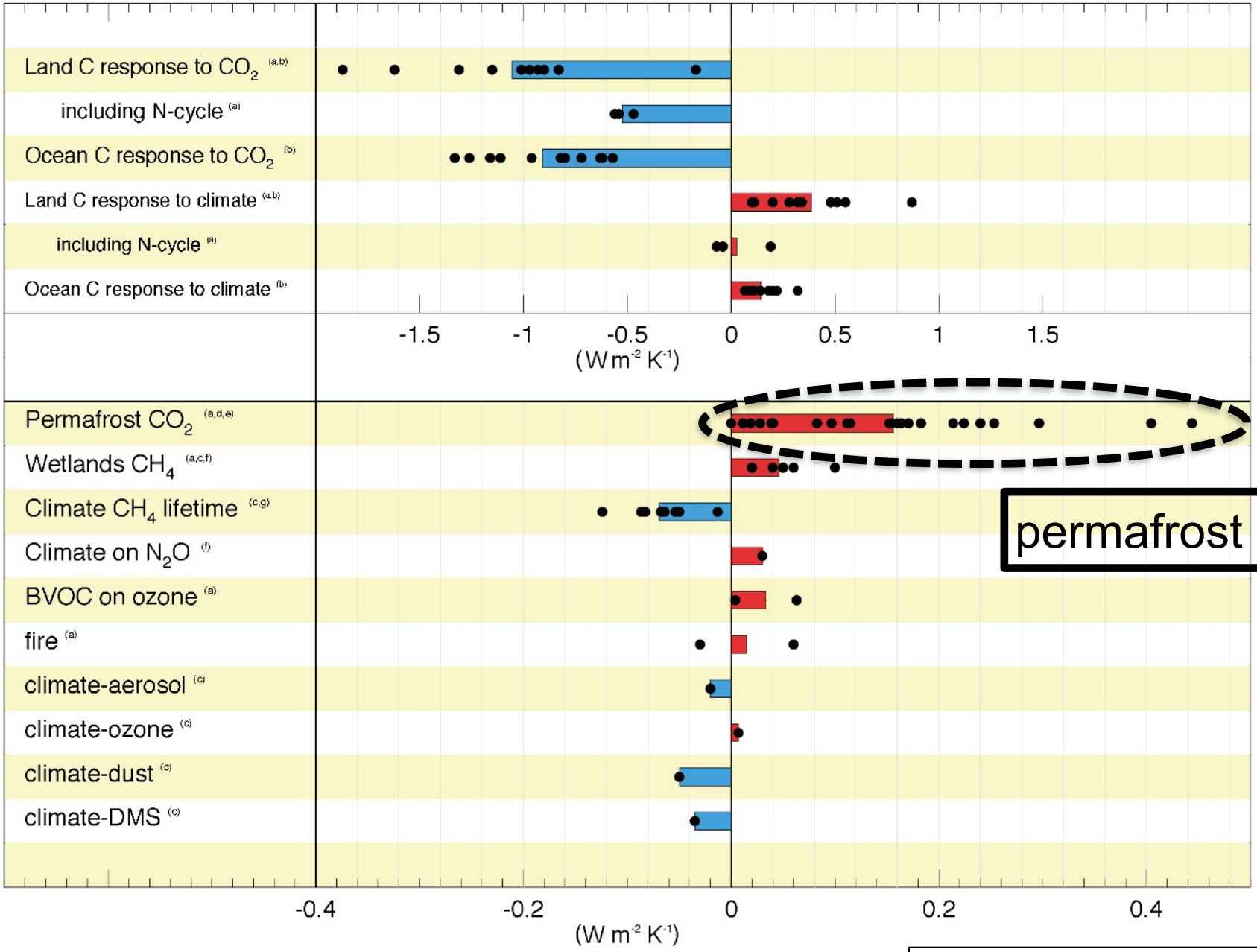
- Can we choose a “top 3” priority list?



