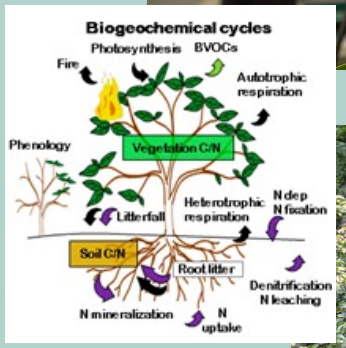
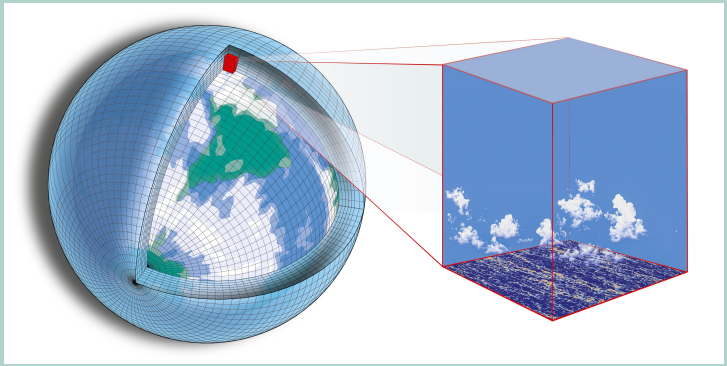
Plant Physiological Responses to CO2 Influence the Transient Climate Response in CMIP6 Earth System Models

Claire Zarakas, Abigail Swann, Marysa Laguë, Kyle Armour, Jim Randerson

Plant Physiology



Climate Sensitivity



CO_2 influences global temperature through both its radiative and physiological effects.

CO_2

CO_2

CO_2

Physiological Effect

Image source: Sibley Guide to Trees

Radiative Effect

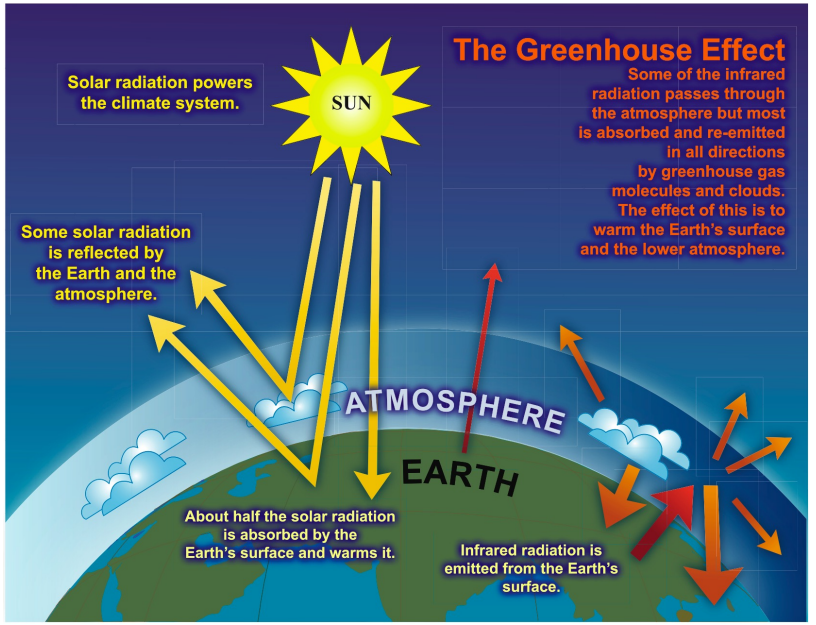
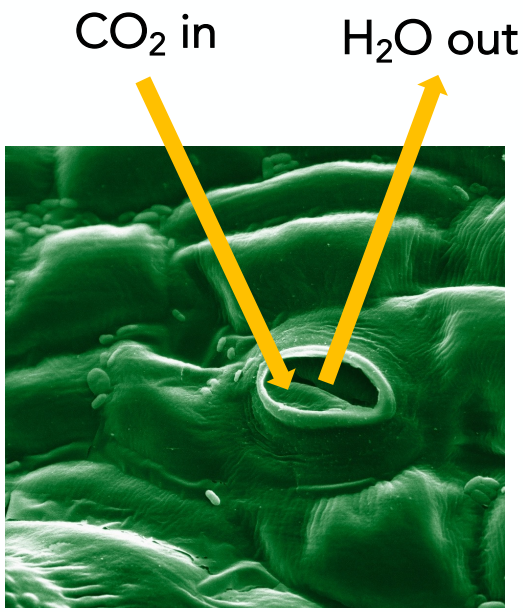


Image source: IPCC AR4 WG1 FAQ

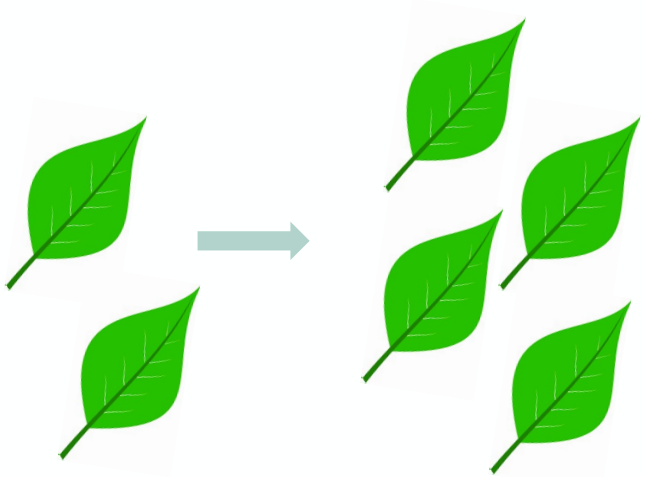
Plants' physiological responses to CO_2 can influence land temperatures.

Direct plant-level responses to increasing CO_2 concentrations:

