Emergent constraints on Carbon Cycle Feedbacks

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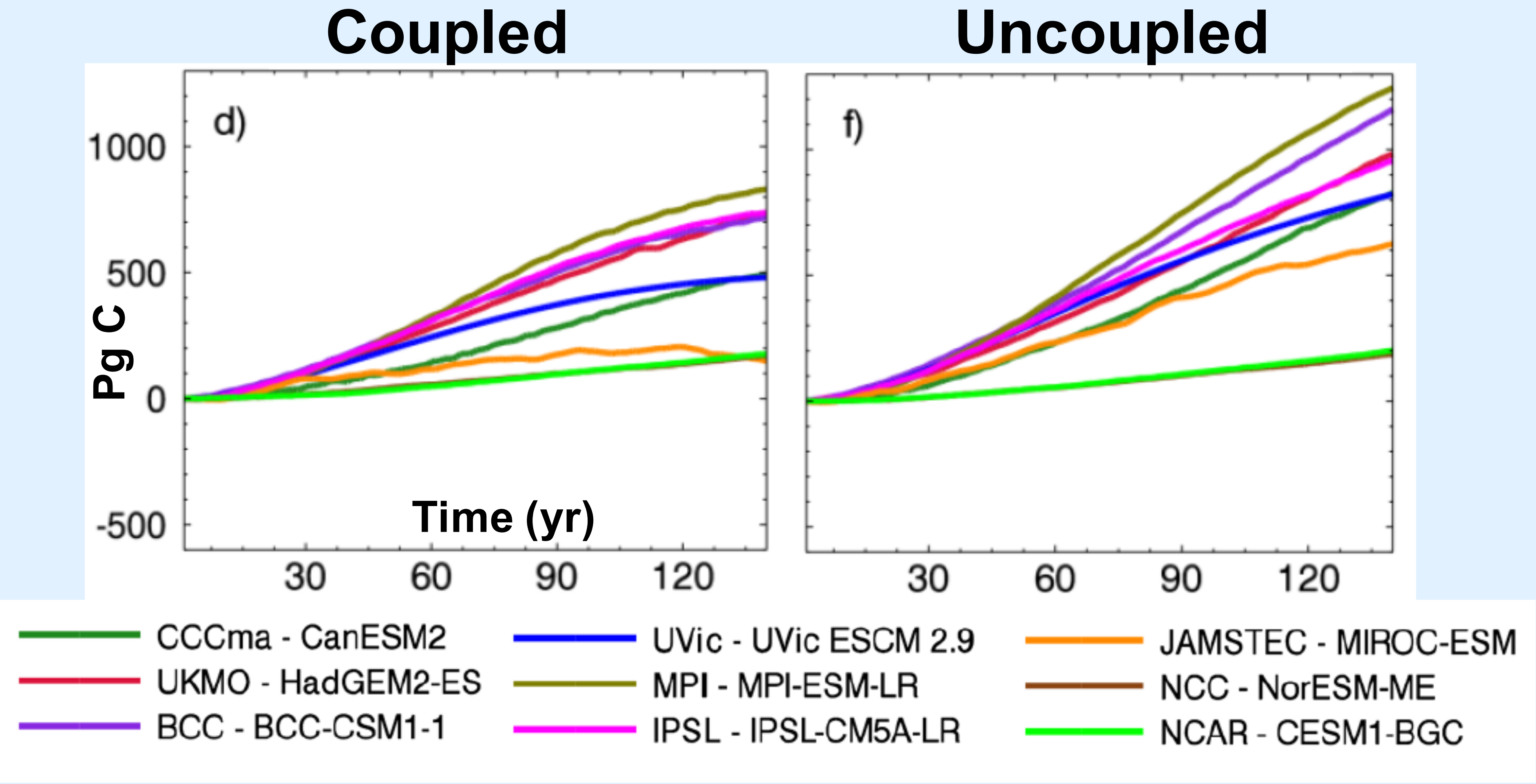
..an honour and a privilege…..

Uncertainties in Climate-Land Carbon Feedbacks

(1% per year increase in CO_2)



Arora et al., 2013

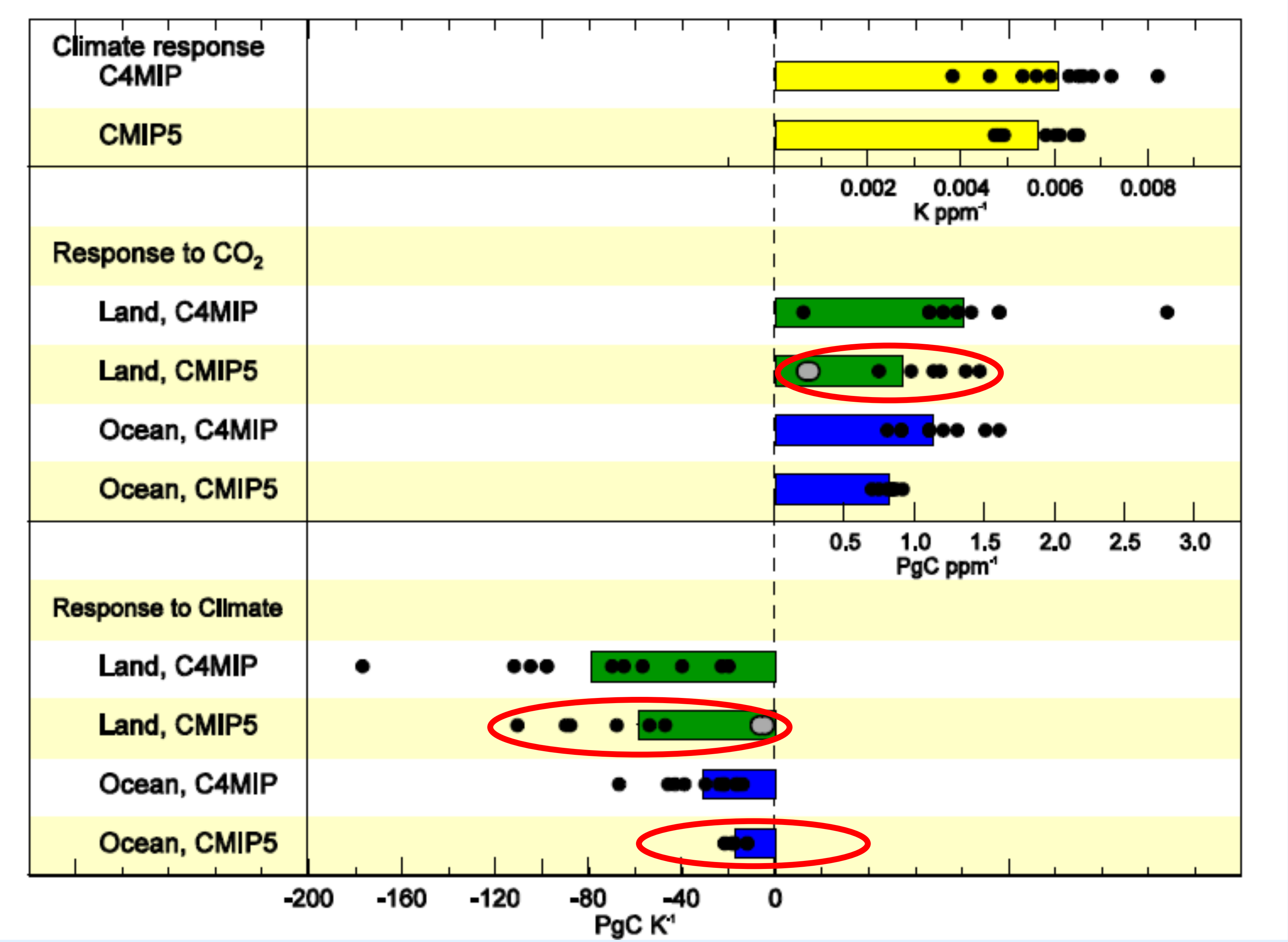
Diagnosis of Climate and CO_2 Effects on Land Carbon Storage

$$\Delta C_L = \beta . \Delta CO_2 + \gamma . \Delta T_L$$

Change in Land Carbon	=	CO_2 Fertilization x Change in CO_2	+	Climate impact on land C x Change in Temperature

Friedlingstein et al., 2003

Uncertainties on Carbon Cycle Feedbacks



The Timescale Problem in the Evaluation of Earth System Models

We need to find constraints on changes in the Earth System over the next century

BUT

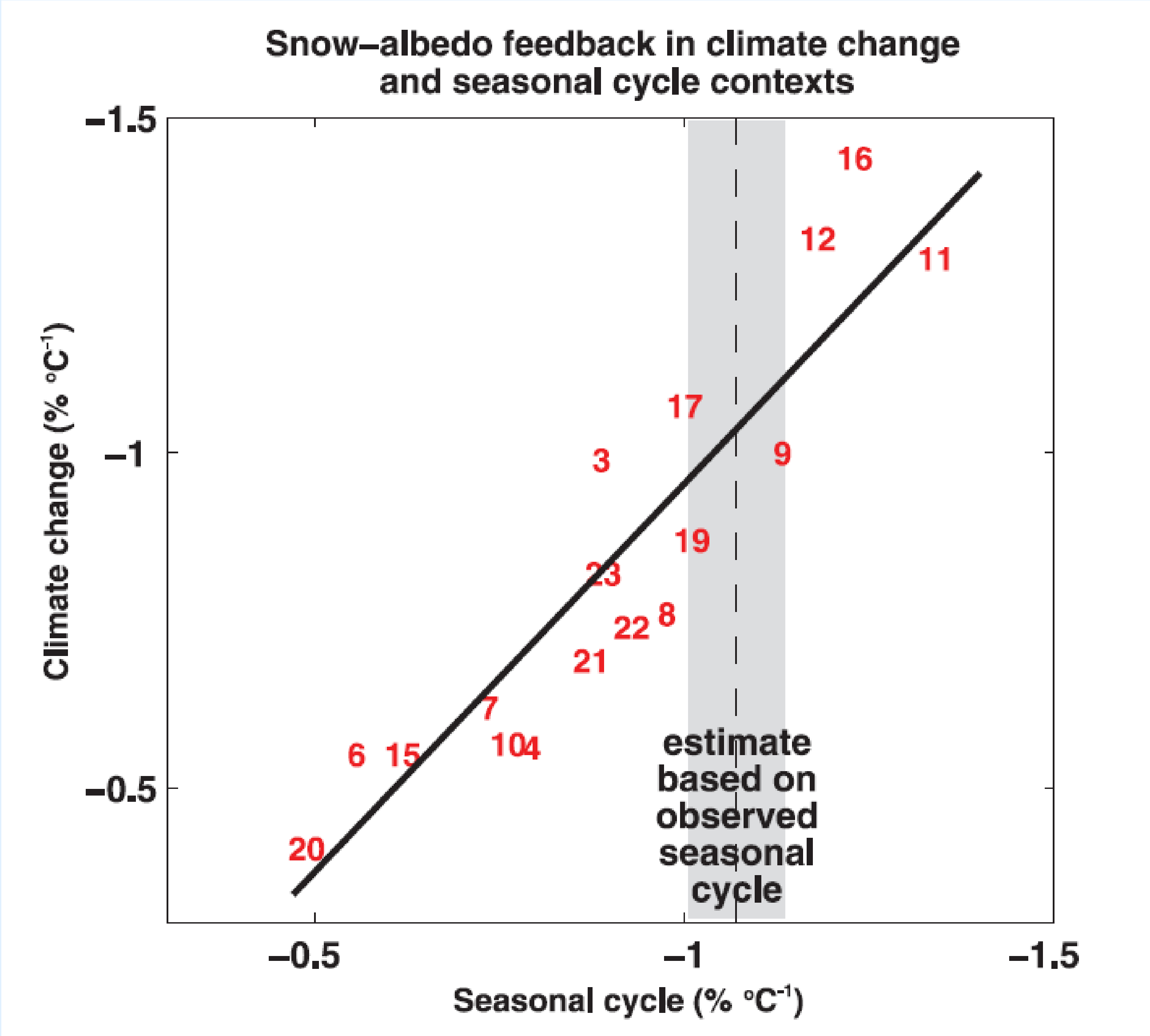
The observational data that we have relates to shorter timescales.

What can we do?

Emergent Constraints:

Using Earth System Models
to identify the relationships between
observable contemporary variations
and future sensitivity

Archetypal Example of an *Emergent Constraint*



Hall & Qu (2006)

..but its not black magic!

Variability and Sensitivity

We expect to find relationships between variability and sensitivity for two main reasons:

a) short-term and long-term changes are often linked by conservation laws (e.g. relationships between changes in carbon fluxes and changes in carbon stores);

Variability and Sensitivity: Stores and Fluxes

- Consider a carbon store, ***C***, that is increased by a flux, ***F***, and has a turnover time, $\boldsymbol{\tau}$:

$$\frac{dC}{dt} + \frac{C}{\tau} = F$$

- The equilibrium solution of the carbon store is give by:

$$C_{eq} = \tau \ F$$

Variability and Sensitivity: Stores and Fluxes

- Thus the sensitivity of the store to an environmental variable ***T***, is:

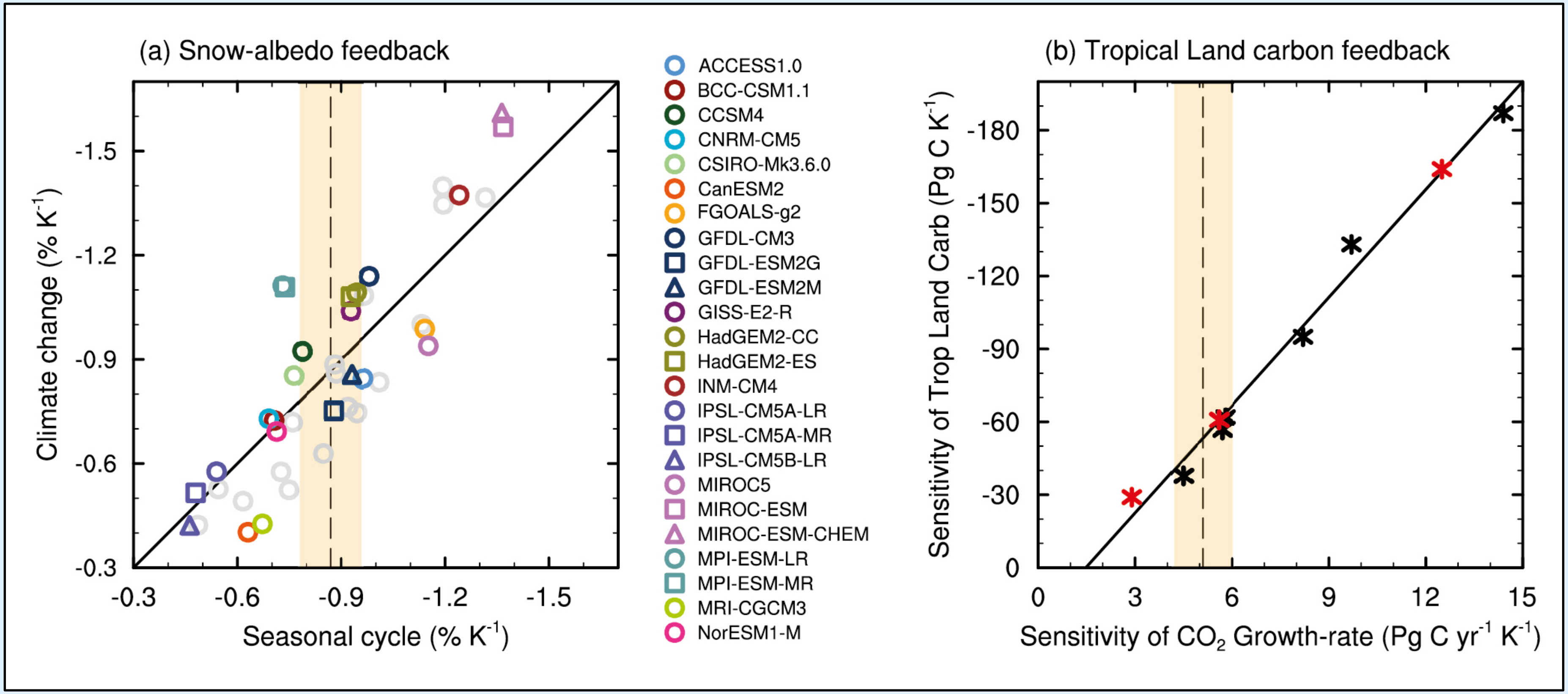
$$\frac{dC_{eq}}{dT} = \tau \frac{dF}{dT} + F \frac{d\tau}{dT} = \tau \frac{dN}{dT}$$

where ***N*** is the net flux:

$$N = F \left\{ 1 + \frac{1}{\tau} \frac{d\tau}{dT} \right\}$$

- If **τ** is near-constant across models, we therefore expect to find an Emergent Relationship between the sensitivity of the net flux to ***T*** (***dN/dT***) and the sensitivity of the store to ***T*** (***dC/dT***).