IPCC AR5 Ciais et al., fig 6-20



IPCC AR5 Ciais et al., fig 6-20



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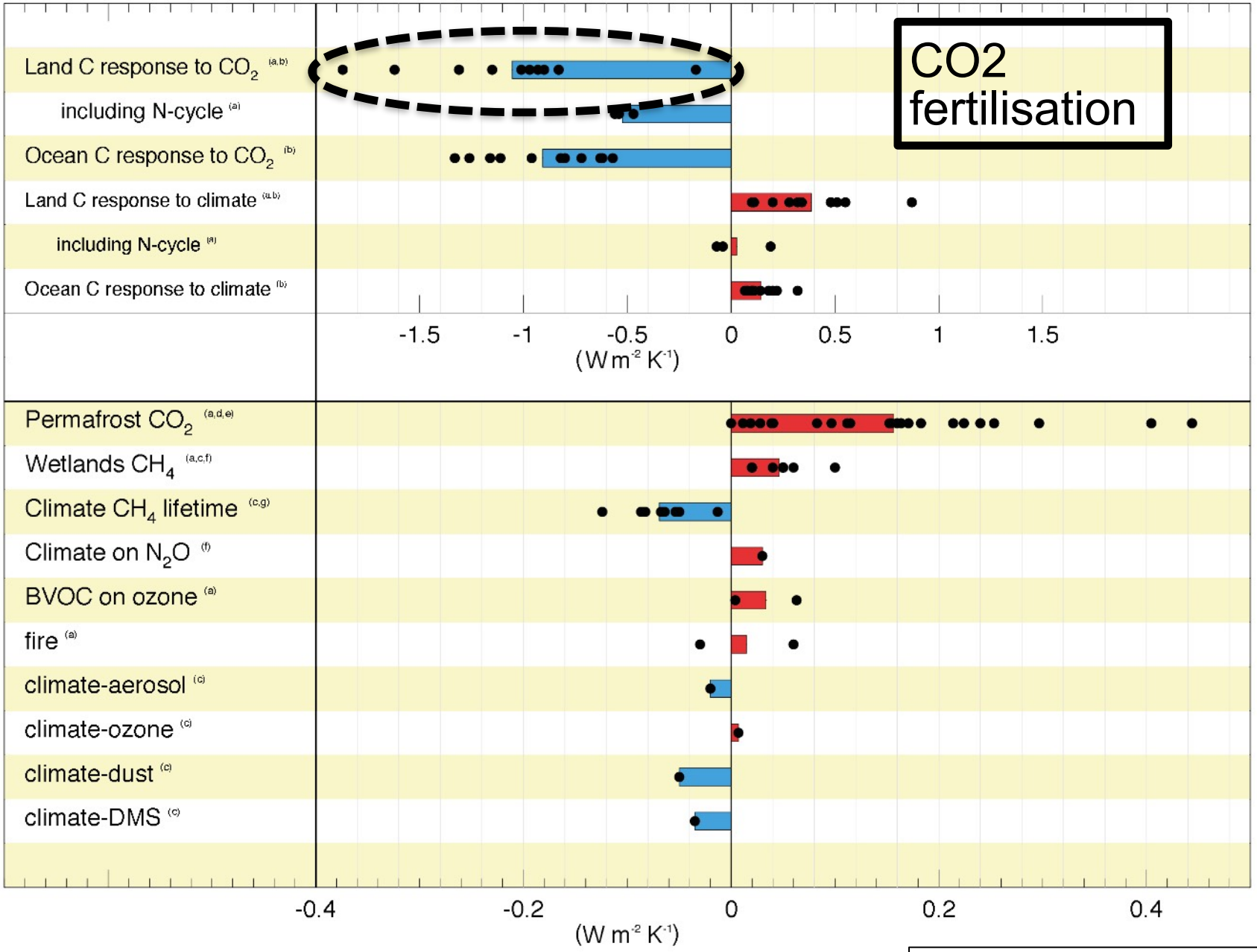
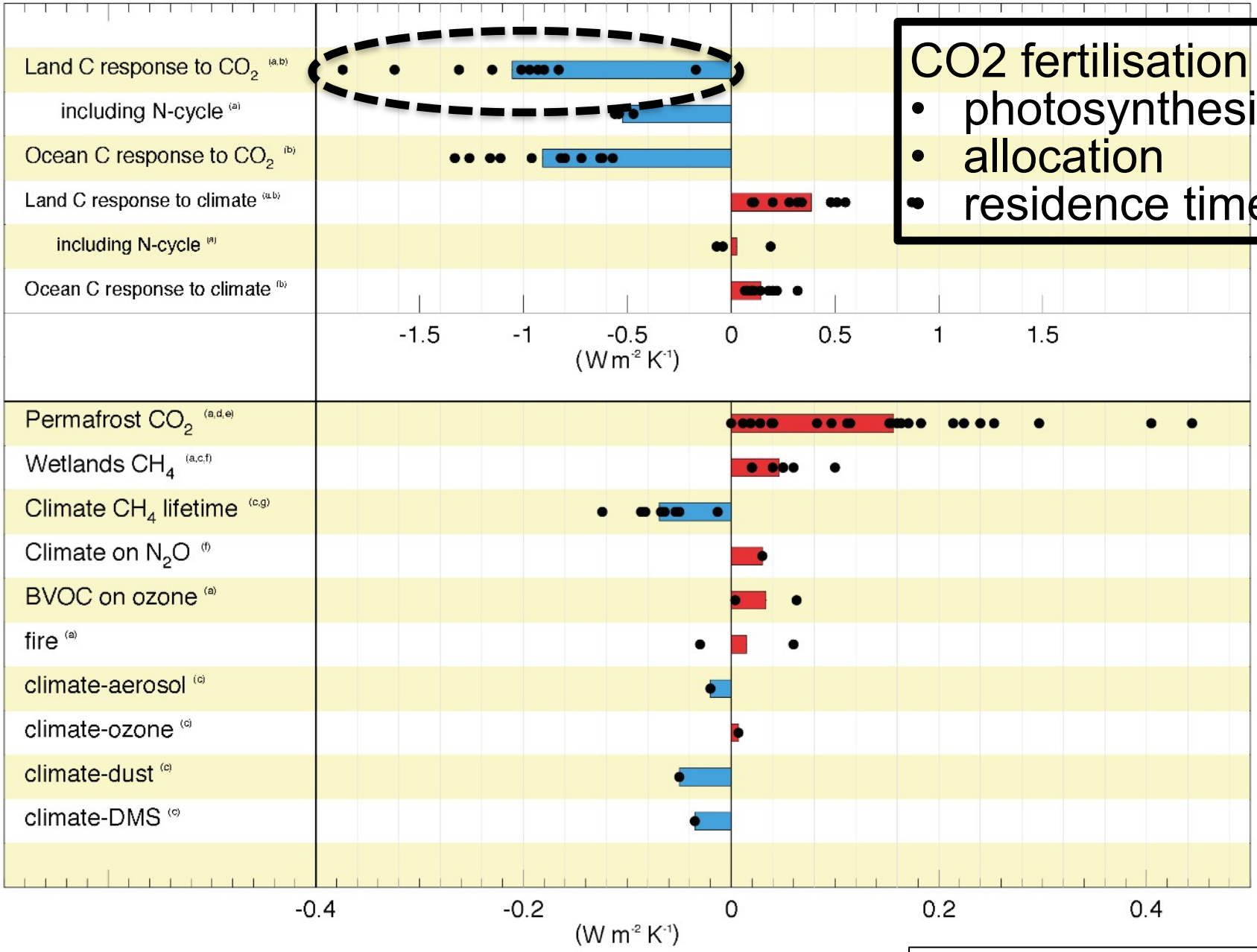


IPCC AR5 Ciais et al., fig 6-20



CO2 fertilisation
- photosynthesis
- allocation
- residence time

IPCC AR5 Ciais et al., fig 6-20

Conclusions (3)

- Still pressing need to develop models
  - Improving representation of existing processes as important as adding new ones
  - Our rush towards shoving in fancy new stuff has left evaluation trailing…