1. Stomatal closure
2. **More photosynthesis ➡ More leaf area**



Stomata



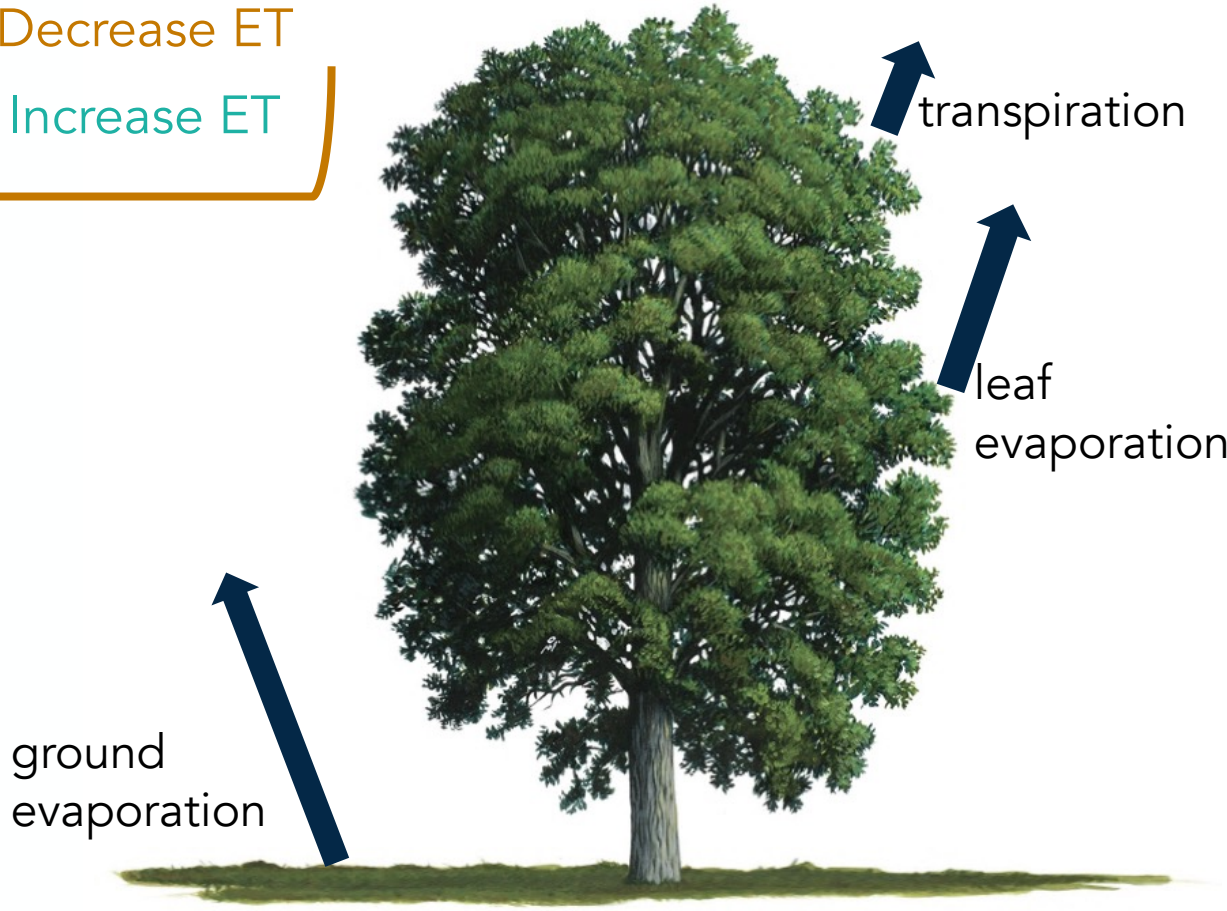
Plants' physiological responses to CO_2 can influence land temperatures.

Direct plant-level responses to increasing CO_2 concentrations:

Stomatal closure → Decrease ET

More photosynthesis → More leaf area → Increase ET

Net: Decrease ET



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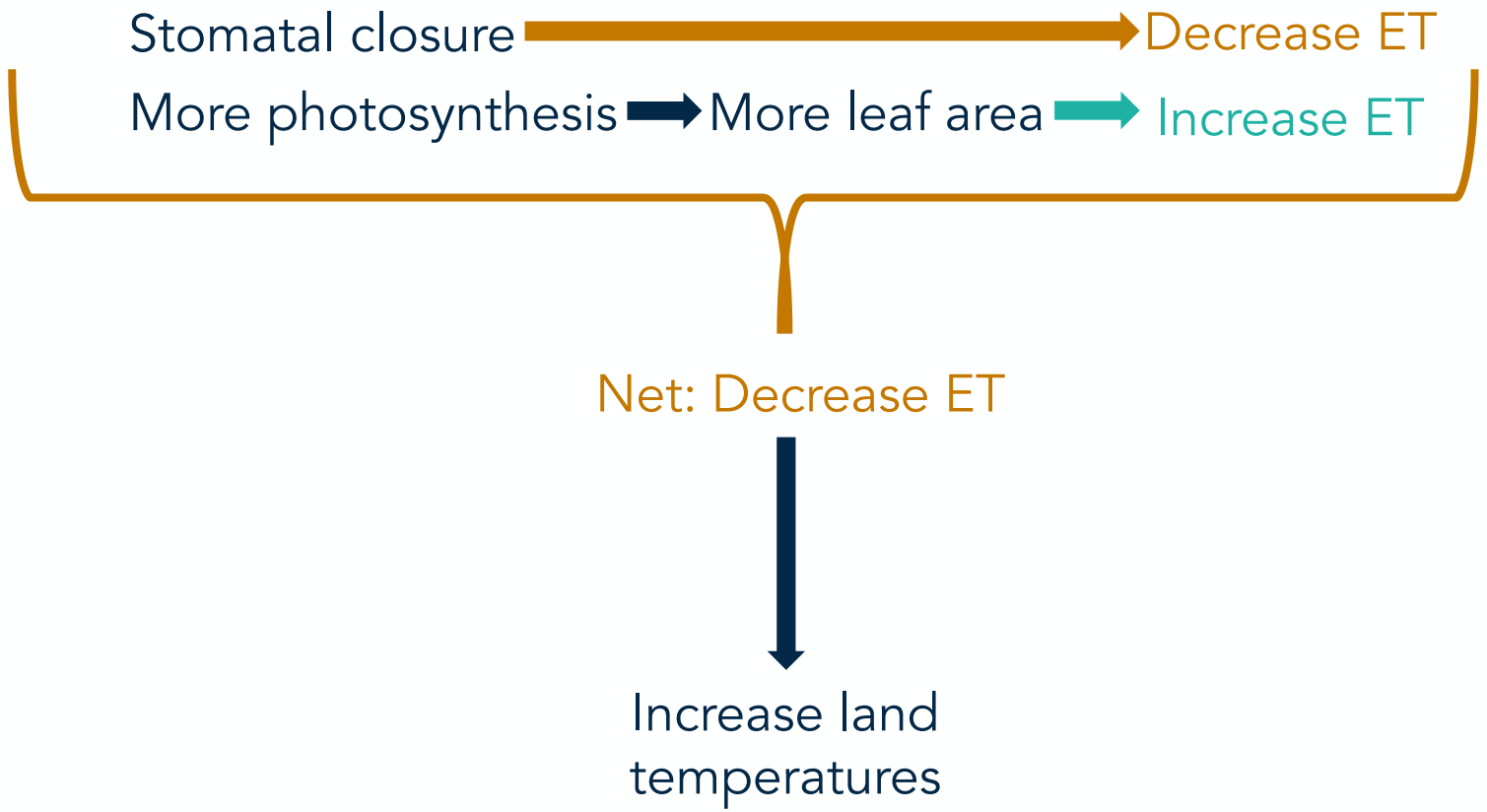
Direct plant-level responses to increasing CO_2 concentrations:



Plants' physiological responses to CO_2 can influence land temperatures.