Emergent Constraints in IPCC AR5



After Hall & Qu (2006)

After Cox et al. (2013)

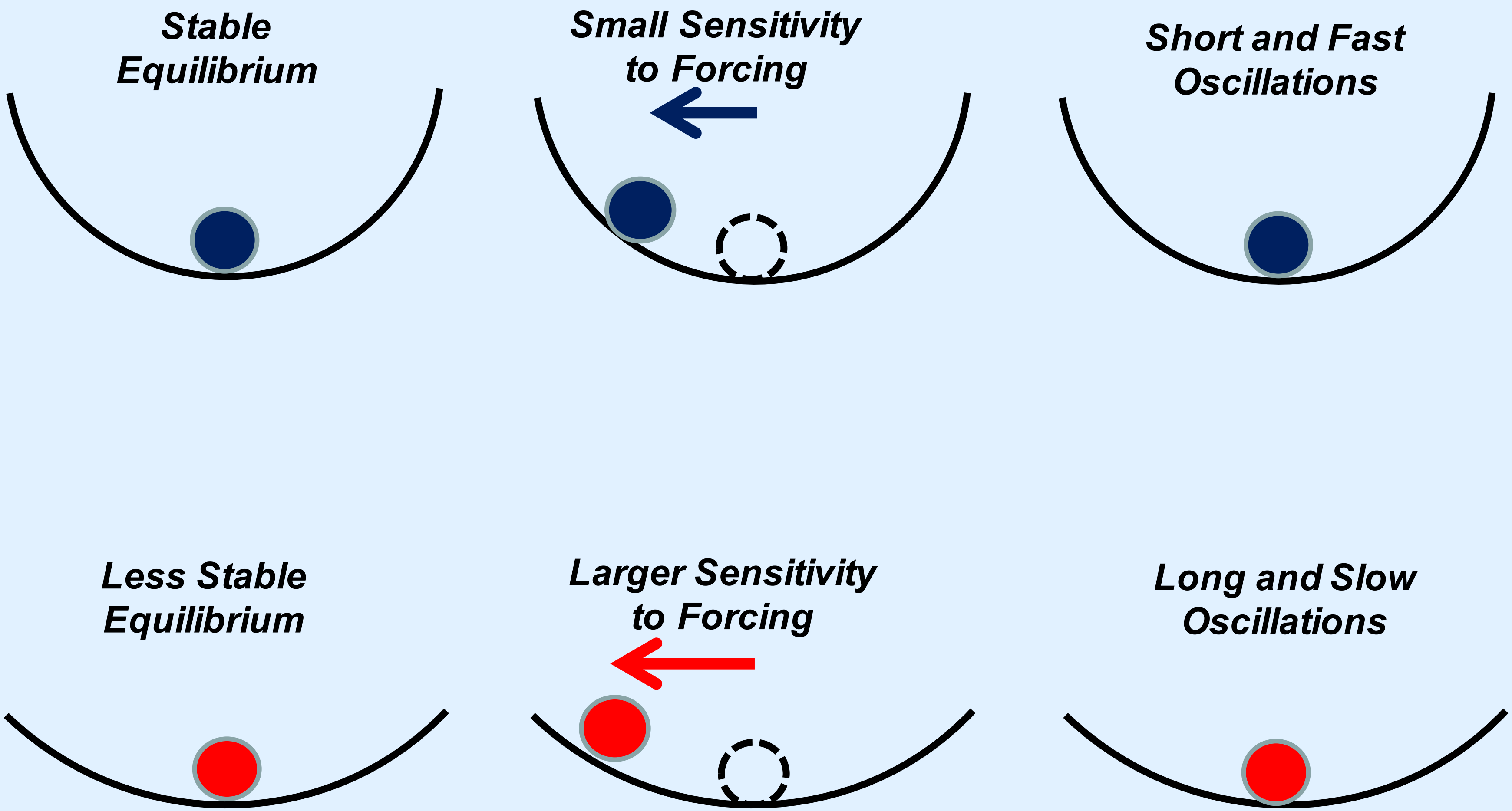
Variability and Sensitivity

We expect to find relationships between variability and sensitivity for two main reasons:

a) short-term and long-term changes are often linked by conservation laws (e.g. relationships between changes in carbon fluxes and changes in carbon stores);

b) there are theoretical reasons (e.g. the *Fluctuation-Dissipation Theorem*) to expect variability and sensitivity to be linked in a large-class of (*near-linear*) systems.

Stability, Sensitivity and Variability



A system is defined by its “noise’…

“That’s not white noise. That’s the ocean”

Emergent Constraints

- **Emergent** because it a relationship that emerges from the ensemble of ESM projections.
- **Constraint** because it enables an observation to constrain the estimate of the ES sensitivity in the real world.
- *Allow model ensembles to be more than the sum of the parts.*
- *Identify metrics of current system which are most relevant to projected changes.*

"Recipe" for Finding Emergent Constraints

1. Identify a key uncertainty in future projections.

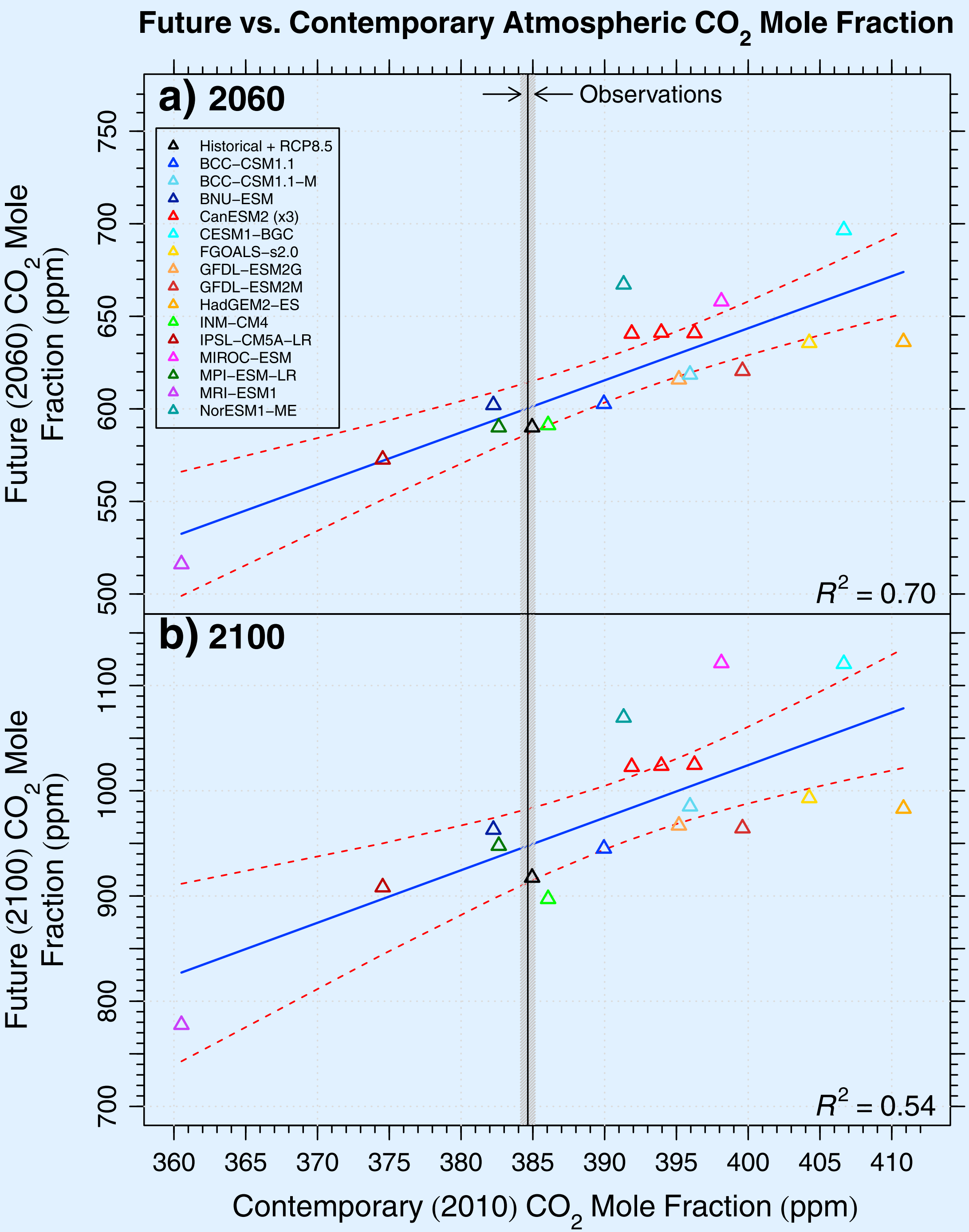
Actually, we often start with an interesting observation

2. Identify observed trend or variability that could plausibly be related to that uncertainty.

3. Check for an *Emergent Relationship* between the Uncertainty and the Observation, across the ESM ensemble.

4. Apply the *Observational Constraint* to the *Emergent Relationship*, to derive an *Emergent Constraint* on the key uncertainty in future projections.