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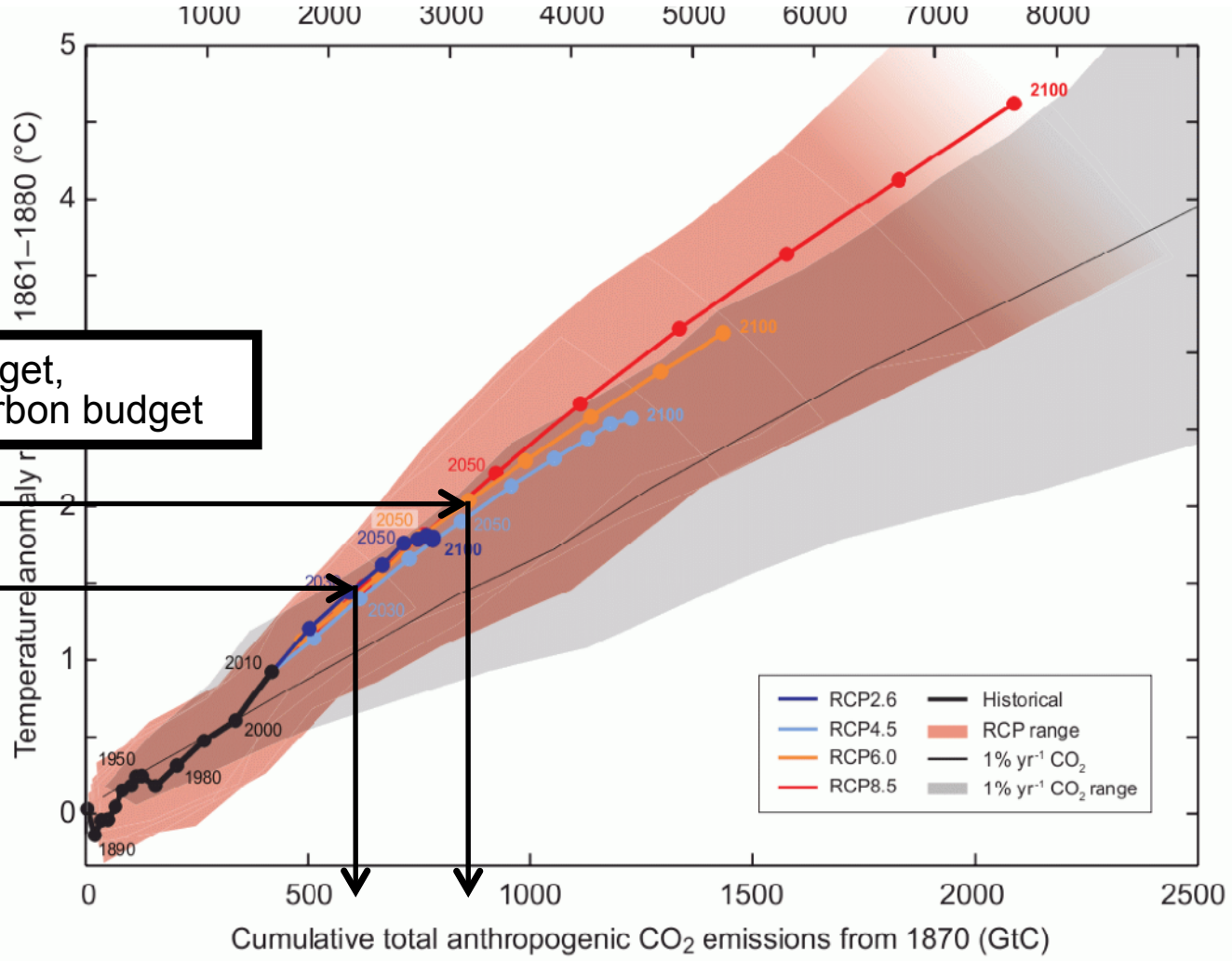
Evaluation and analysis

- Can we (a) understand, (b) constrain TCRE?

Global climate closely tied to accumulation of emissions ("TCRE"):
but large uncertainty hinders usefulness

For any temperature target,
read off an allowed carbon budget



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Global climate closely tied to accumulation of emissions ("TCRE"): but large uncertainty hinders usefulness

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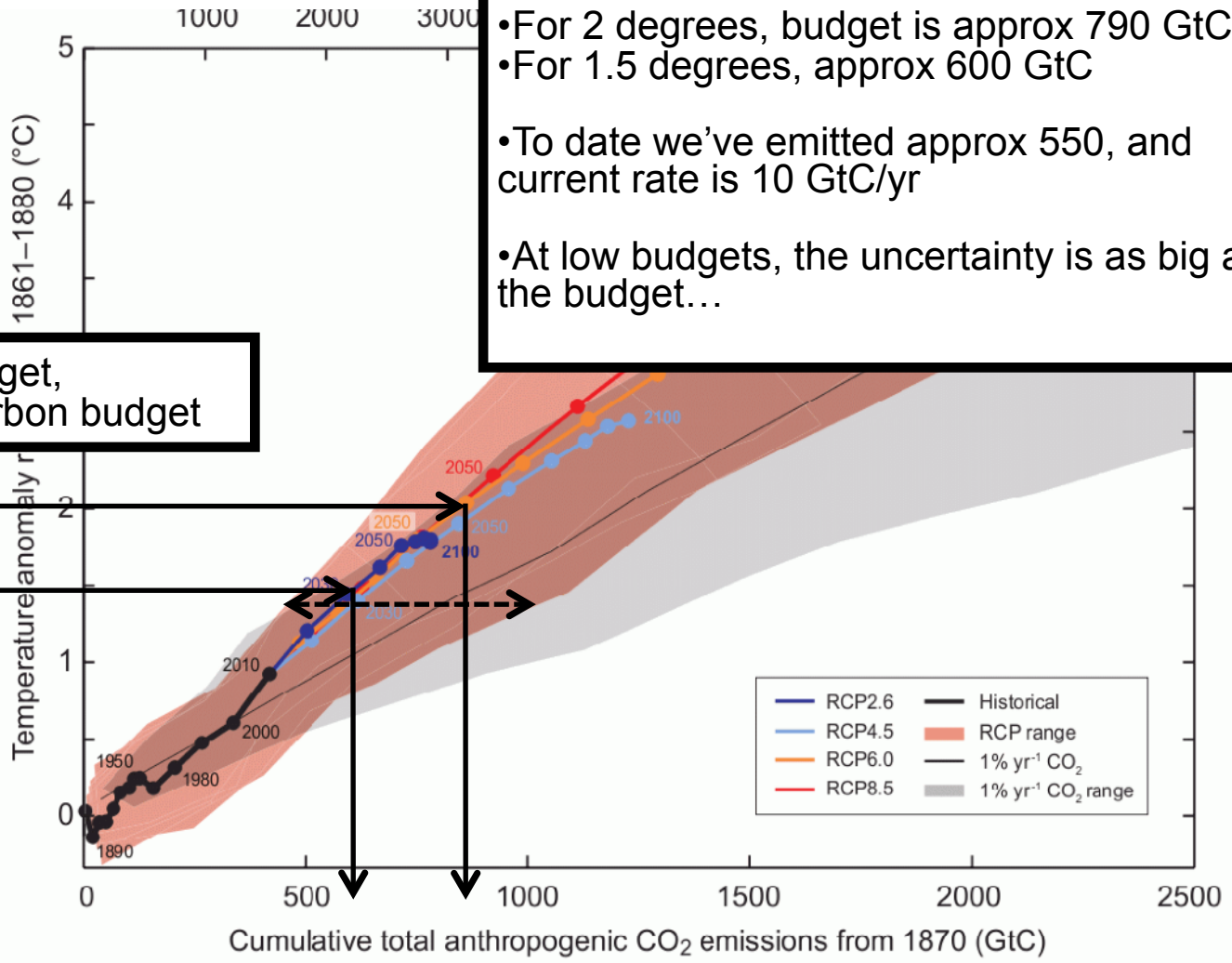
- For 2 degrees, budget is approx 790 GtC
- For 1.5 degrees, approx 600 GtC