Direct plant-level responses to increasing CO_2 concentrations:

Stomatal closure → Decrease ET

More photosynthesis → More leaf area → Increase ET

Net: Decrease ET

Decrease albedo

Increase land temperatures

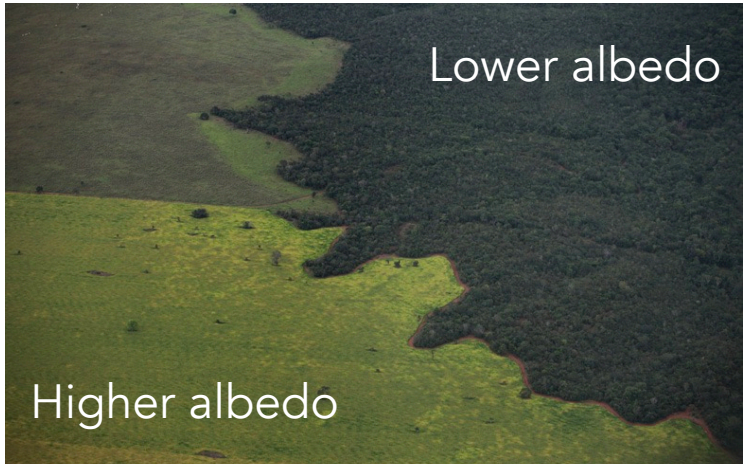


Image source: Rhett A. Butler, Mongabay

Plants' physiological responses to CO_2 can influence temperatures *on a global scale.*

- Global-scale temperature implications acknowledged since Sellers et al. 1996. Physiologically driven temperature changes:
  - On land at 2xCO_2: +0.3°C
  - Globally at 2xCO_2: +0.1°C
- Since then, multiple studies in the carbon cycle feedback literature have demonstrated that physiological responses increase land temperatures in modern earth system models (ESMs)

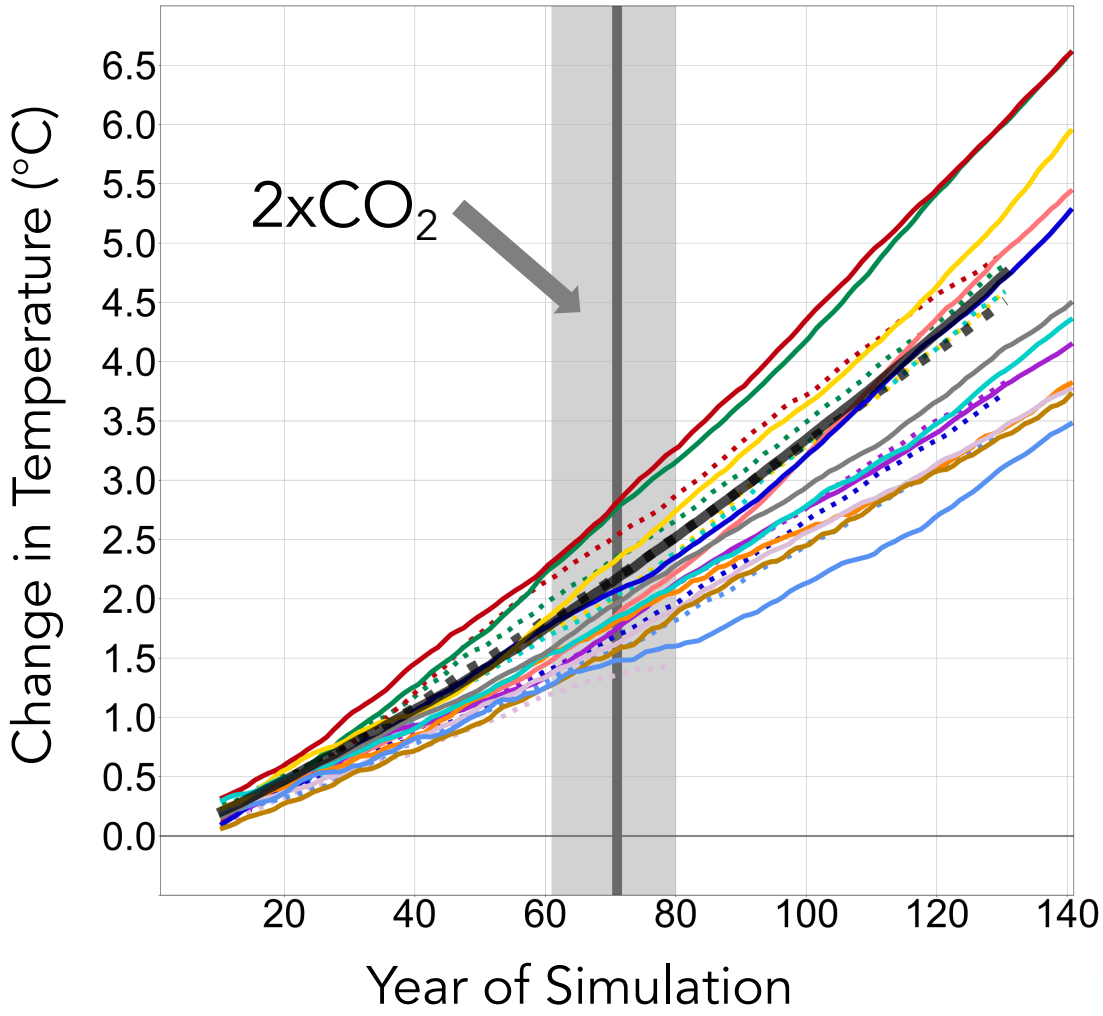
The physiological effect has received limited recognition by the climate dynamics community.

Physiology's contribution to the transient climate response (TCR) has not been systematically assessed across models and CMIP phases

Some previous research on physiological contribution to CO_2-forced warming

- Studies limited to a few modeling centers (Hadley Centre, NCAR)
- Inconsistent model experimental designs (e.g. can leaf area respond?)

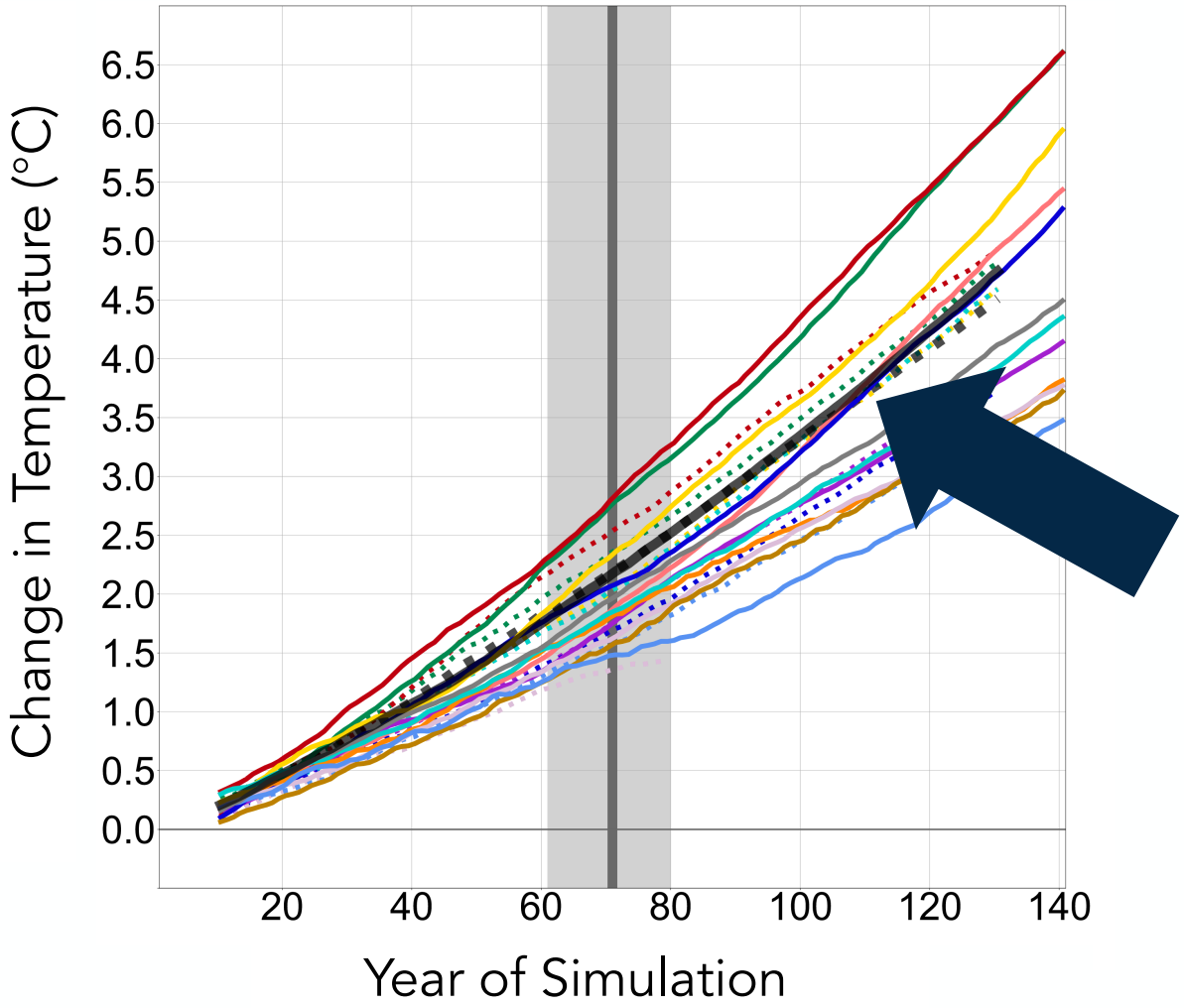
Definition of the Transient Climate Response (TCR)