Trend-on-trend Emergent Constraints



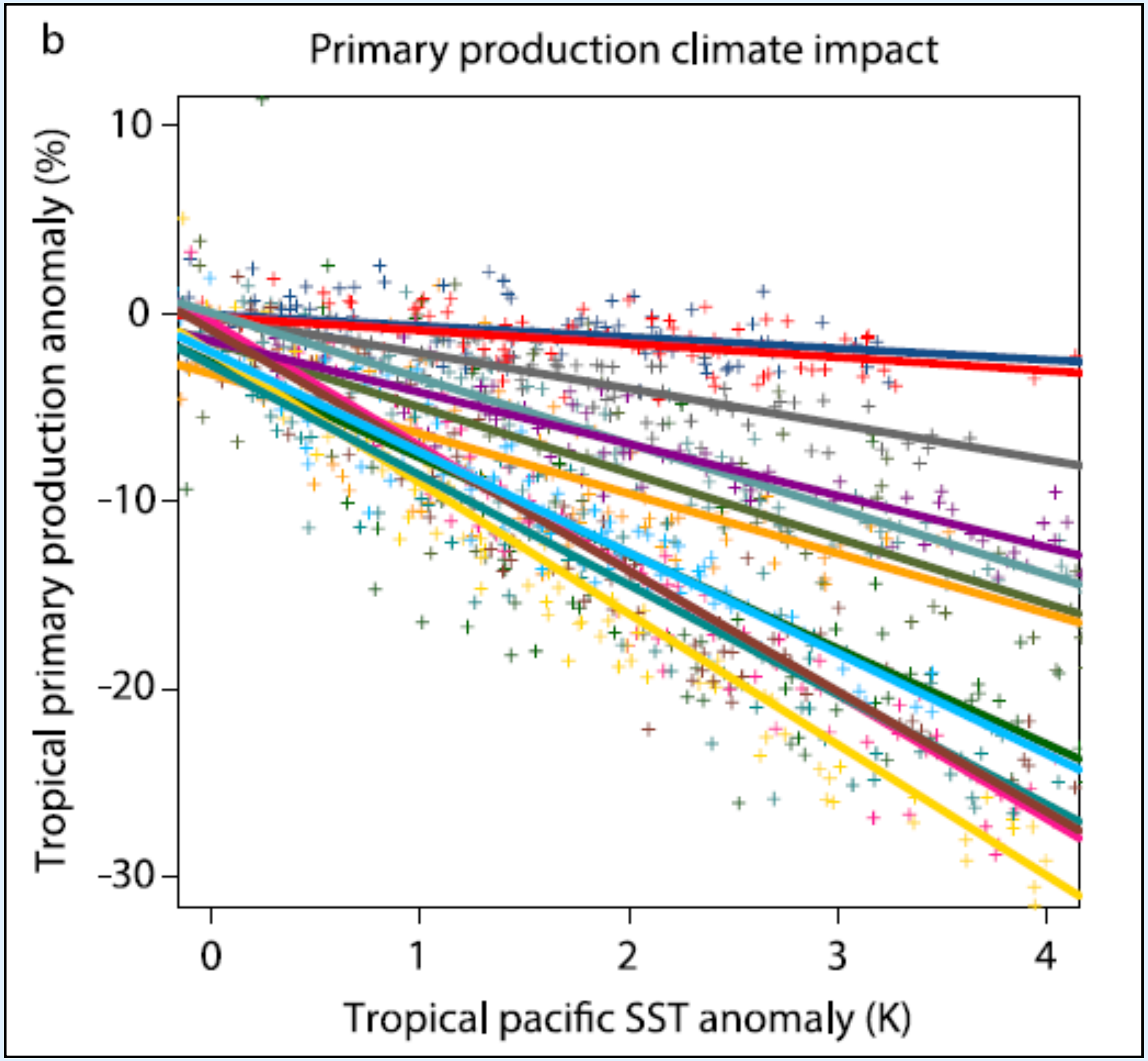
Hoffman *et al.*, 2014

Emergent Constraint on Reduction in Ocean Primary Production with Global Warming

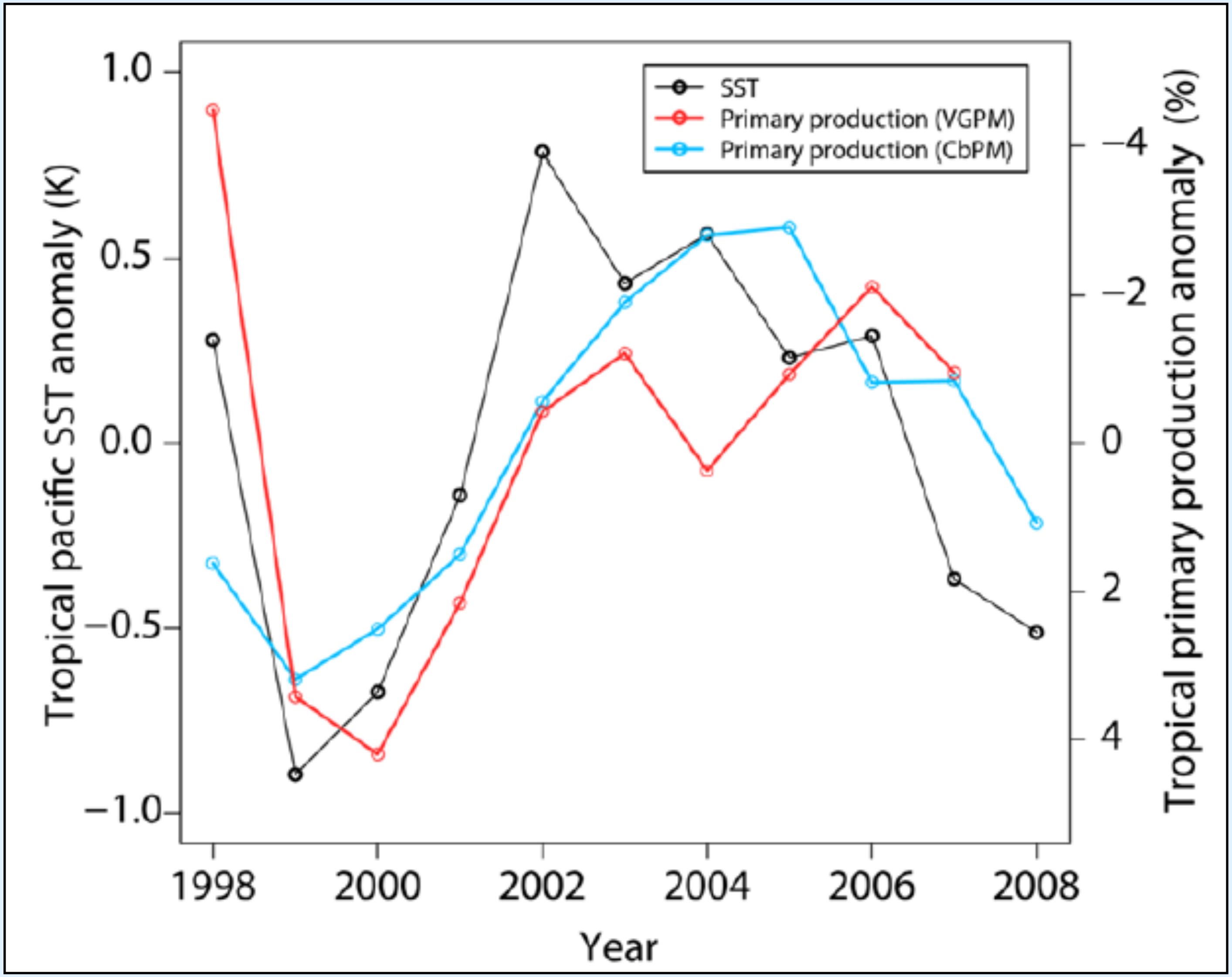
from interannual variability in Chlorophyll

Kwiatkowski *et al*., 2017

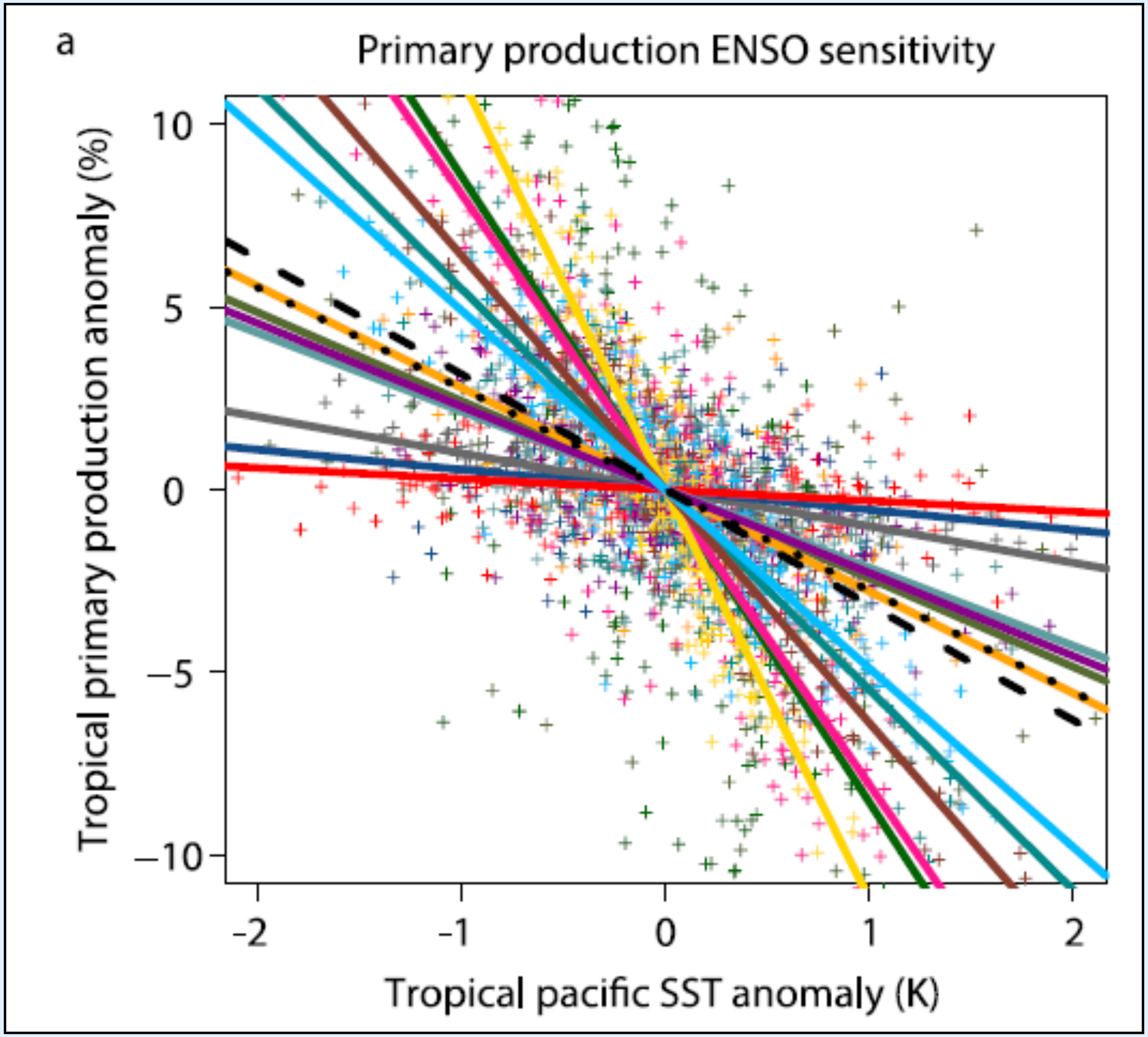
The Unknown: Sensitivity of Ocean Primary Production to Warming



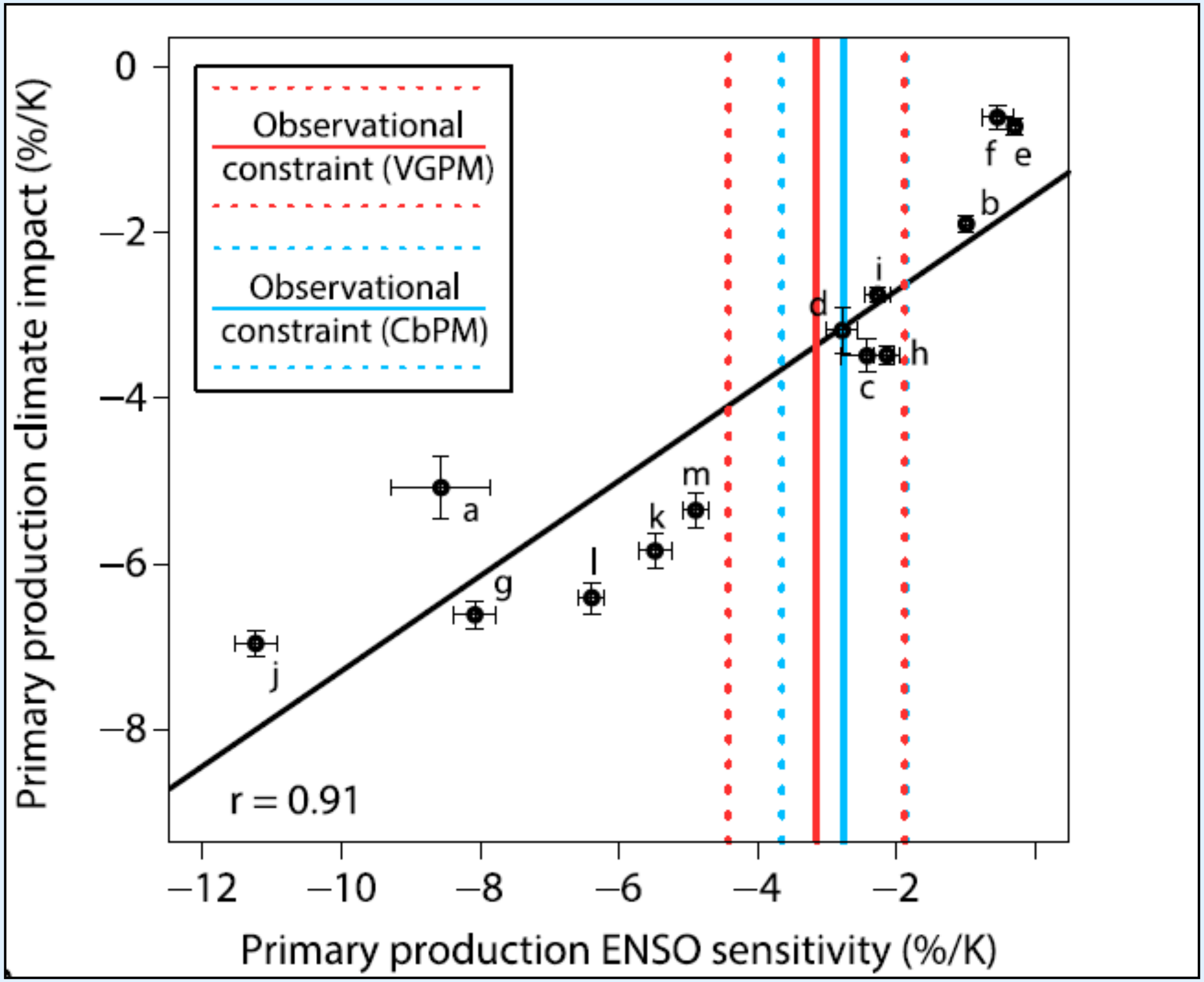
Observations: Variation in Primary Production (~Chlorophyll) and SST in Tropical Pacific



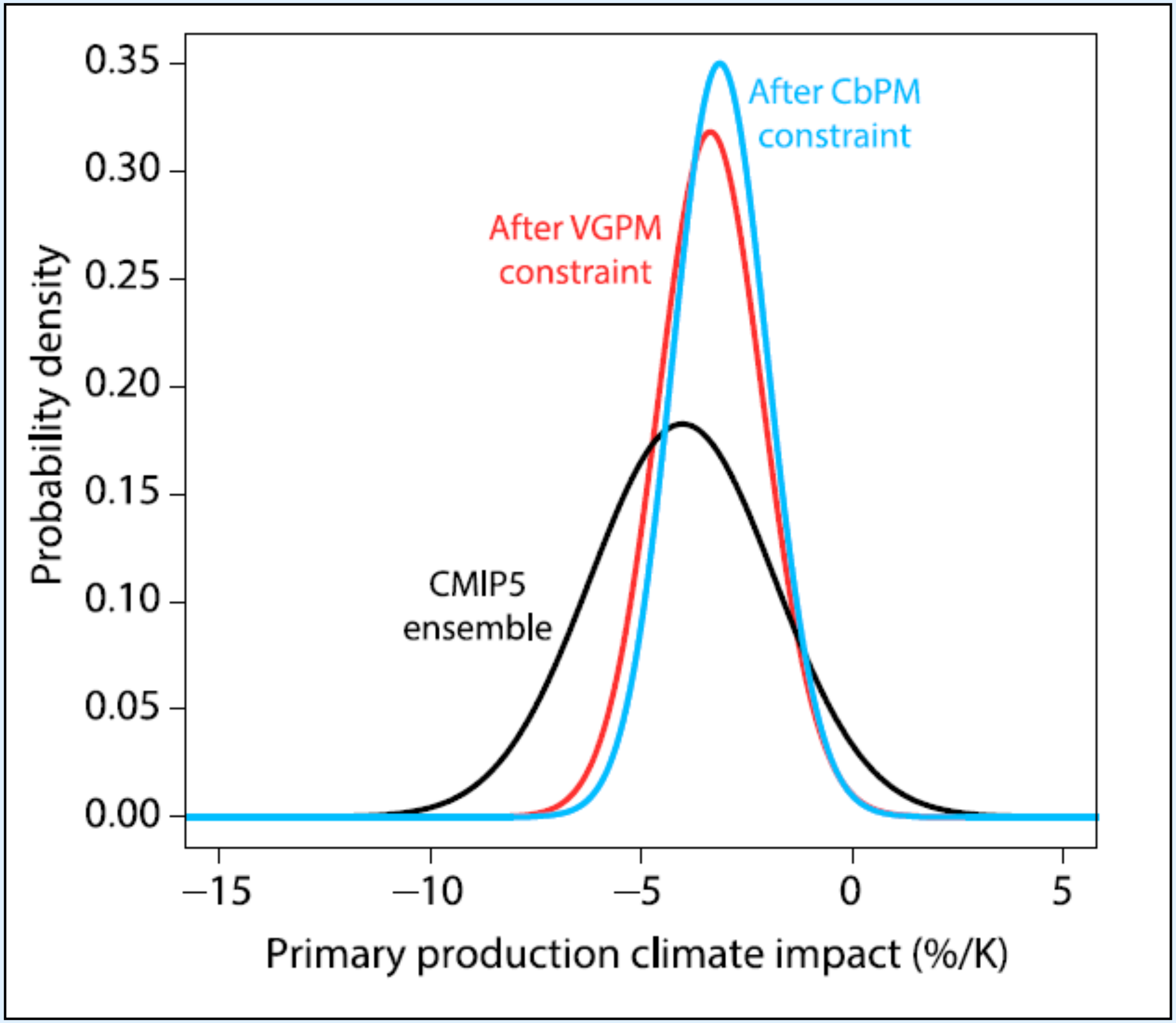
Models vs Data: Interannual Sensitivity



The Emergent Relationship:
Interannual versus Long-term Sensitivity



The Emergent Constraint: Sensitivity of Tropical Ocean Primary Production to Future Warming