- To date we've emitted approx 550, and current rate is 10 GtC/yr

- At low budgets, the uncertainty is as big as the budget…

For any temperature target, read off an allowed carbon budget



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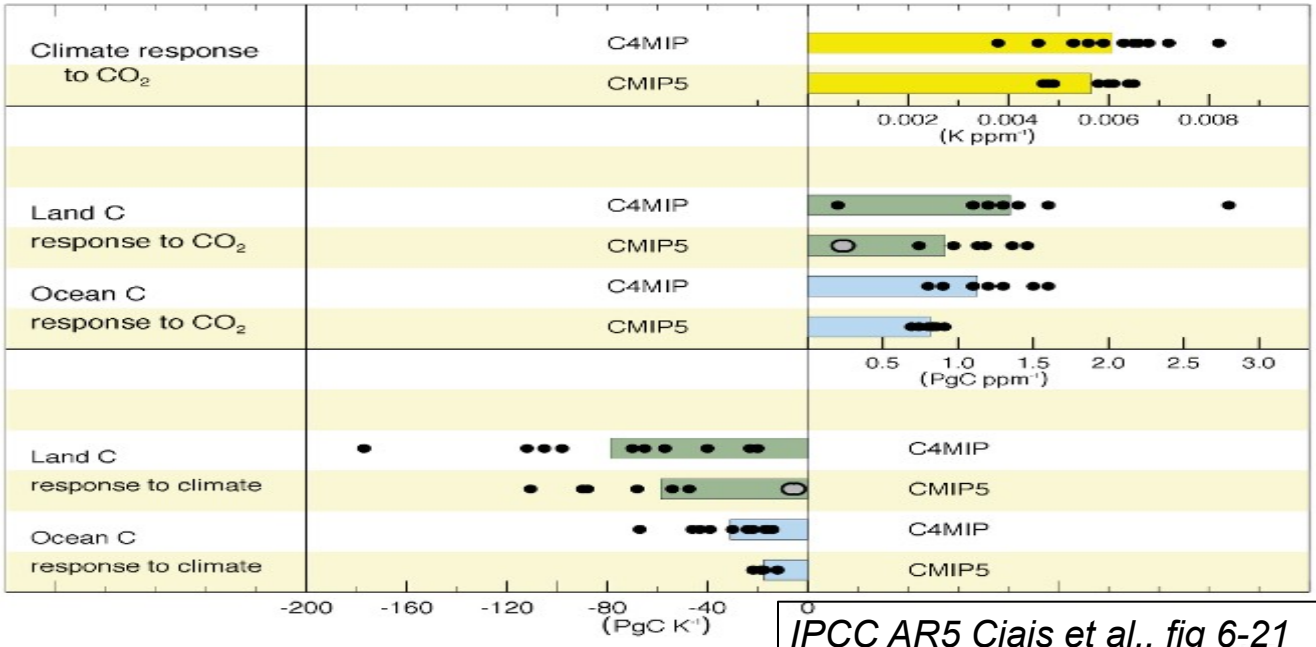
What contributes to TCRE uncertainty?

C4MIP defined carbon cycle feedback framework:

alpha, $\alpha = \Delta T / \Delta CO2$ *(basically TCR)*
beta, $\beta = \Delta C / \Delta CO2$
gamma, $\gamma = \Delta C / \Delta T$

AR5 quantified these for ESMs:



IPCC AR5 Ciais et al., fig 6-21

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Explore sources of uncertainty

We can manipulate these to form certain quantities:

C-cycle feedback Gain,
$g = \alpha * \gamma / (1+\beta)$

Cumulative airborne fraction,
$AF = 1 / (1 + \beta + \alpha * \gamma)$

$TCRE = \alpha / (1 + \beta + \alpha * \gamma)$

By varying any parameter (or it's spread) we can see it's effect on TCRE

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Alpha	Beta_L	Beta_O	Gamma_L	Gamma_O
0.006 +- 0.001	1.1 +- 0.4	0.8 +- 0.2	-90 +- 30	-20 +- 5

	Fractional reduction in range due to constraining:		
	alpha	beta	gamma
g	30%	22%	50%
AF	16%	62%	26%
TCRE	48%	37%	17%

We can quantify uncertainty reduction by constraining different bits

We can use this to prioritise what we want to constrain. Processes/regions to reduce uncertain (most bang-for-buck)