$$TCR = T_{global}(2\times CO_2) - T_{global}(1\times CO_2)$$

- Conceptually simple
- Widely used
- **Outstanding challenge:** understanding and constraining uncertainty in the TCR across ESMs

Definition of the Transient Climate Response (TCR)



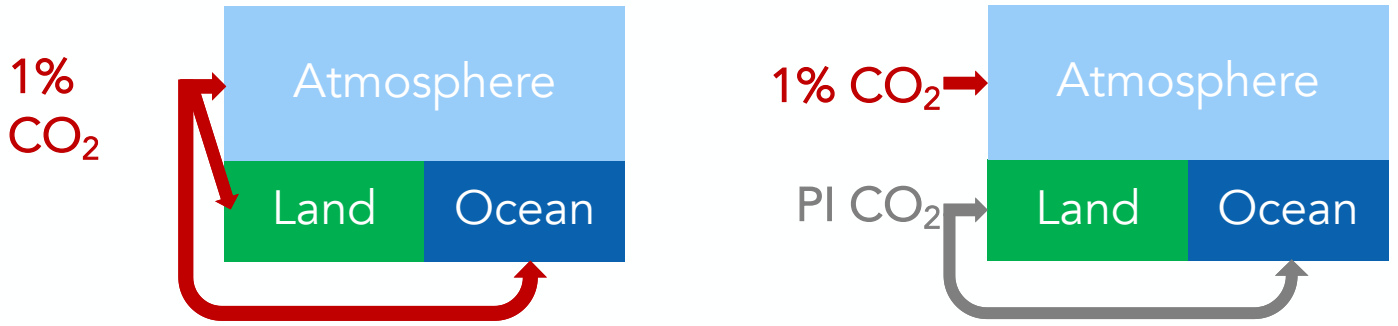
How much of this comes from plant physiological responses to CO_2?

Questions

1. How much do plants contribute to the TCR in models?
2. What mechanisms drive plants' contribution to global near-surface warming?
3. How much do plants contribute to uncertainty in CO_2-forced warming?

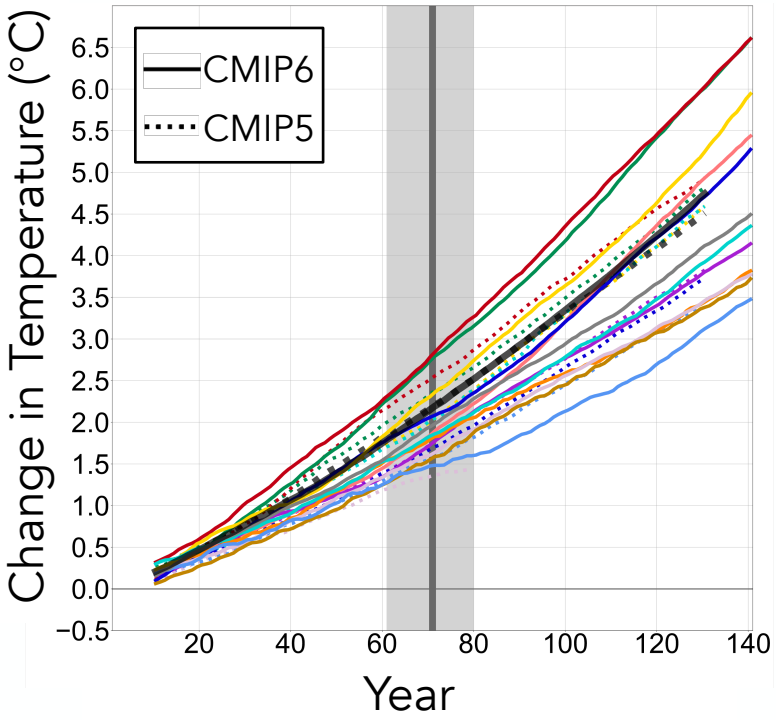
CMIP Model Experiments

- Monthly ESM output from Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP), CMIP5 and CMIP6
- Analyzed all CMIP5 and CMIP6 ESMs that uploaded data for C4MIP experiments:
  - 8 CMIP5 models
  - 12 CMIP6 models
- Concentration-driven experiments