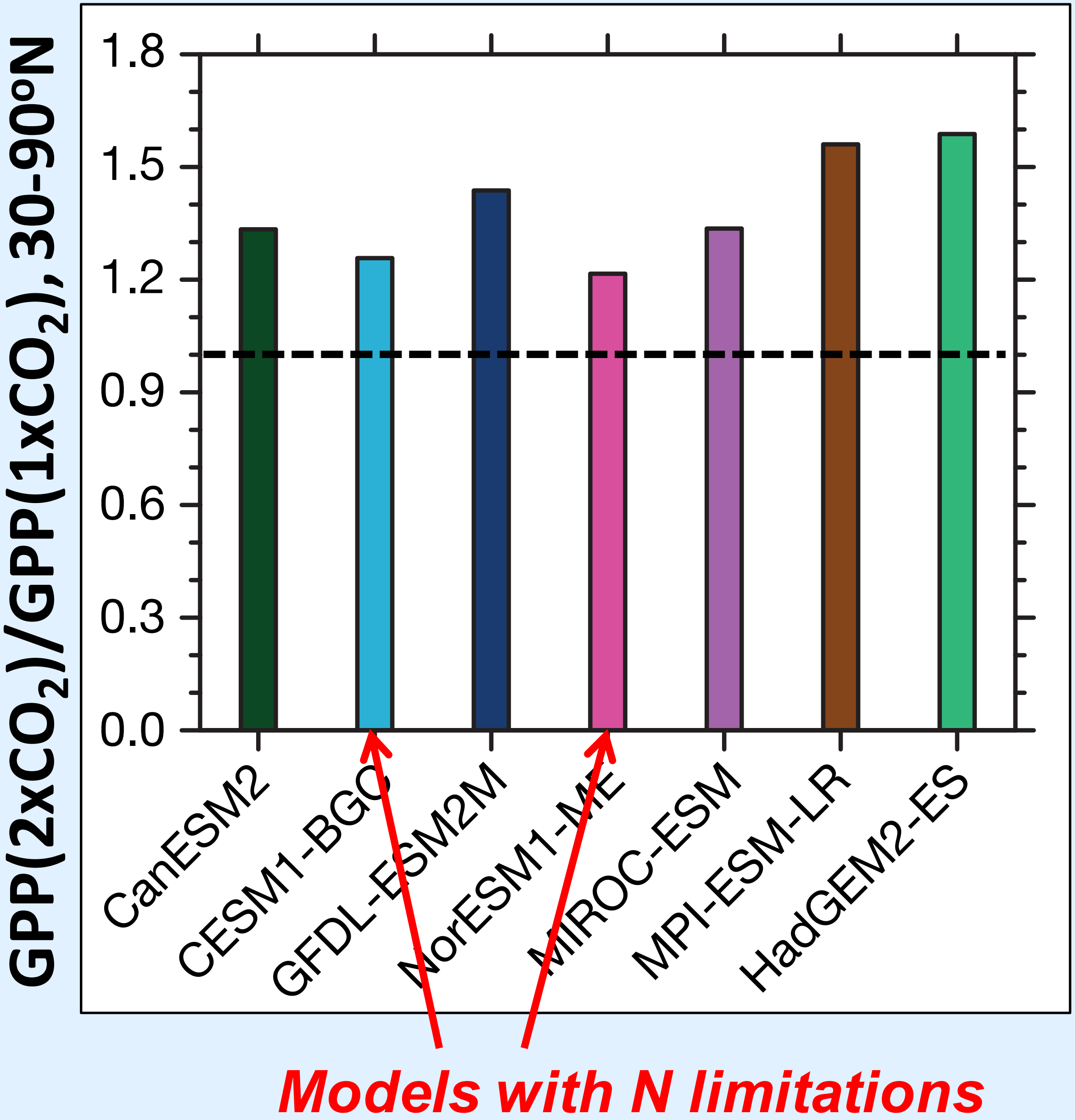


An Emergent Constraint on CO_2 Fertilization of Photosynthesis, *from trends in the CO_2 seasonal cycle*

Wenzel *et al.*, *Nature*, 2016

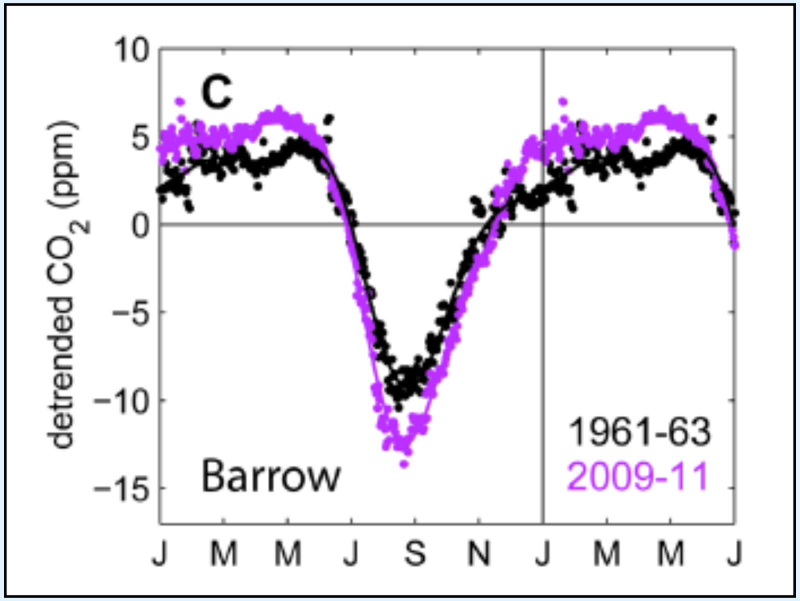
The Unknown: CO_2 Fertilization of Photosynthesis

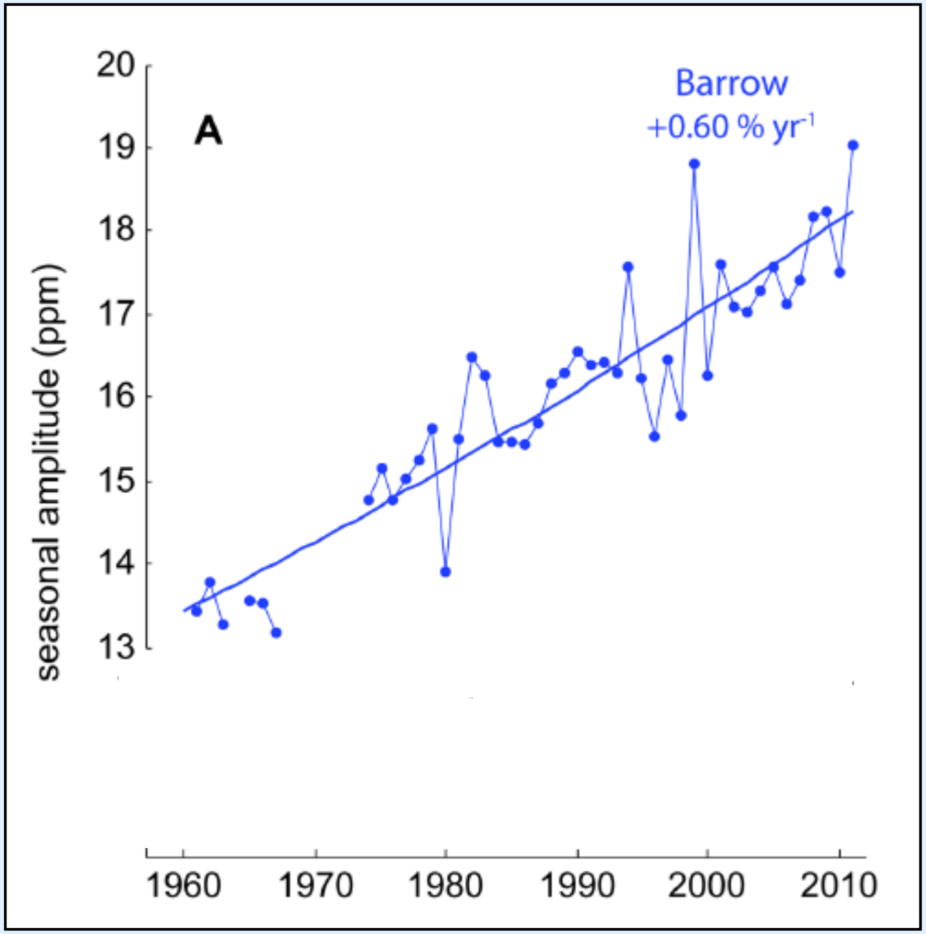
20% to 60% projected increase of GPP due to doubling CO_2



Wenzel et al., 2016

The Observations: Increasing Seasonal Amplitude of Atmospheric CO_2

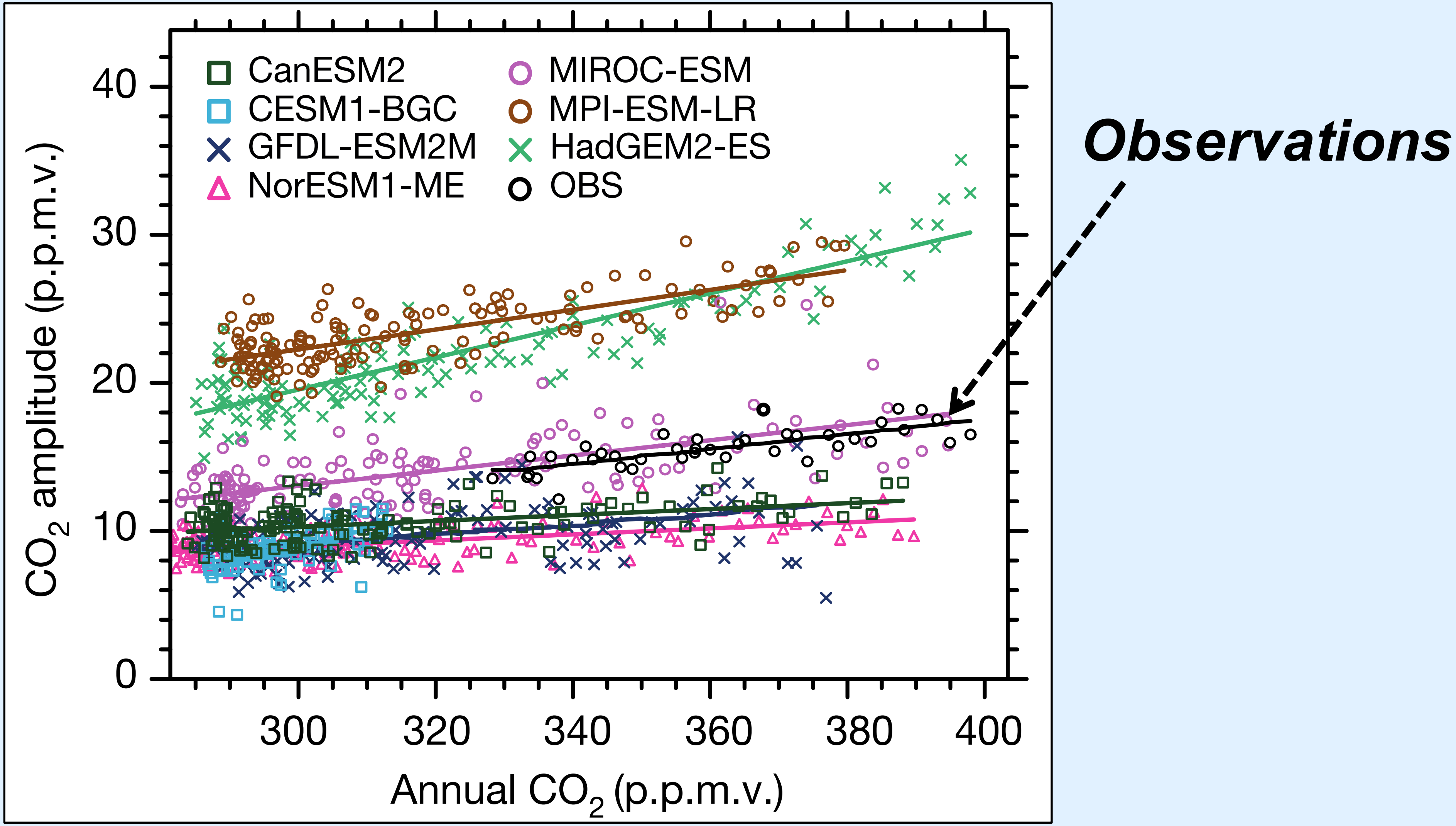




Graven et al., 2013

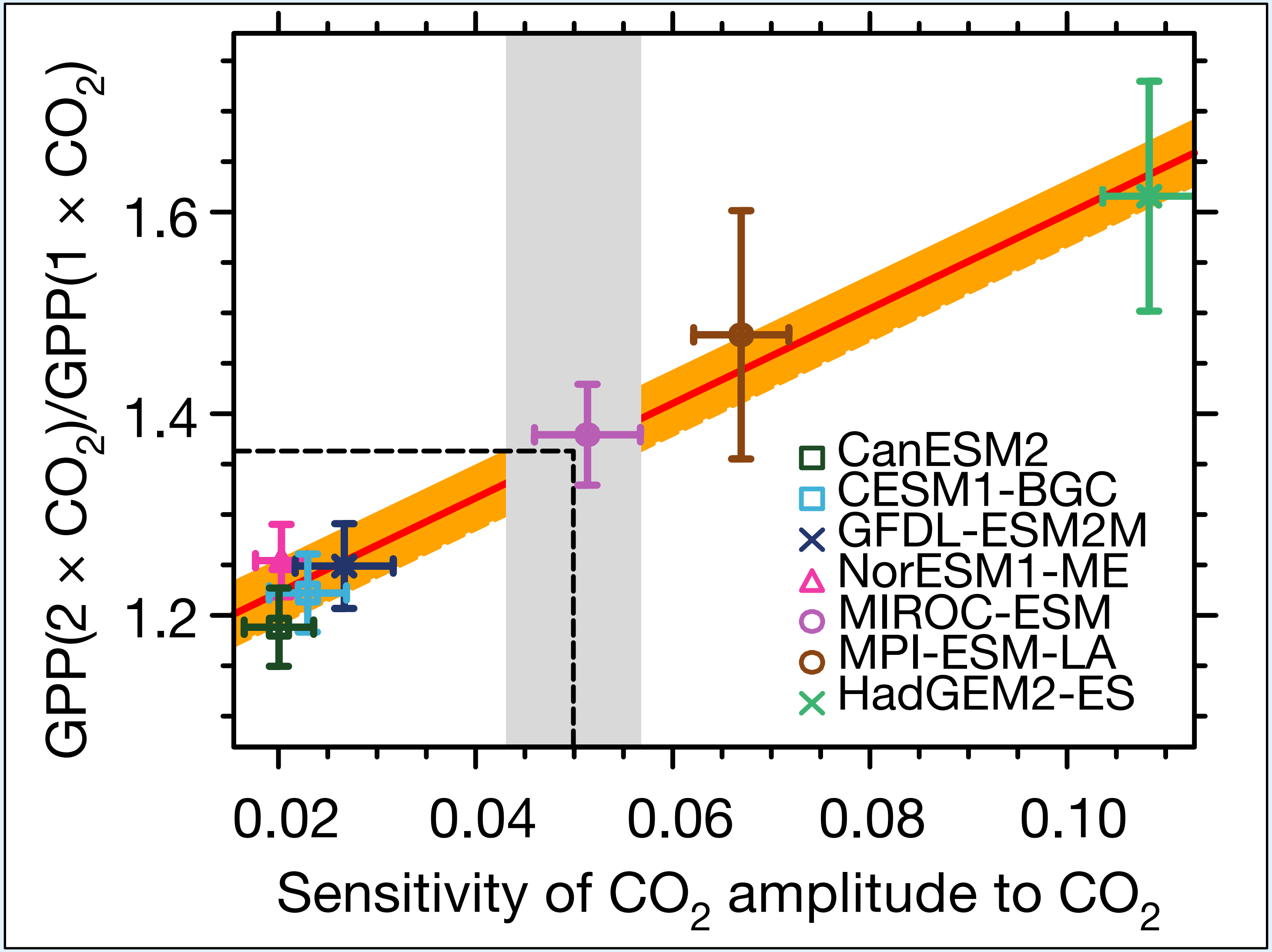
Comparing Models to Data:

BRW CO_2 Amplitude against Annual Mean CO_2



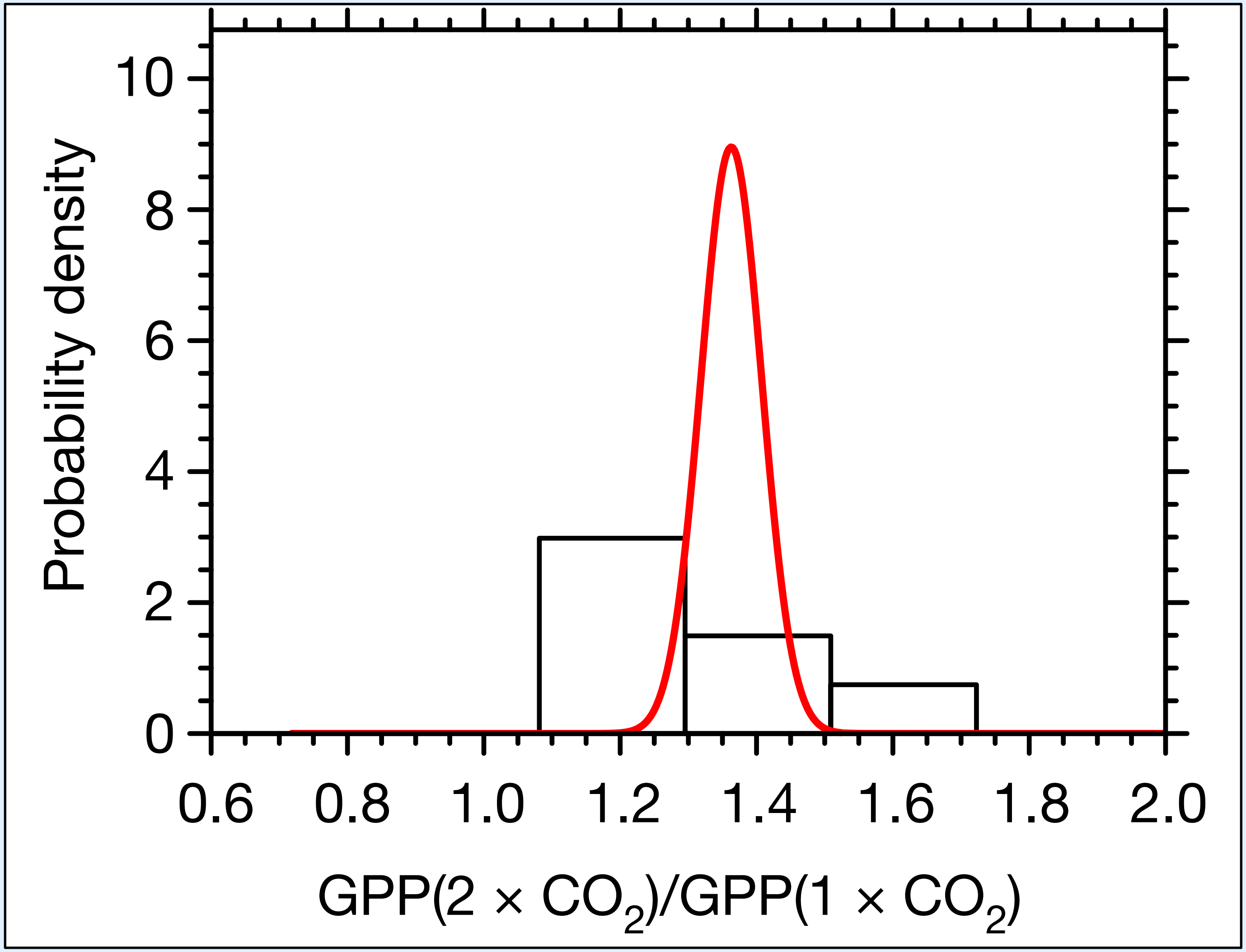
Wenzel et al., 2016

The Emergent Relationship



Wenzel et al., 2016

The Emergent Constraint: PDF of CO_2 Fertilization

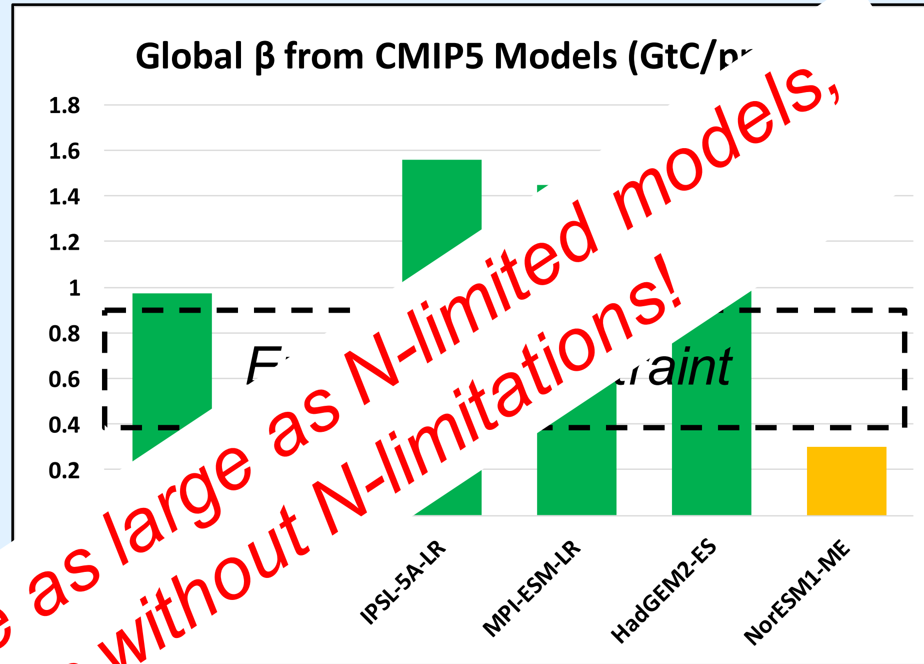


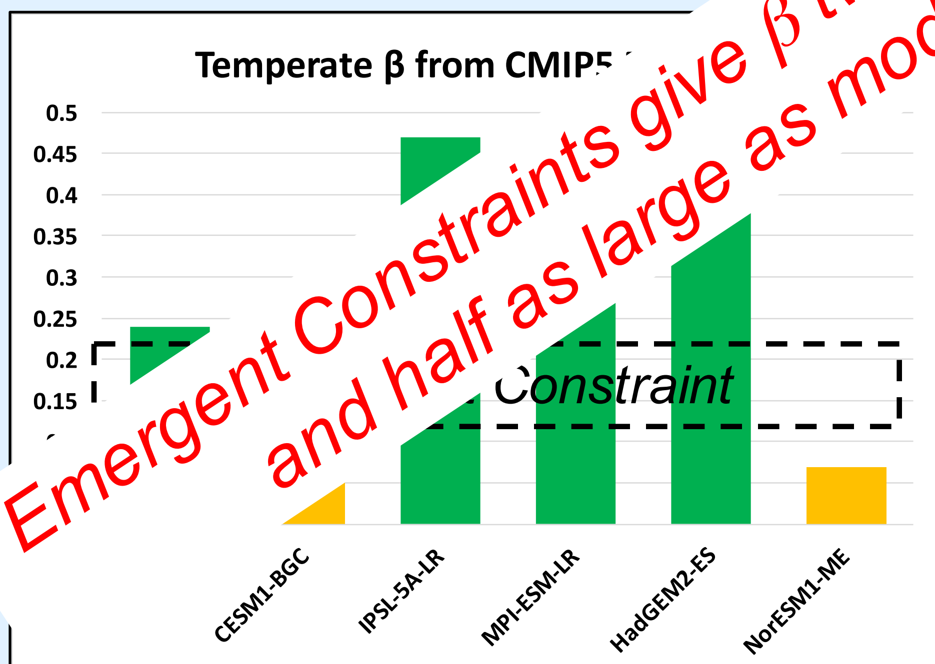
Wenzel et al., 2016

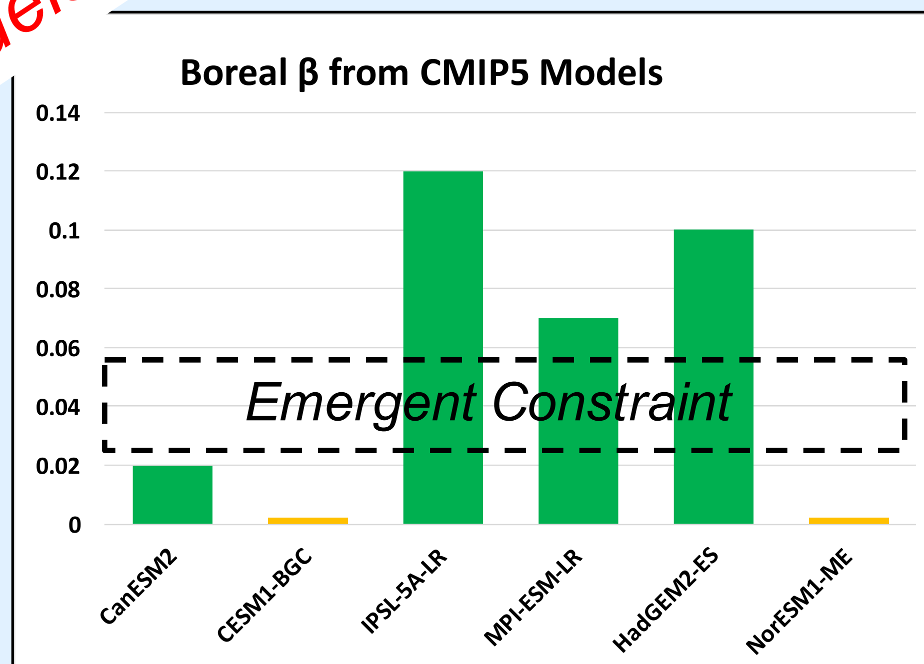
Emergent Constraints on CO_2 Fertilization of Land Carbon Stores, *from trends in the CO_2 seasonal cycle*

Jones, Cox, *in prep*

The Unknown: Direct CO_2 Effect on Land Carbon Storage







Emergent Constraints give β twice as large as N-limited models, and half as large as models without N-limitations!

Conclusions

- Emergent constraints relate observable variability to future sensitivity, using an ensemble of Earth System Models to reduce uncertainty.
- Recently, Emergent Constraints have been identified on the loss of tropical land carbon due to climate change; on CO_2 fertilization of photosynthesis in the high-lats; and on reductions in tropical ocean primary production under global warming.
- ***Great promise of further Emergent Constraints relating observed spatial variability (e.g. Chadburn et al., 2017) to Earth System sensitivities…***

..but dangerously seductive……

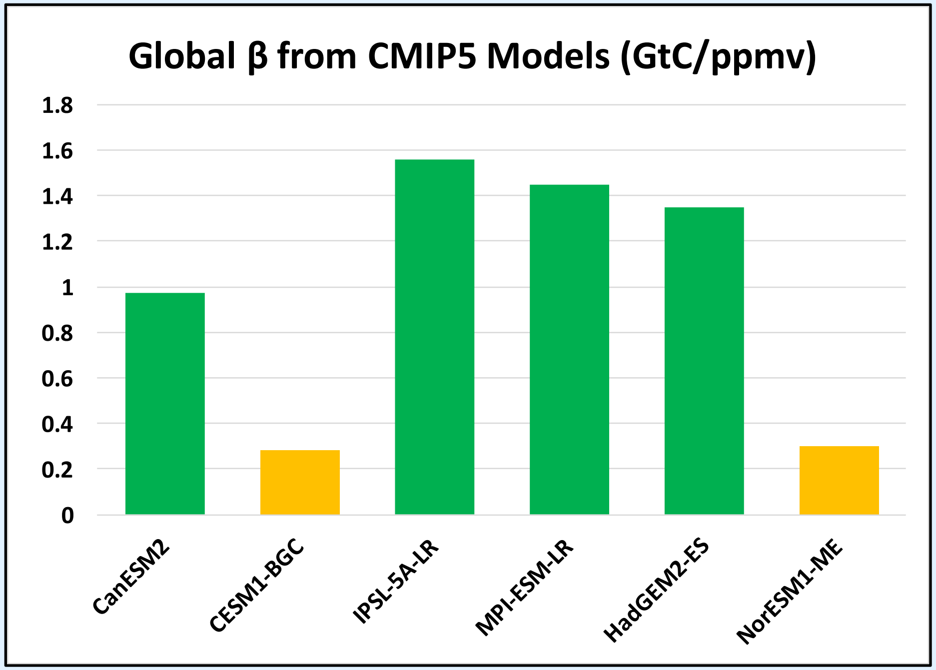
… so note Caldwell *et al*. (2014)

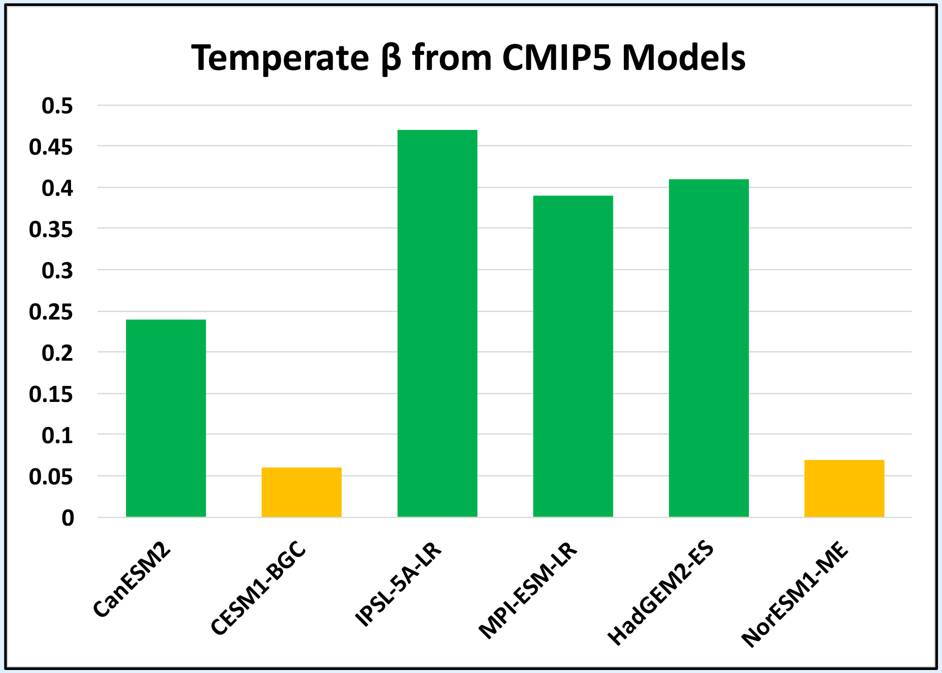
Don’t worry!!