This priority varies with quantity we want – for TCRE it's alpha and beta

- **Once again – carbon cycle response to CO2 is paramount!**

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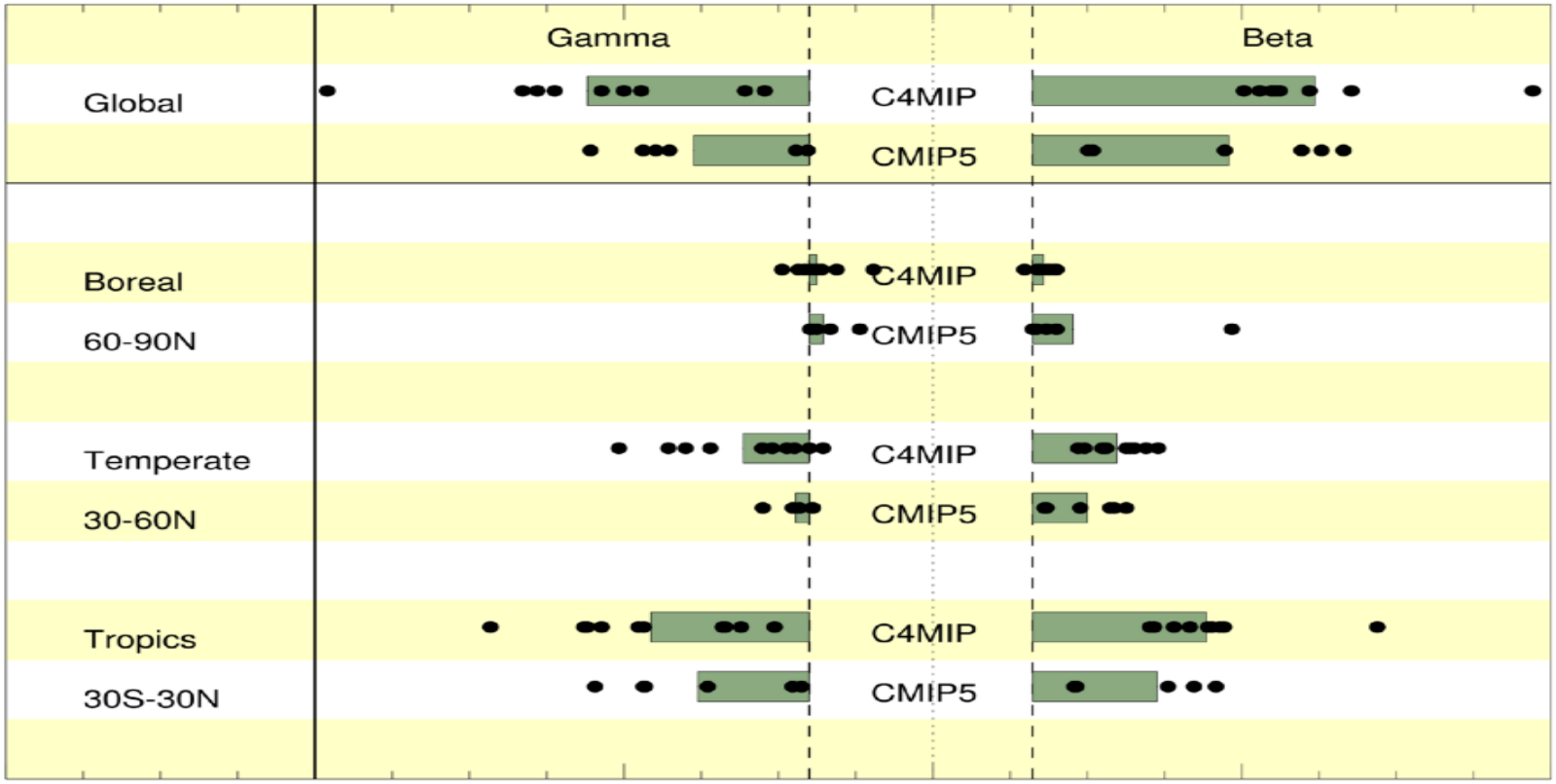
But… we don't have global constraints on beta/gamma

But we can break this down further into regions. Here for land:



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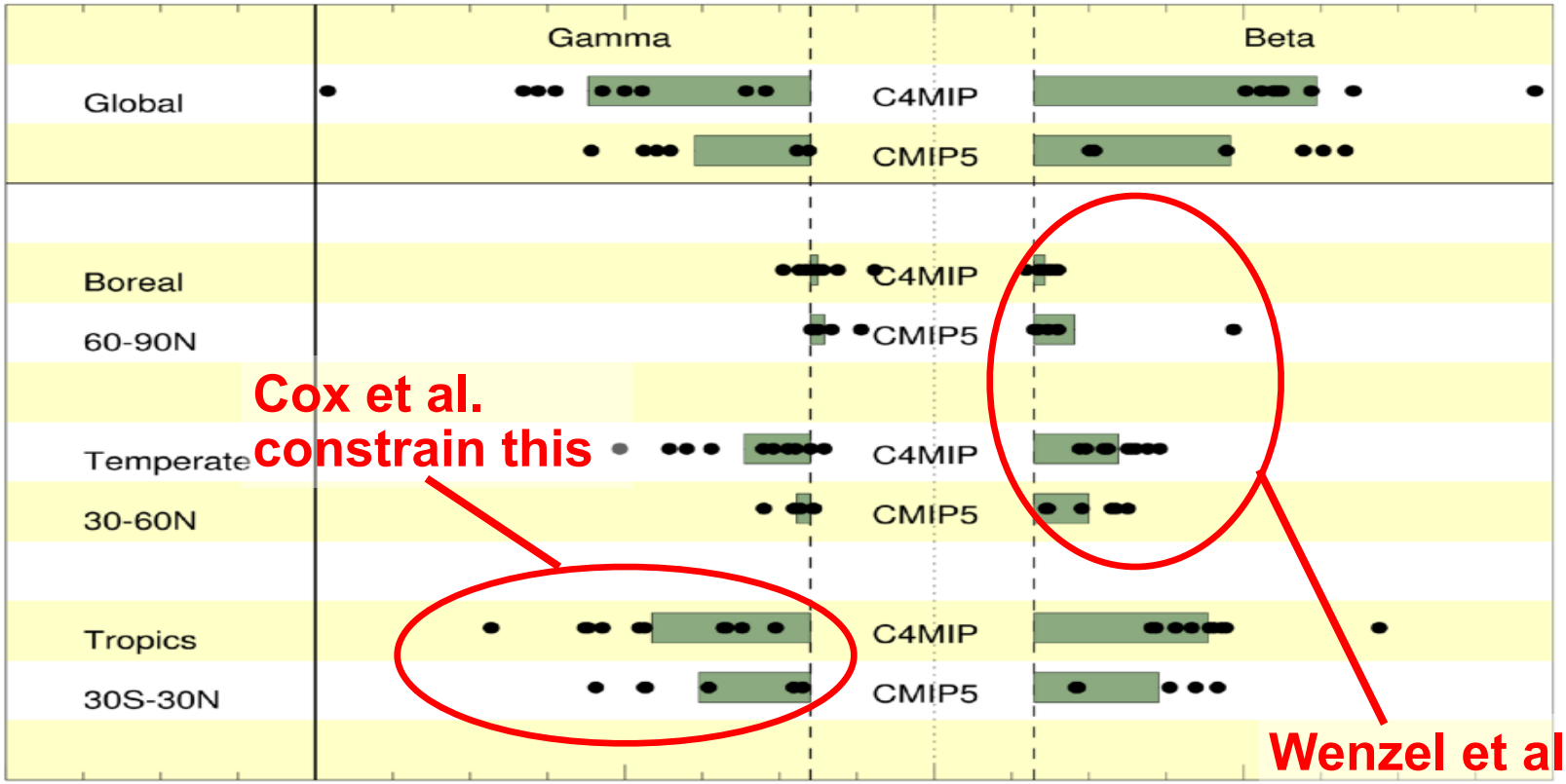
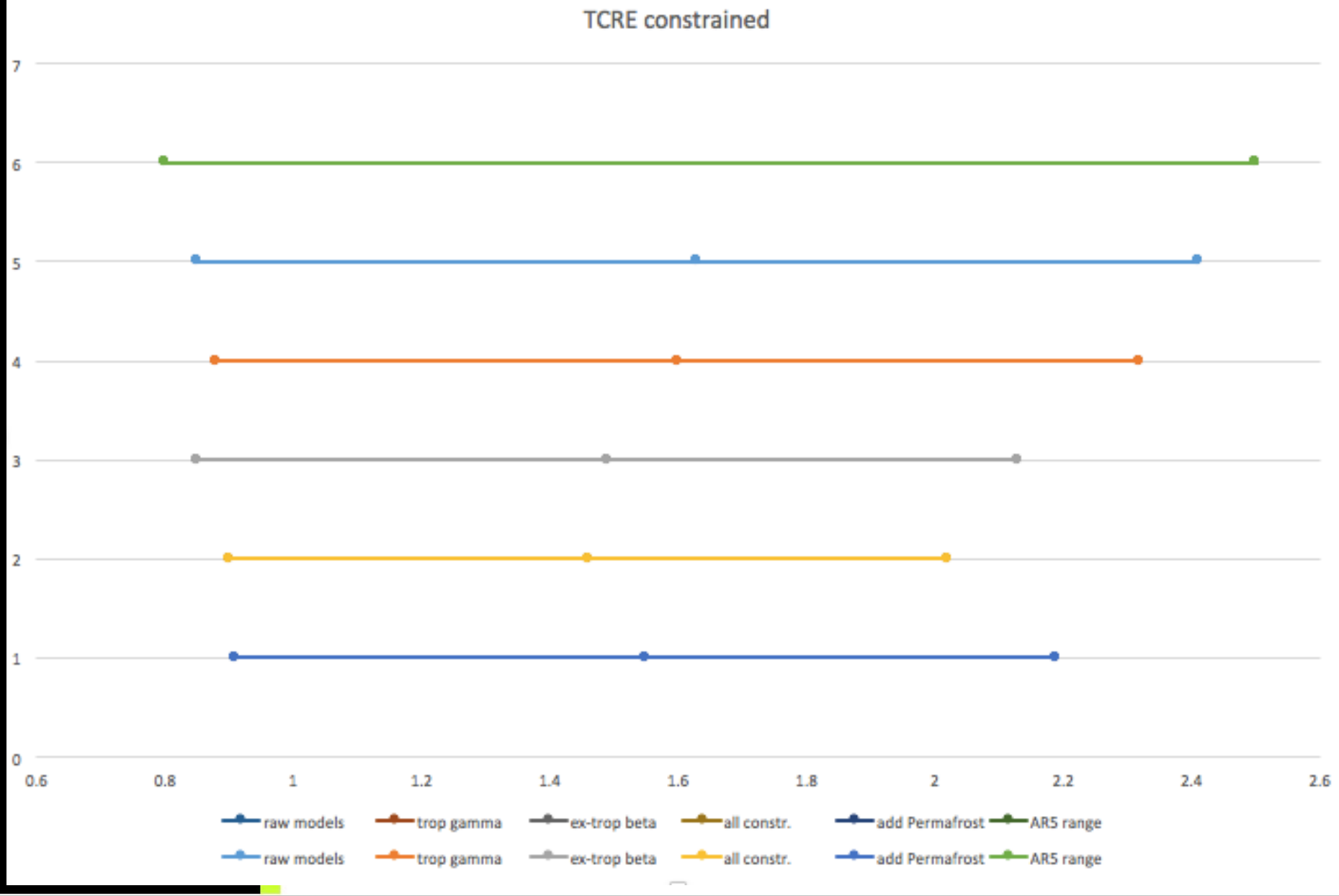
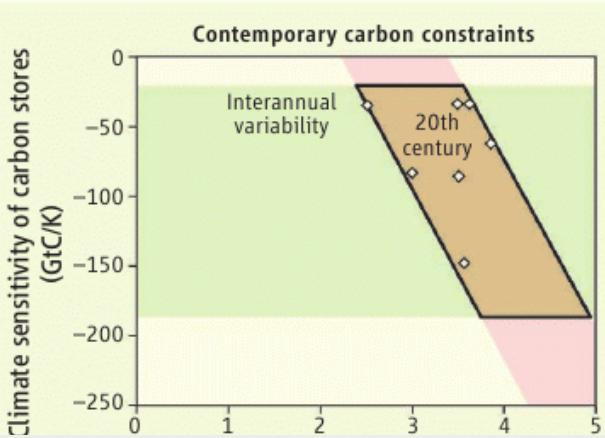


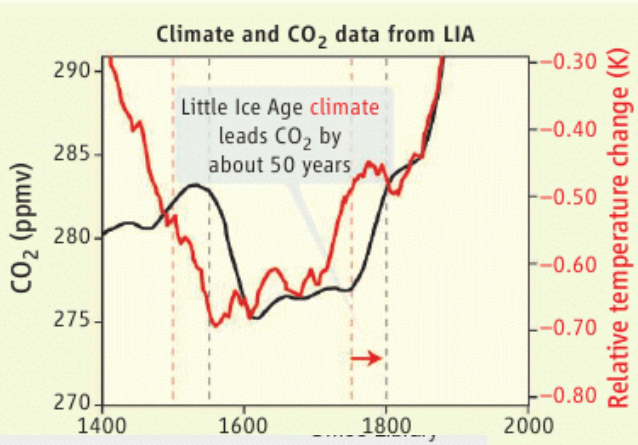
Cox et al., 2013, Nature ; Wenzel et al., 2016, Nature