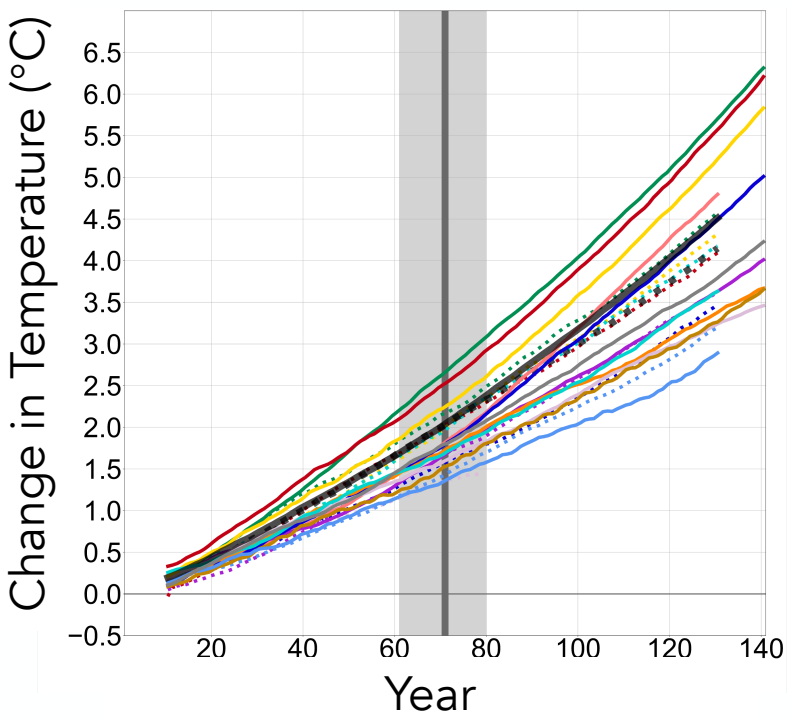


Starting with a *global-scale* metric

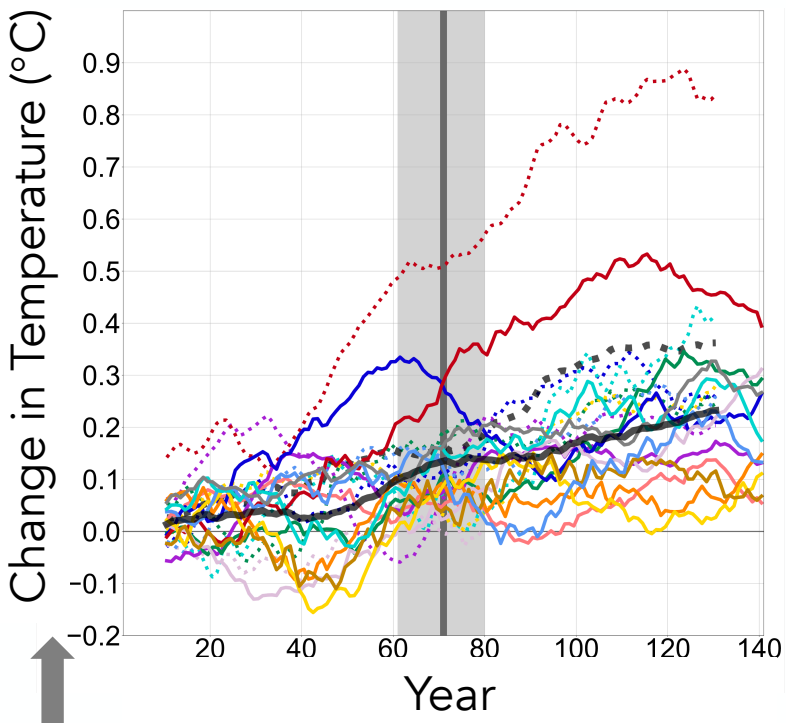
FULL



RAD



FULL – RAD = PHYS

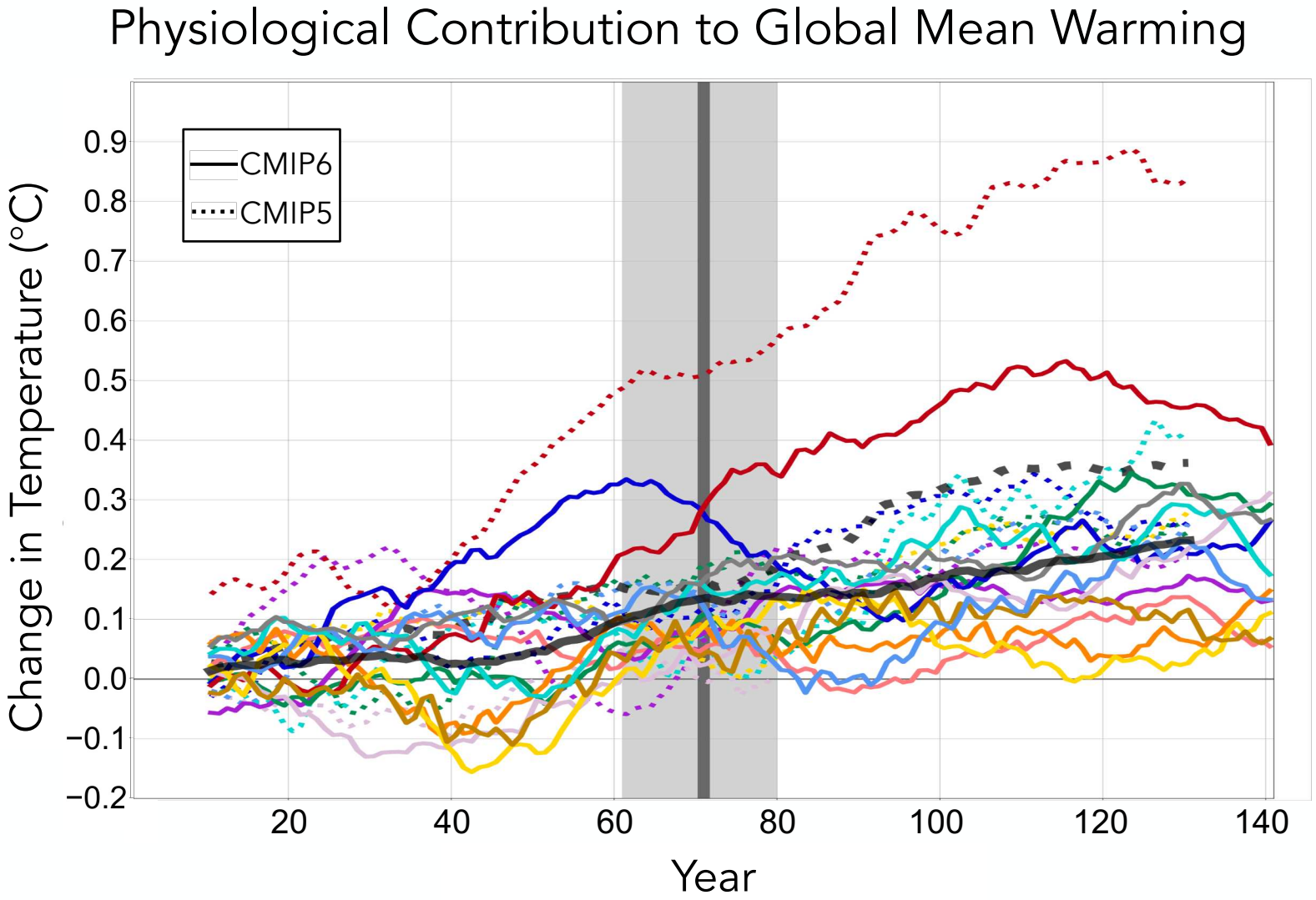


y-axis on different scale

The physiological effect is a small but significant contributor to the TCR.