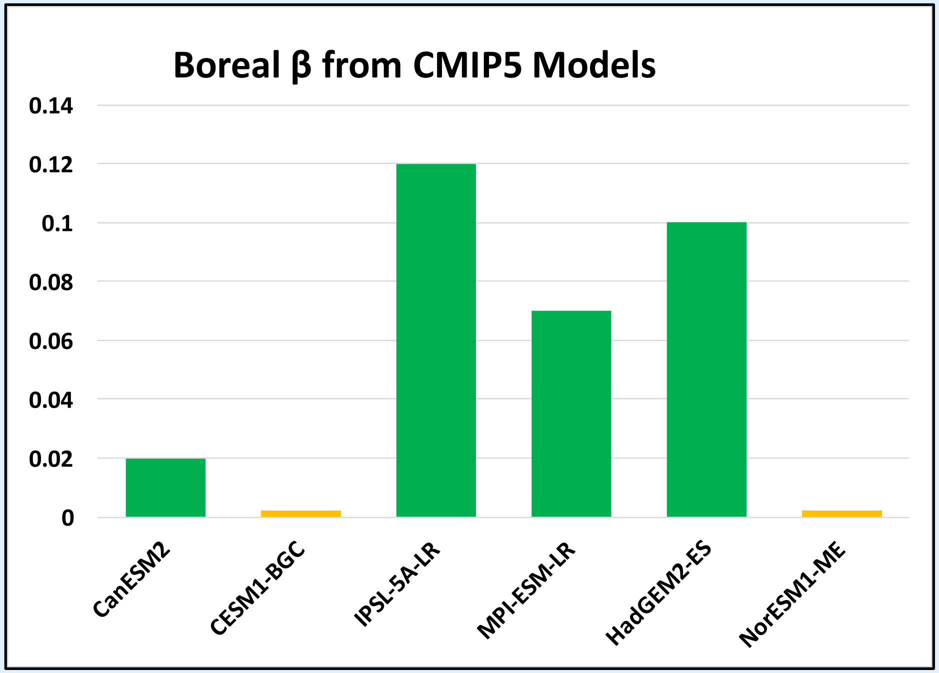
I’m planning to stop here …. ☺

The Unknown:

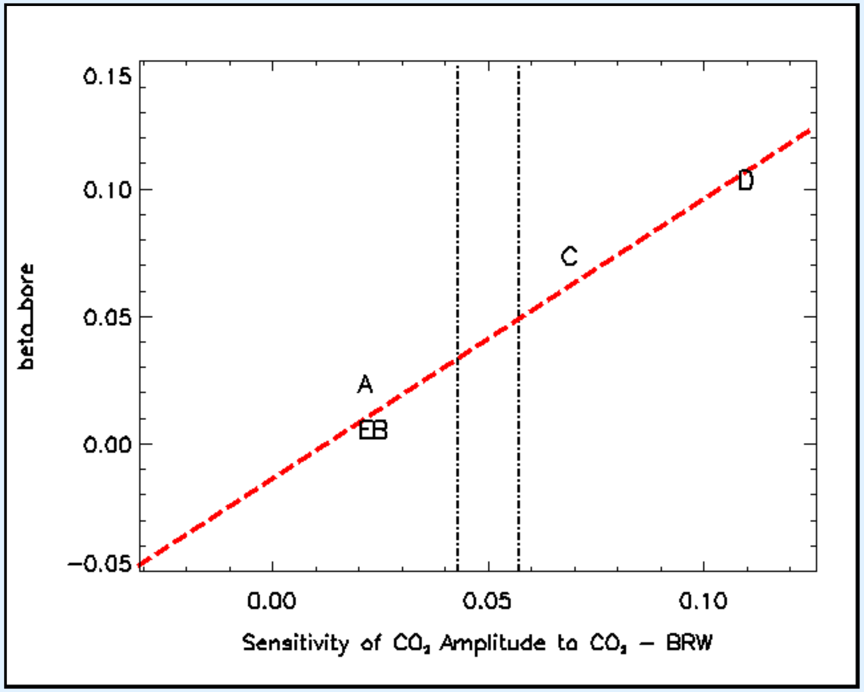
Direct CO_2 Effect on Land Carbon Storage

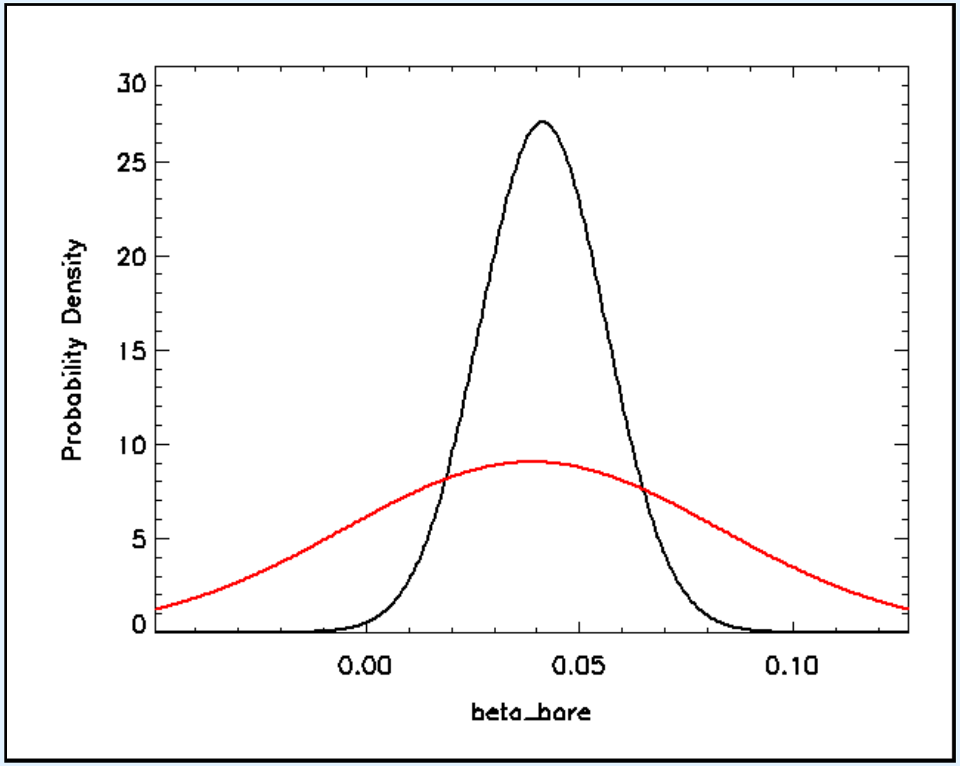






Boreal β versus BRW Seasonal Cycle





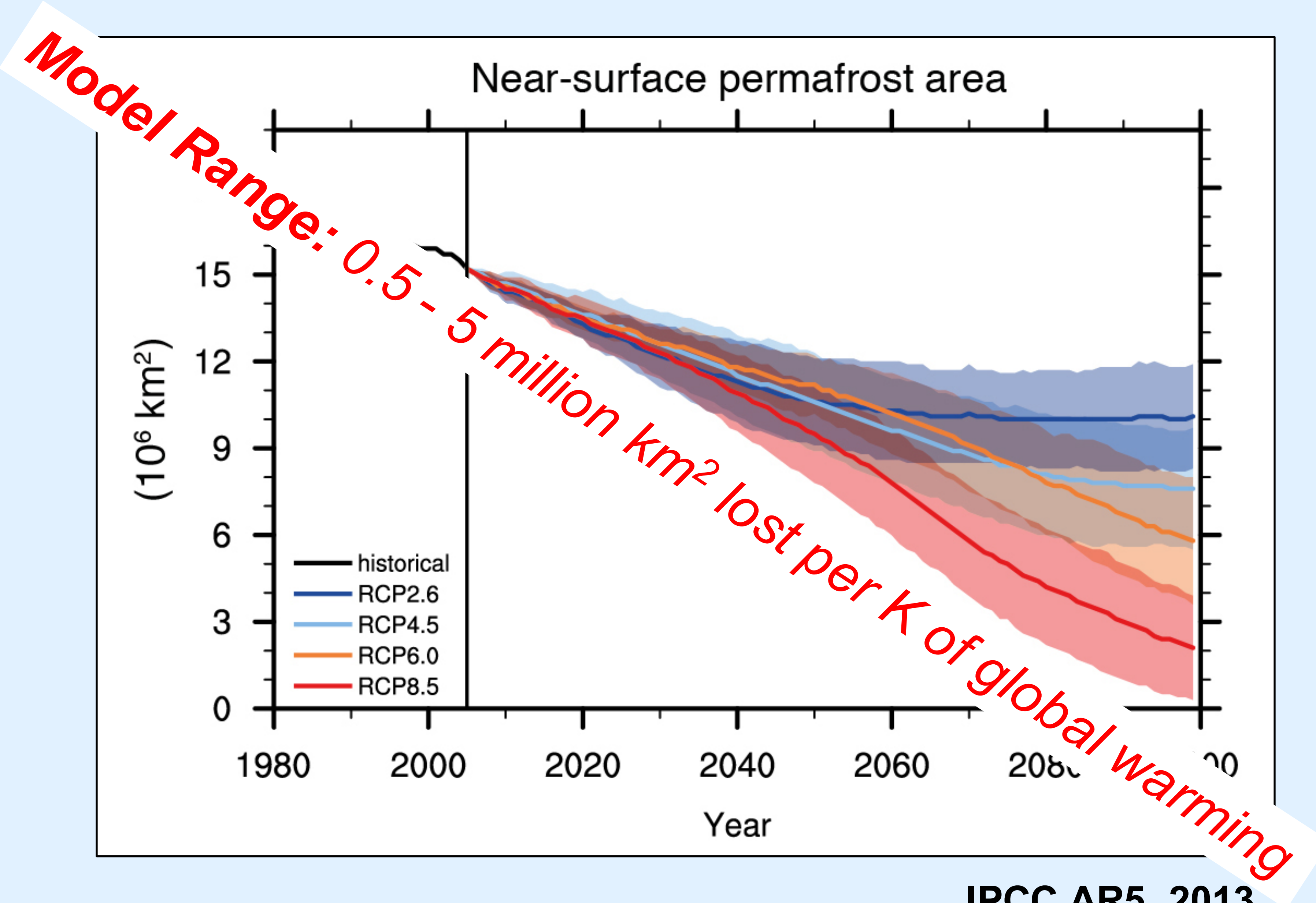
Emergent Constraint: β_{bore} **= 0.041 +/- 0.015 GtC/ppmv**

An Emergent Constraint on Sensitivity of Permafrost Area to Warming

from observed spatial variability in temperature and permafrost area

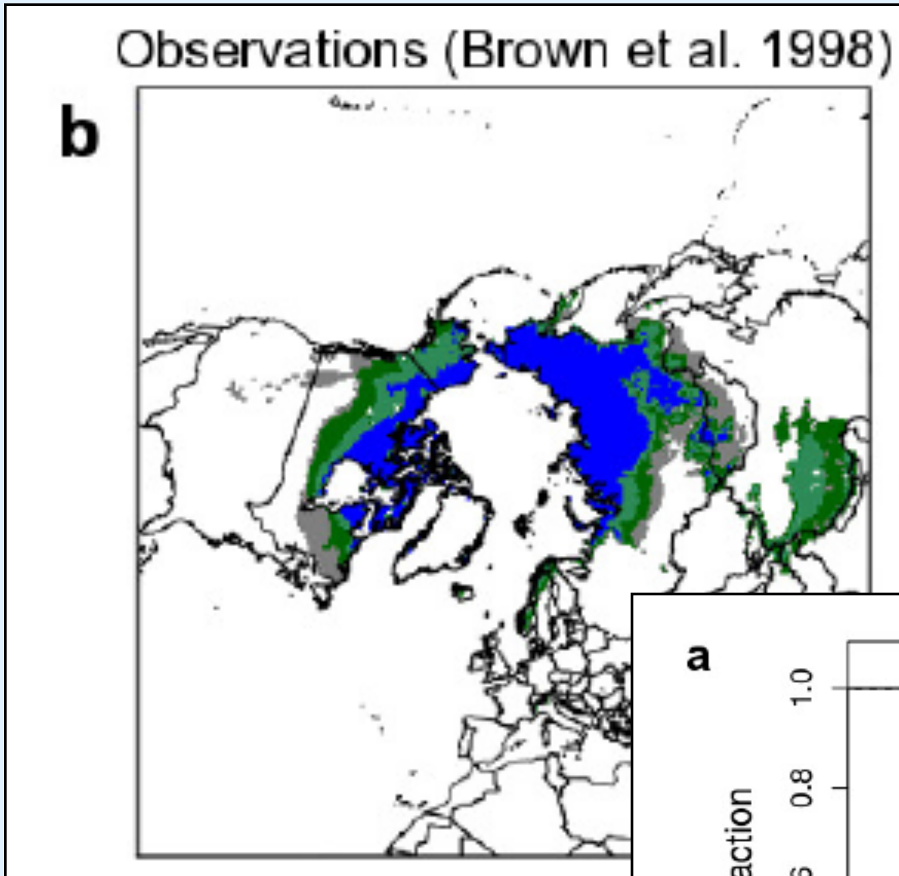
Chadburn *et al.*, *Nature Climate Change*, **2017**