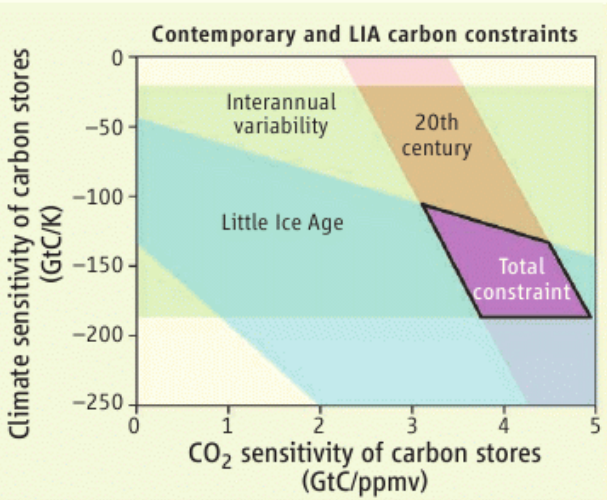
What does this give us?

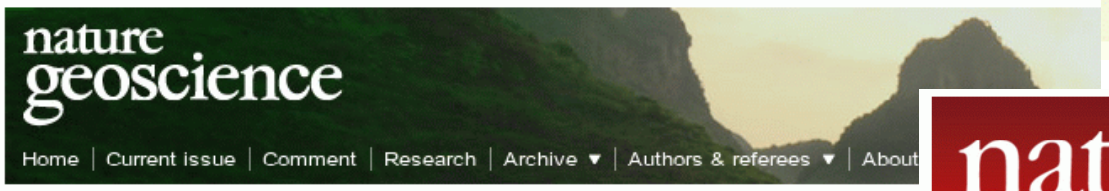


Other constraints?









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NATURE GEOSCIENCE | LETTER

Low atmospheric CO_2 levels during the Little Age due to cooling-induced terrestrial uptake

M. Rubino, D. M. Etheridge, C. M. Trudinger, C. E. Allison, P. J. Rayner, I. Enting, Mulvaney, L. P. Steele, R. L. Langenfelds, W. T. Sturges, M. A. J. Curran & A. M.

Affiliations | Contributions | Corresponding author

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Letter

Nature **463**, 527-530 (28 January 2010) | doi:10.1038/nature08769; Received 24 July 2009; Accepted 12 December 2009

Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate

David C. Frank[1,2], Jan Esper[3], Christoph C. Raible[2,4], Ulf Büntgen[1], Valerie Trouet[1], Benjamin Stocker[2,4] & Fortunat Joos[2,4]

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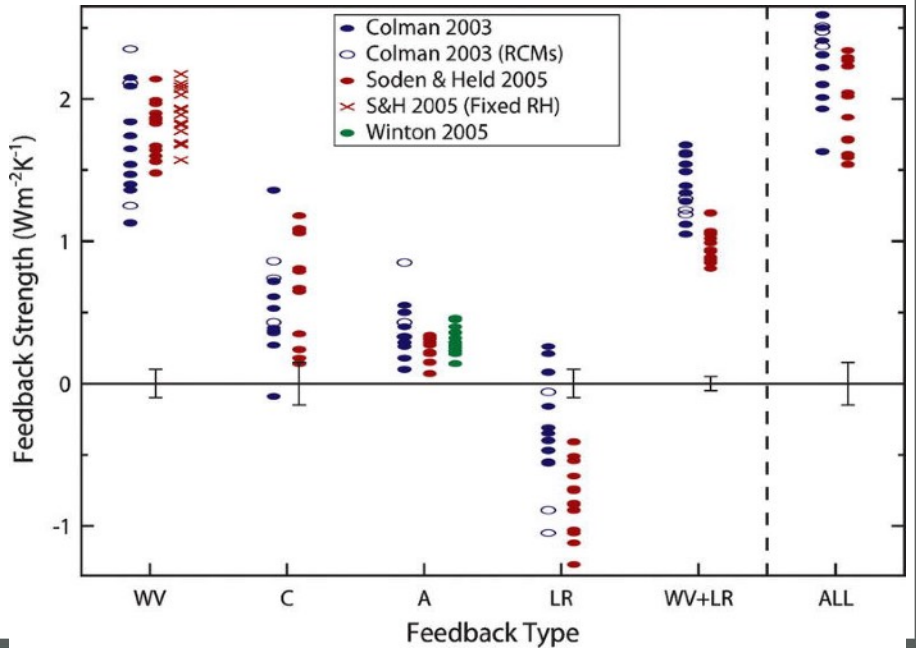
Not just land beta/gamma

Ocean beta/gamma
- split by region? S. Ocean? N. Atl?
- split by process? Lester's constraint on NPP?

Alpha (i.e. TCR)
- not easy by region, but split by process?
- Hall & Qu do albedo term?
- Sherwood for clouds?