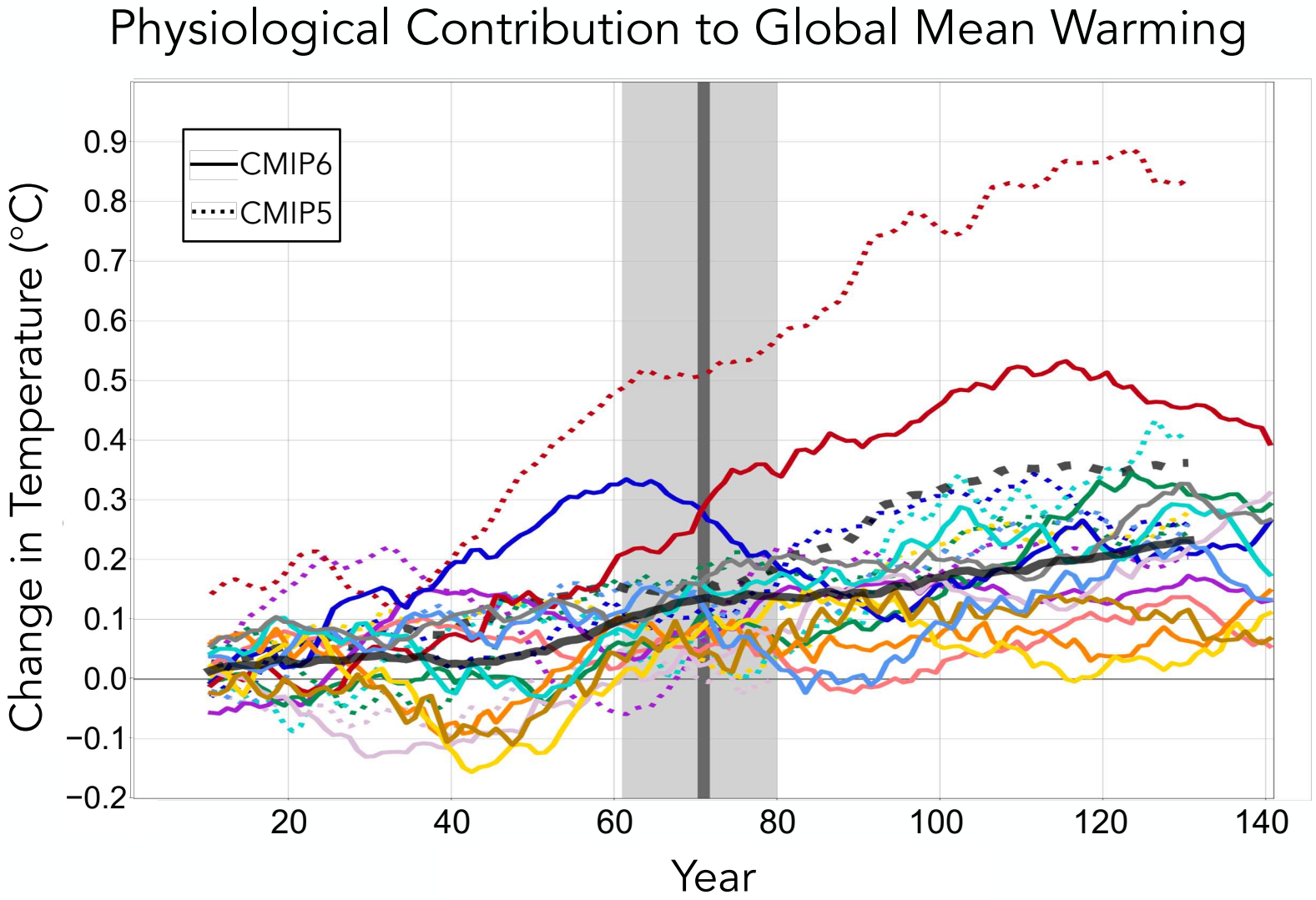
CMIP6 multi-model mean TCR_{PHYS}:

- Absolute: 0.12°C
- Relative: 6.1%



Significant inter-model variation in physiological contribution to warming

Physiological contribution to the TCR varies substantially across models



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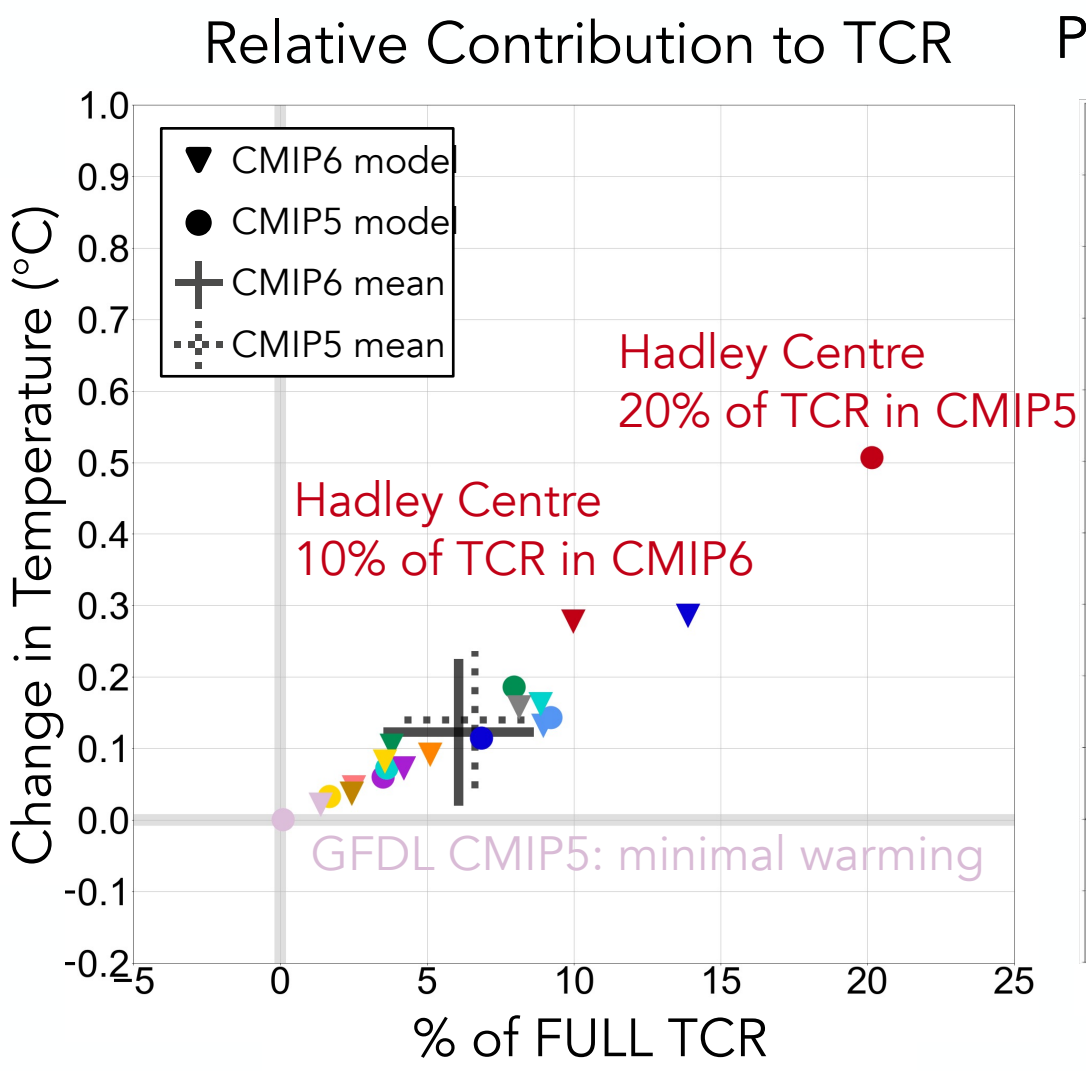
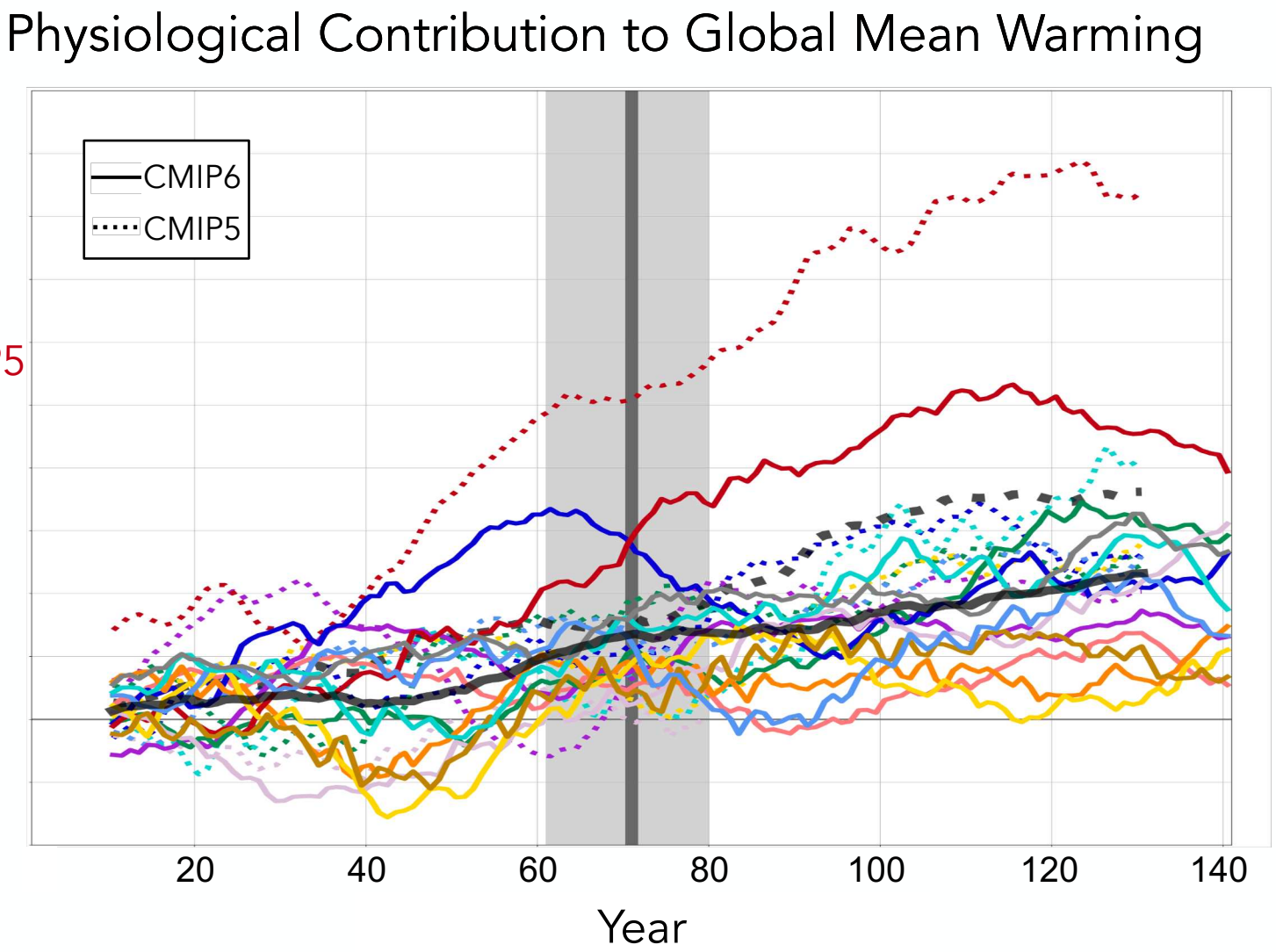
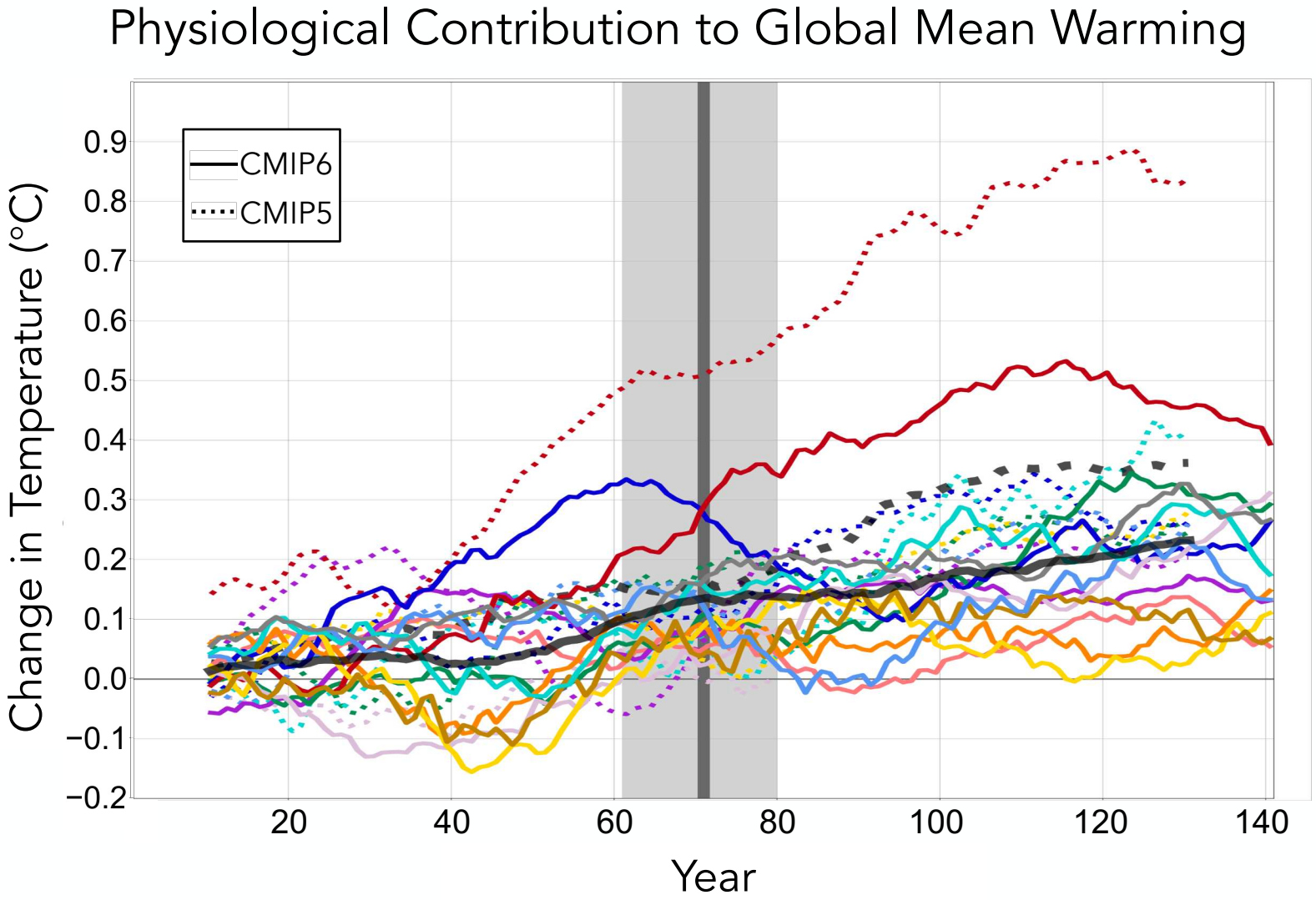