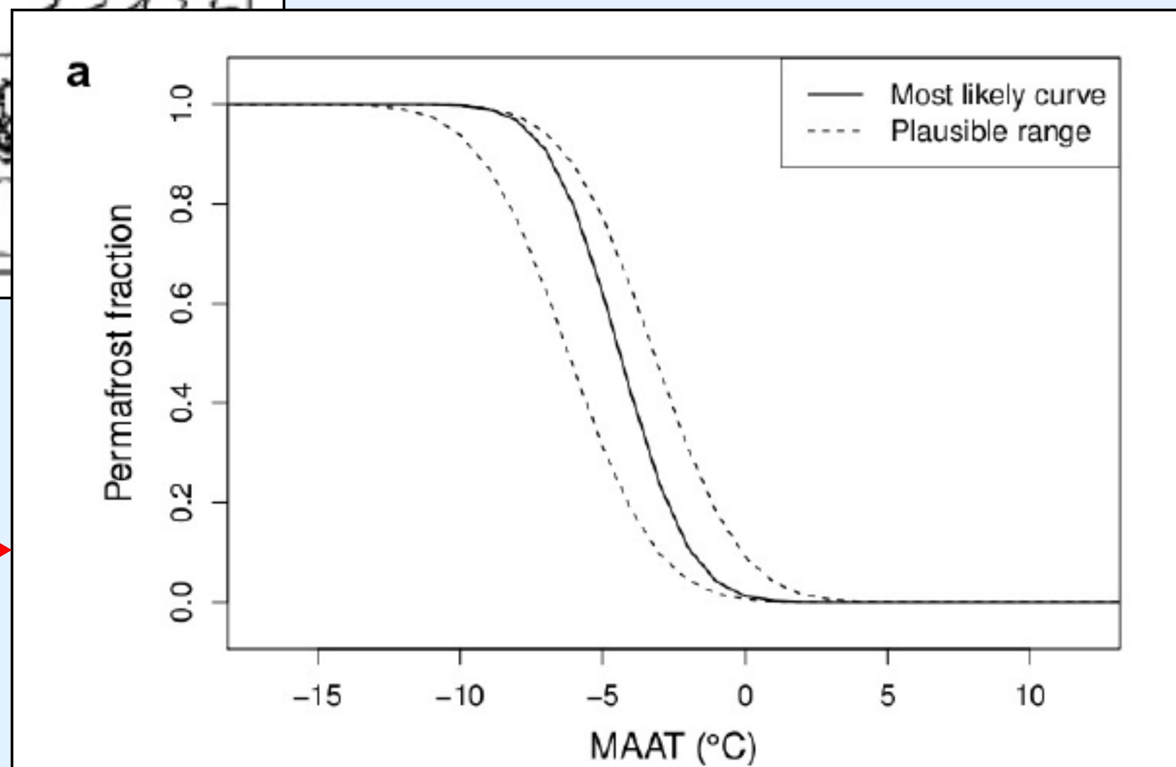
The Unknown: Future Permafrost Area



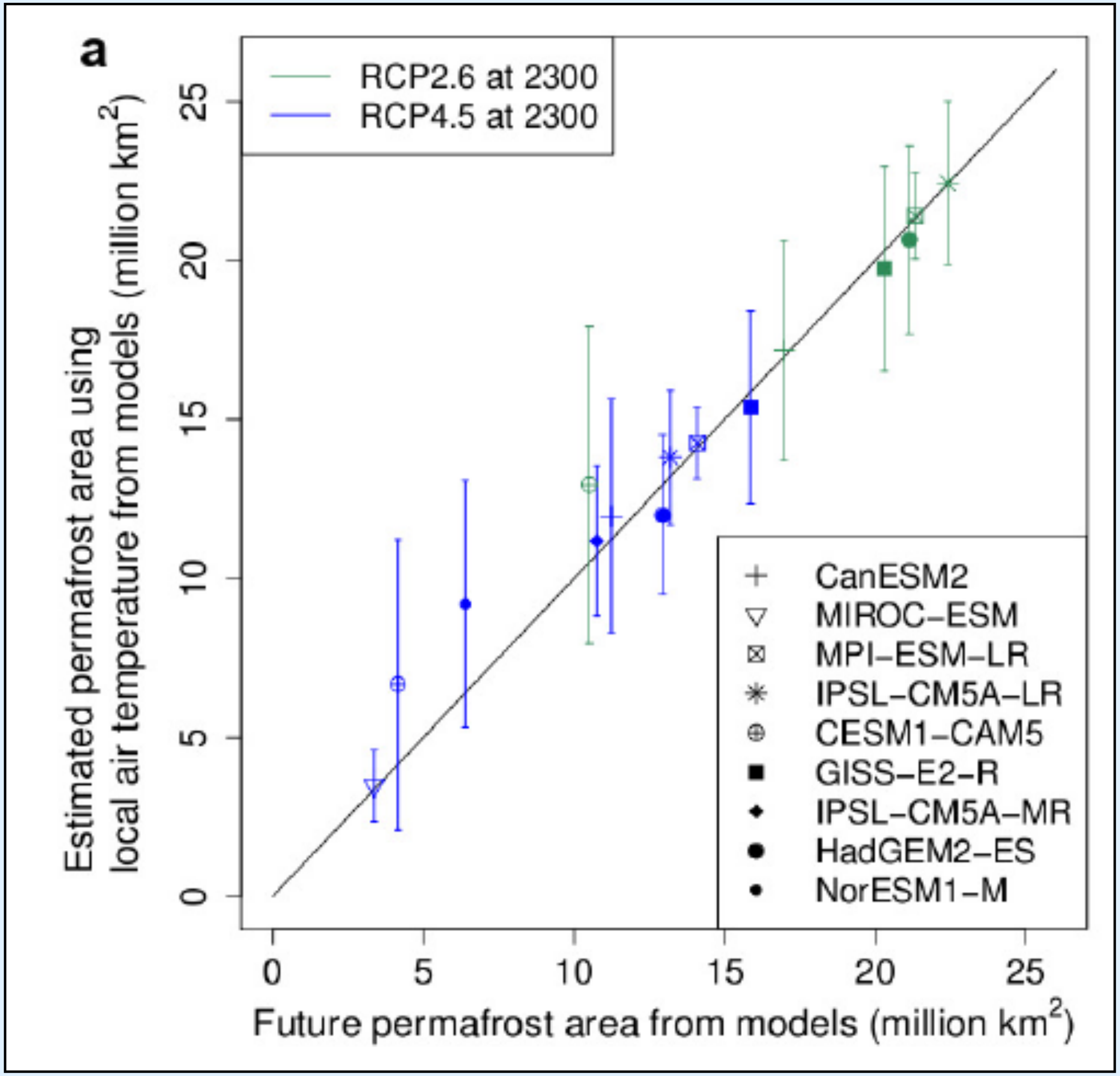
IPCC AR5, 2013

Observations: Current Permafrost Area and Air Temperature

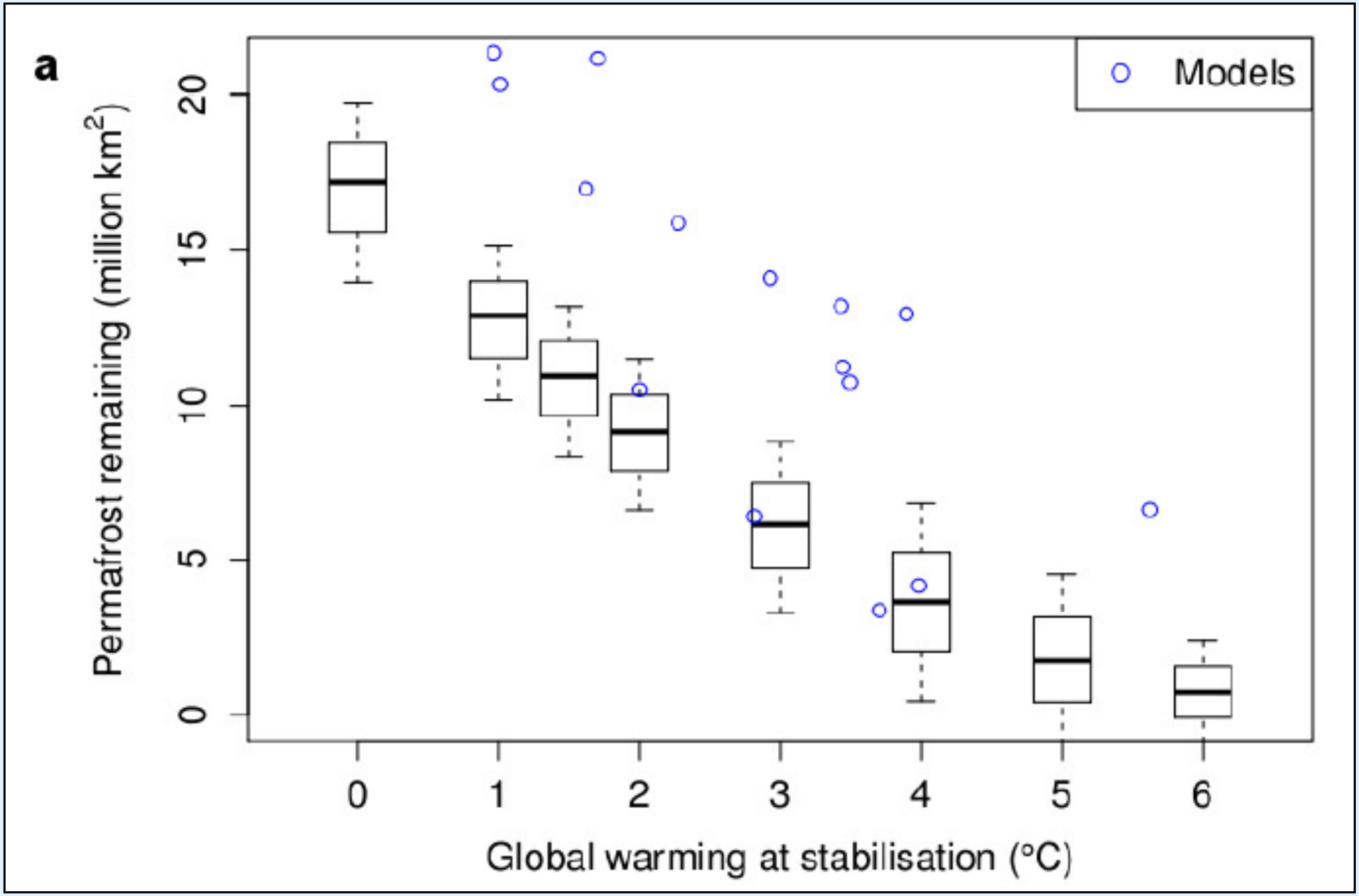




The Emergent Relationship: Estimating Projections from Spatial Variability of Control State



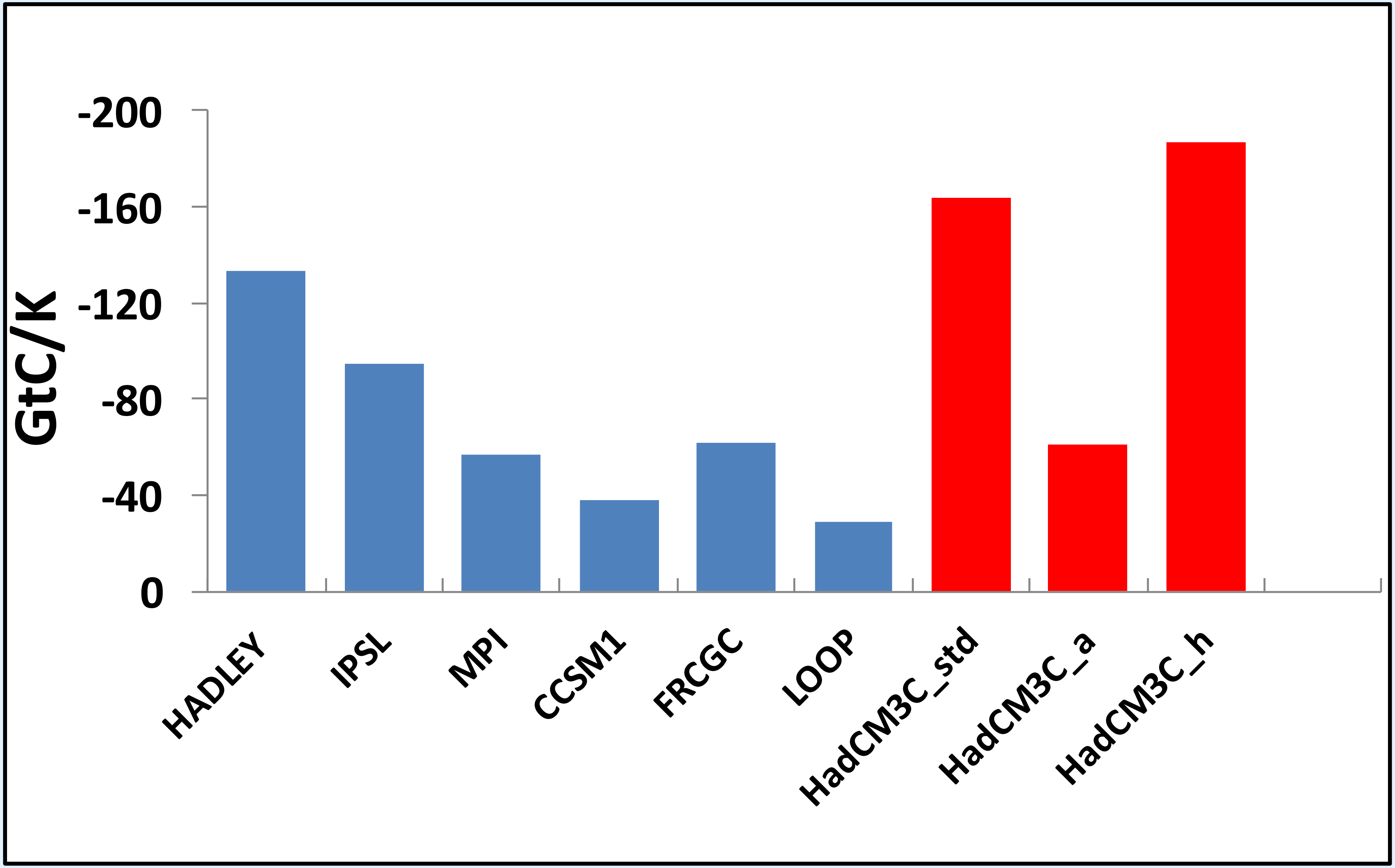
The Emergent Constraint: Sensitivity of Permafrost Area to Future Warming



An Emergent Constraint on Carbon Loss from Tropical Land due to Climate Change, *from interannual variability in atmospheric CO_2*