Can keep combining stuff to chip away at TCRE spread…



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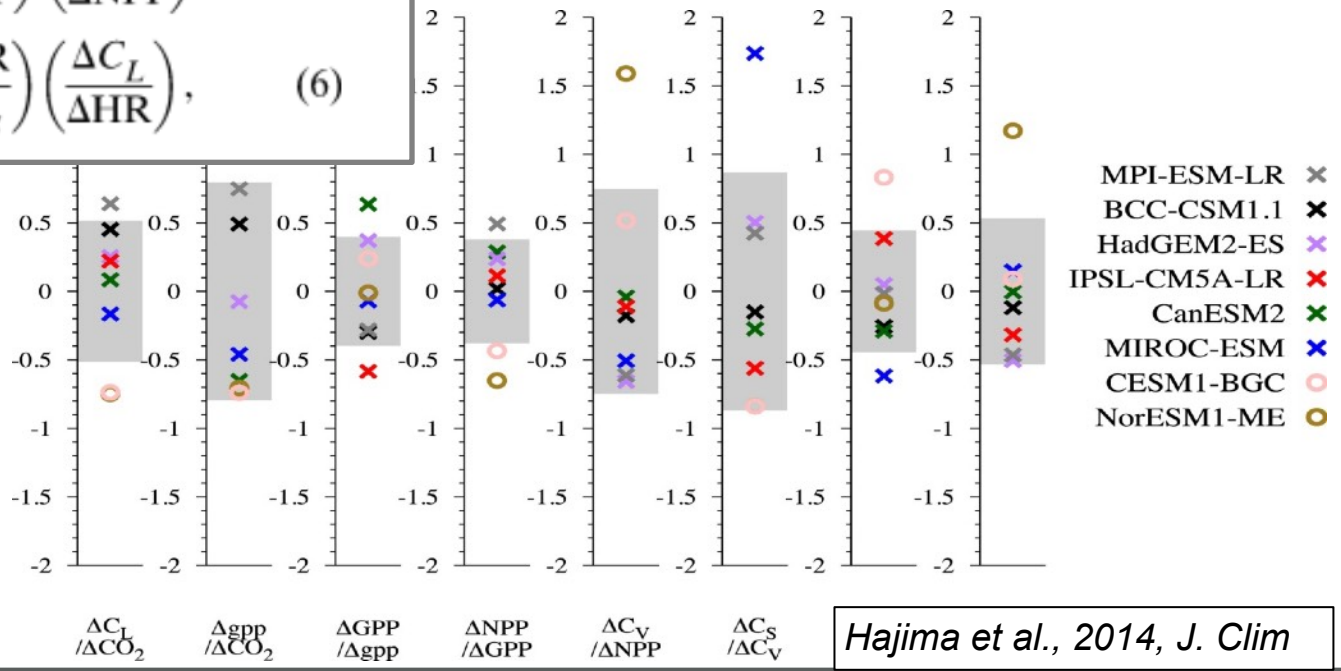
Other analysis frameworks

Hajima et al. breakdown land-carbon response to CO2 into series of sensitivities that can be diagnosed (in models) individually

- Can see how/why/where models differ
  - Models in middle of pack not always the "sensible" ones!
- Can we start to observe/constrain these relationships?

$$\frac{\Delta C_L}{\Delta CO_2} = \left(\frac{\Delta GPP}{\Delta CO_2}\right)\left(\frac{\Delta NPP}{\Delta GPP}\right)\left(\frac{\Delta C_V}{\Delta NPP}\right) \times \left(\frac{\Delta C_S}{\Delta C_V}\right)\left(\frac{\Delta HR}{\Delta C_S}\right)\left(\frac{\Delta C_L}{\Delta HR}\right), \quad (6)$$



Hajima et al., 2014, J. Clim

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Other analysis frameworks

Goodwin et al. (2015; *Nat Geosci*) show why TCRE is near-linear due to ocean heat/carbon uptake

Williams et al. build on this to decompose TCRE into process-level components

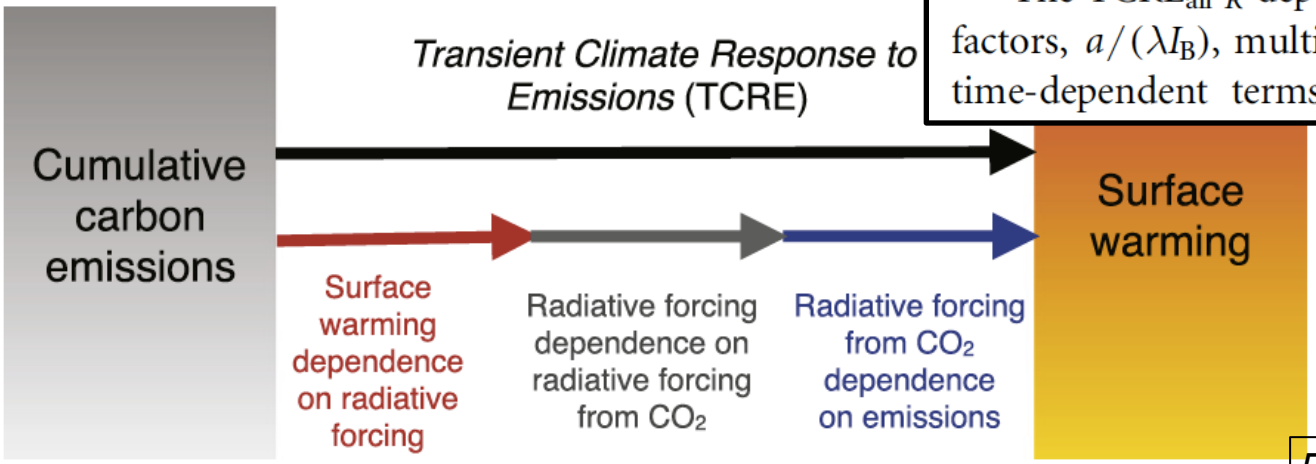
- Again – can understand how/where/why models differ and try to find constraints

$$\mathrm{TCRE}_{\mathrm{all}R} = \frac{a}{\lambda I_{\mathrm{B}}}\left(1 - \frac{\varepsilon N(t)}{\Delta R(t)}\right) \times \left(1 + \frac{I_{\mathrm{Usat}}(t)}{\Delta I(t)} - \frac{\Delta I_{\mathrm{ter}}(t)}{\Delta I(t)}\right)\left(\frac{\Delta R(t)}{\Delta R_{\mathrm{CO_2}}(t)}\right). \quad (11)$$

The $\mathrm{TCRE}_{\mathrm{all}\ R}$ depends on the time-independent factors, $a/(\lambda I_{\mathrm{B}})$, multiplied by the non-dimensional time-dependent terms contained within the three

(b) Schematic representation of the link between emissi

Transient Climate Response to Emissions (TCRE)



Ric Williams et al., 2016, ERL

Conclusions (4)

we can construct TCRE from separate terms and constrain each individually

This allows us to:

- identify/prioritise where uncertainty arises
  - Target model development / obs constraints

- Combine existing constraints
  - To constrain something useful

- There's a need for analytical frameworks, not just multi-model show-and-tell lines on a graph

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Summary

- 1. Carbon sinks are driven by CO2 as well as affected by climate
  - Larger response, larger uncertainty, more relevant under low CO2 pathways
- 2. Previous research has focused on high/monotonic CO2 increase
  - Future research must look more at stablisation/ overshoot
- 3. Model development has focused on new processes
  - Fine. But don't forget to improve existing ones!
- 4. We need to develop new and better analytical frameworks in which to understand system dynamics, and combine constraints

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