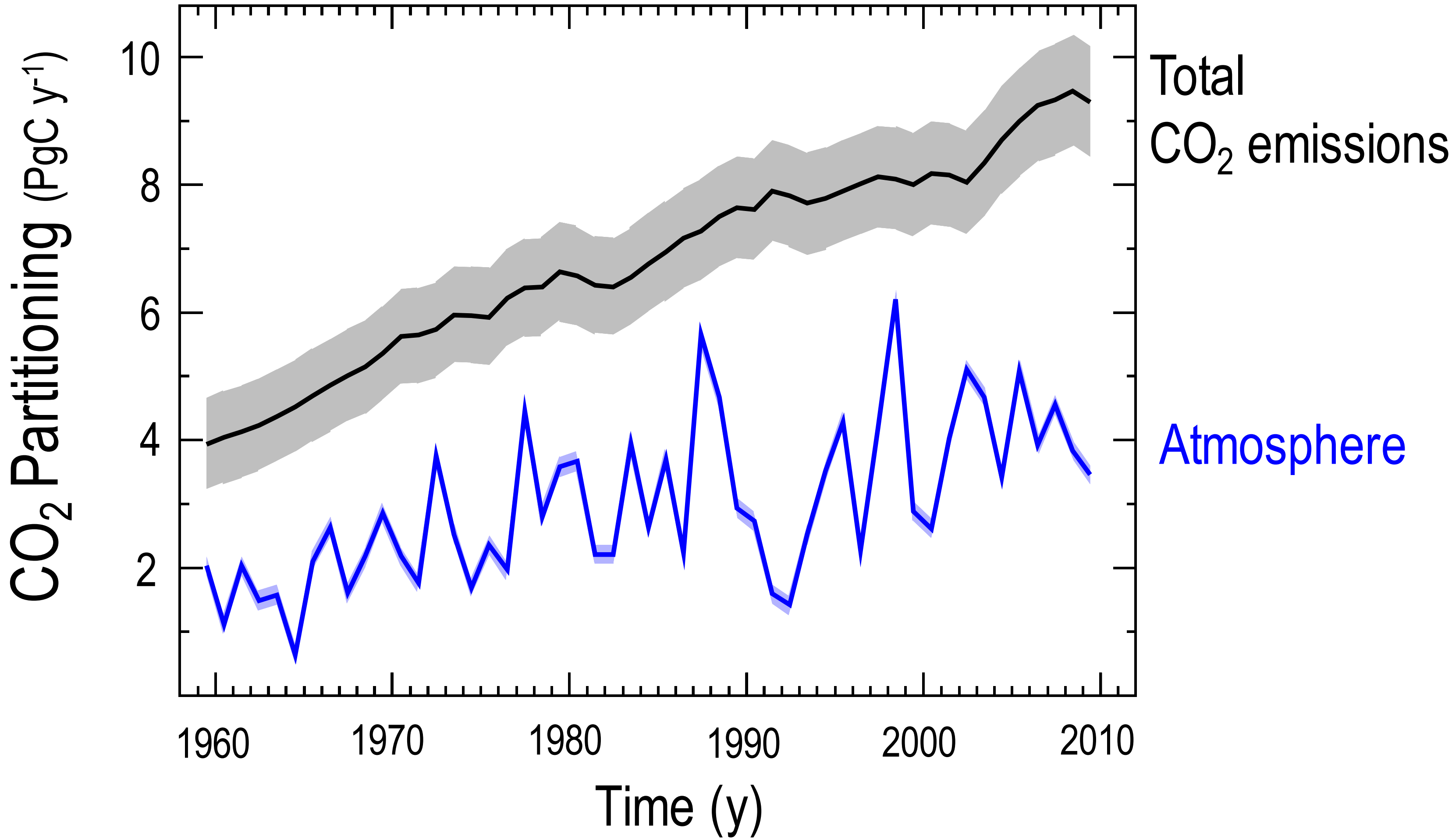
Cox et al., 2013; Wenzel, et al., 2014

The Unknown: Sensitivity of Tropical Land Carbon to Global Warming



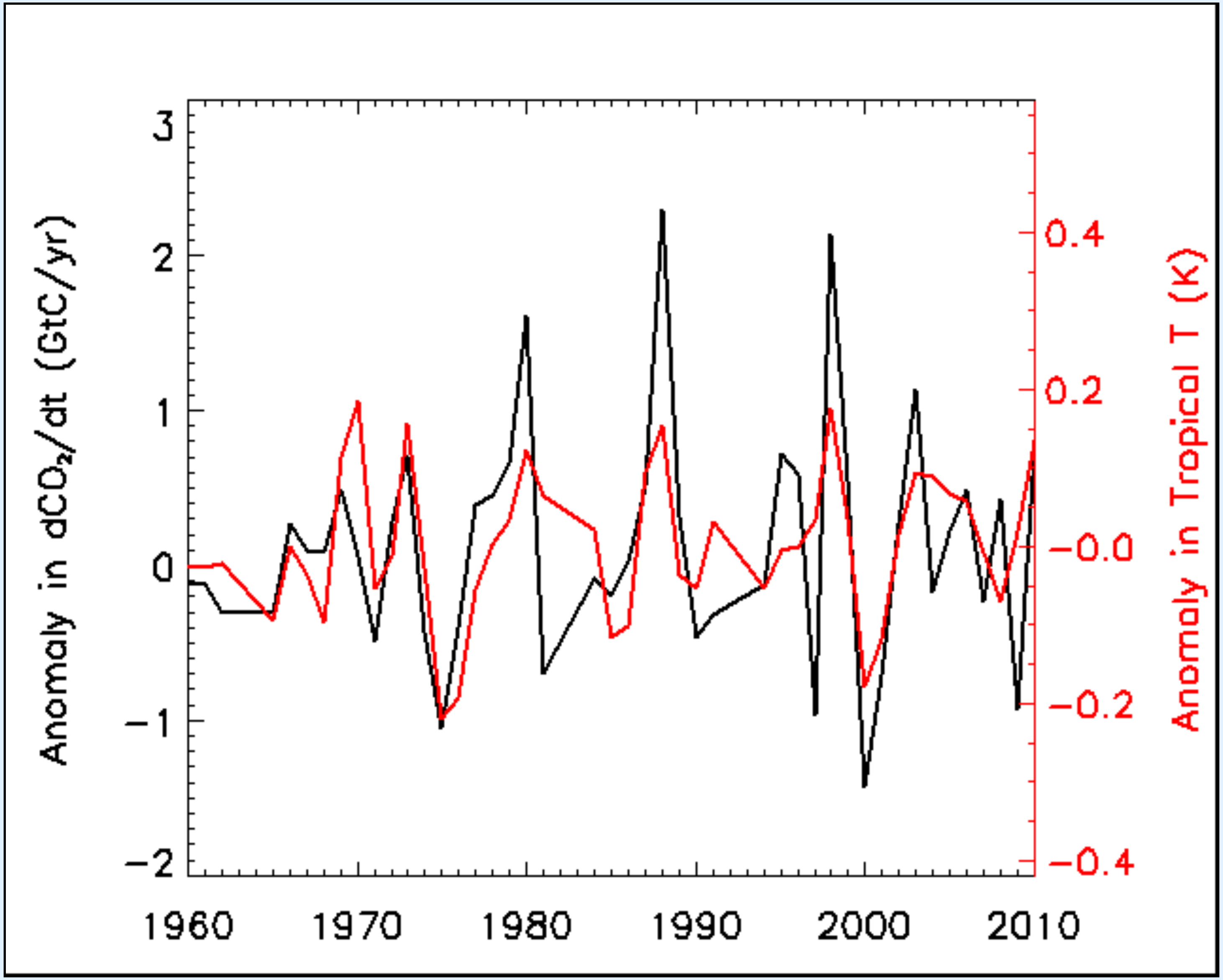
Interannual Variability in CO_2 Growth-rate

Evolution of the fraction of total emissions that remain in the atmosphere

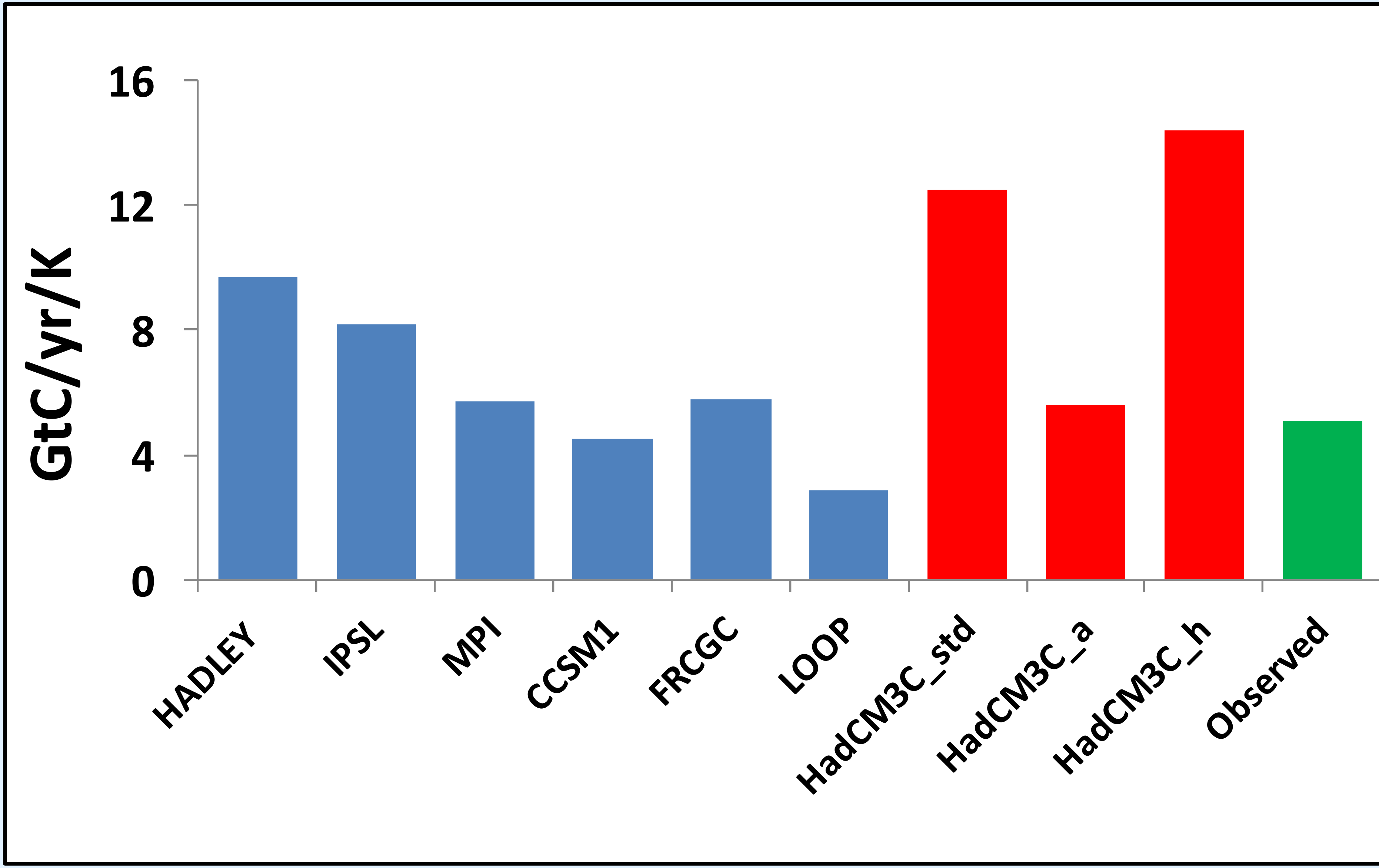


Updated from Le Quéré et al. 2009, Nature Geoscience; Data: NOAA 2010, CDIAC 2010

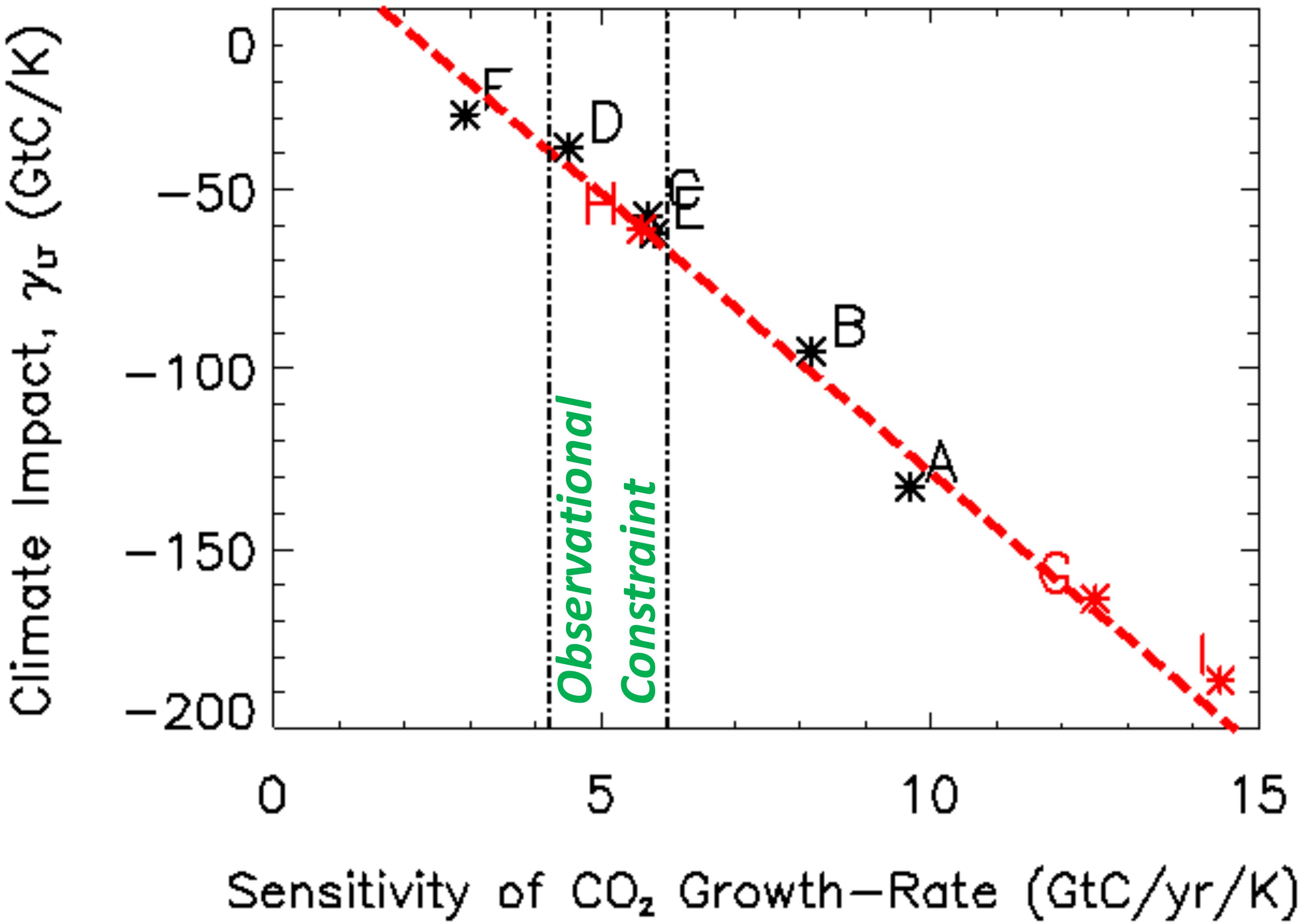
Observations: Interannual Variation in CO_2 Growth-rate and Tropical Temperature



Models vs Data: Interannual Sensitivity of CO_2 growth-rate to Tropical Temperature



The Emergent Relationship



The Emergent Constraint