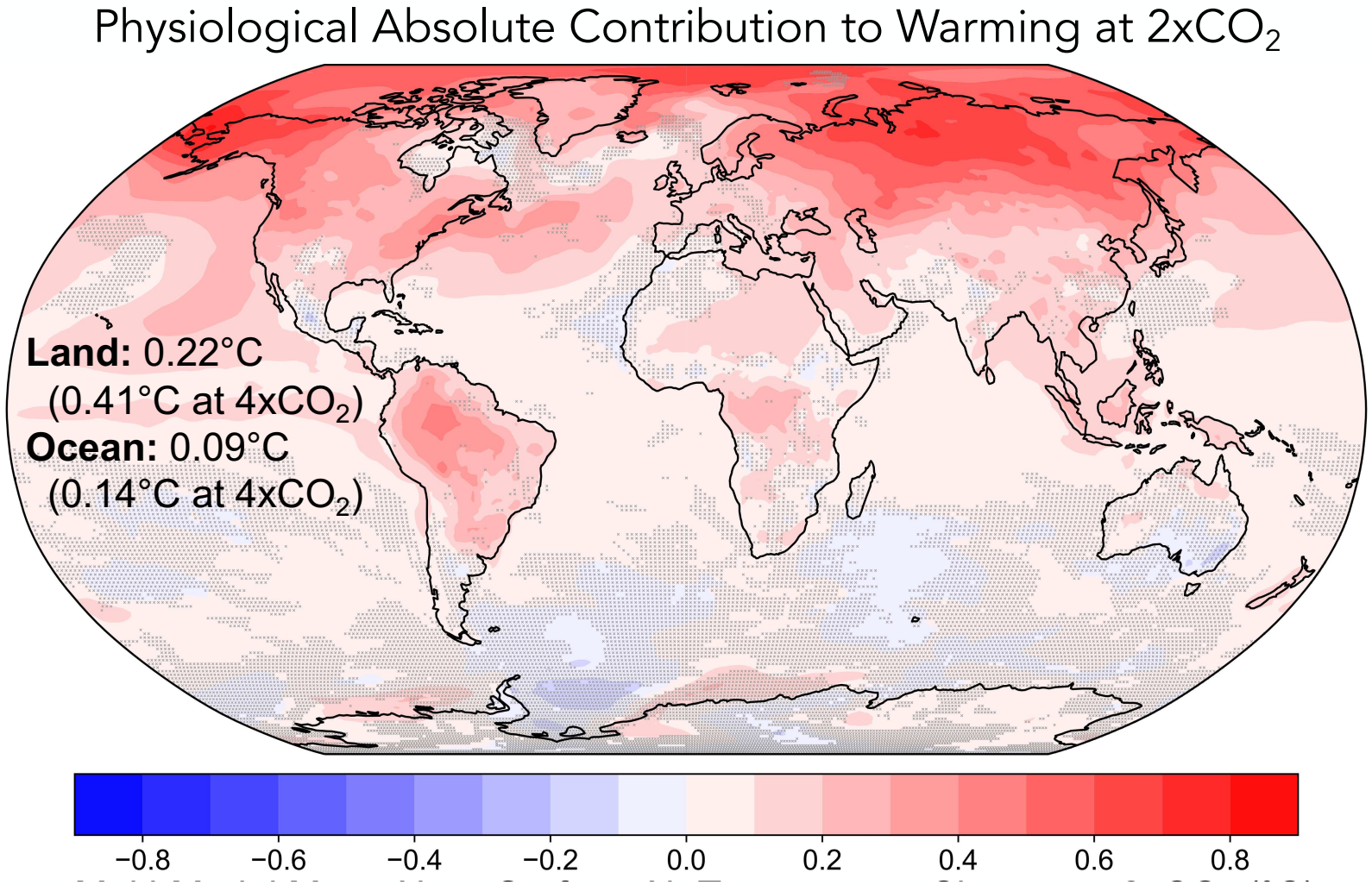
Physiologically-driven warming increases with increasing CO_2 concentration.

- But multi-decadal variability is a source of uncertainty in quantifying physiology's contribution to the TCR

- Global physiologically-driven warming signal is statistically significant for:
  - At 2xCO_2: 7 of 12 models
  - At 4xCO_2: 9 of 12 models

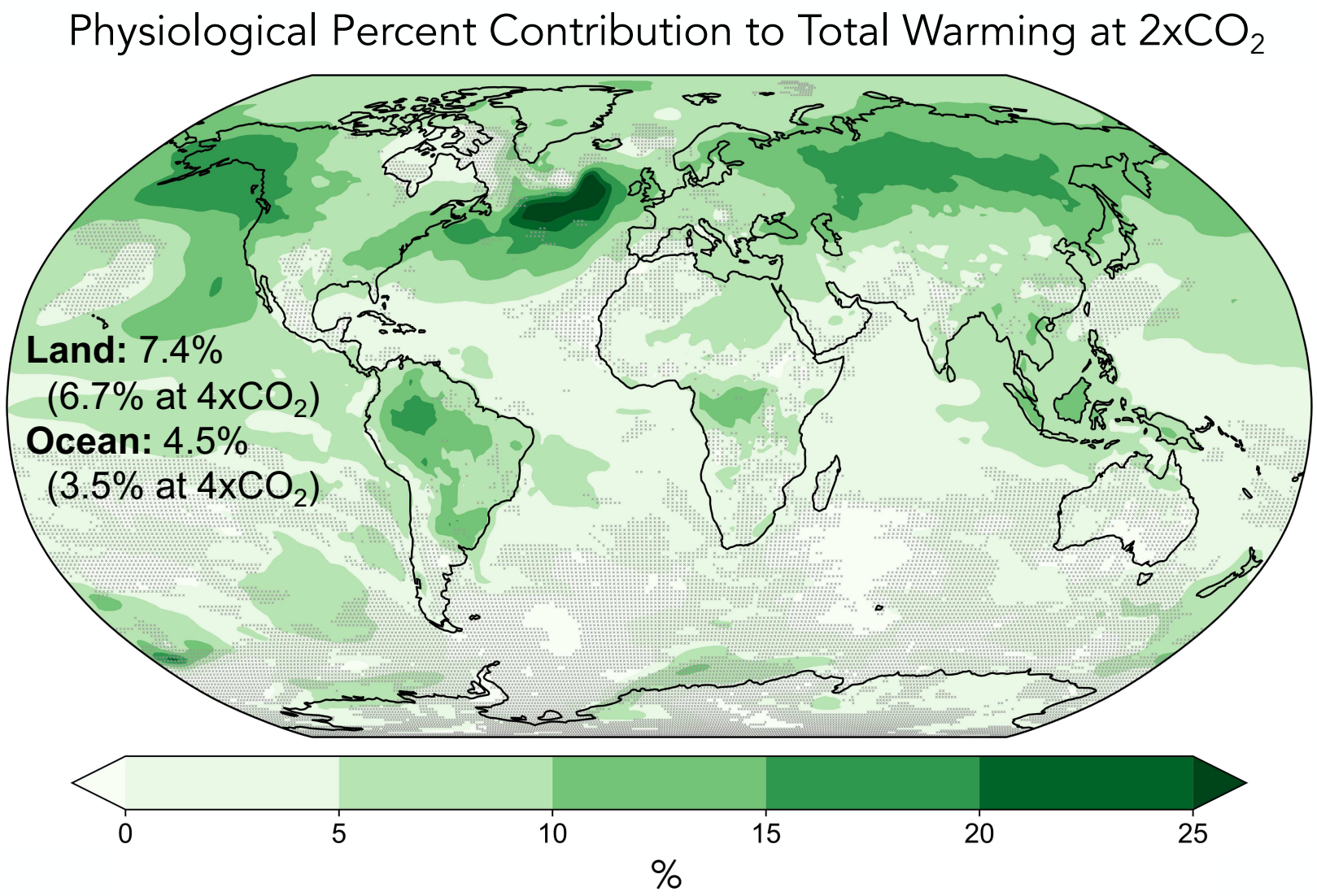


Plant physiological responses warm the land more than the ocean (absolute magnitude).



Stippling indicates *poor* model agreement (<8/12 models agree on sign)

Plant physiological responses warm the land more than the ocean (relative magnitude).



Research Question 1

How much do plants contribute to the TCR in models?

→ Plants account for a small but significant fraction (6.1%) of the TCR

Evidence:

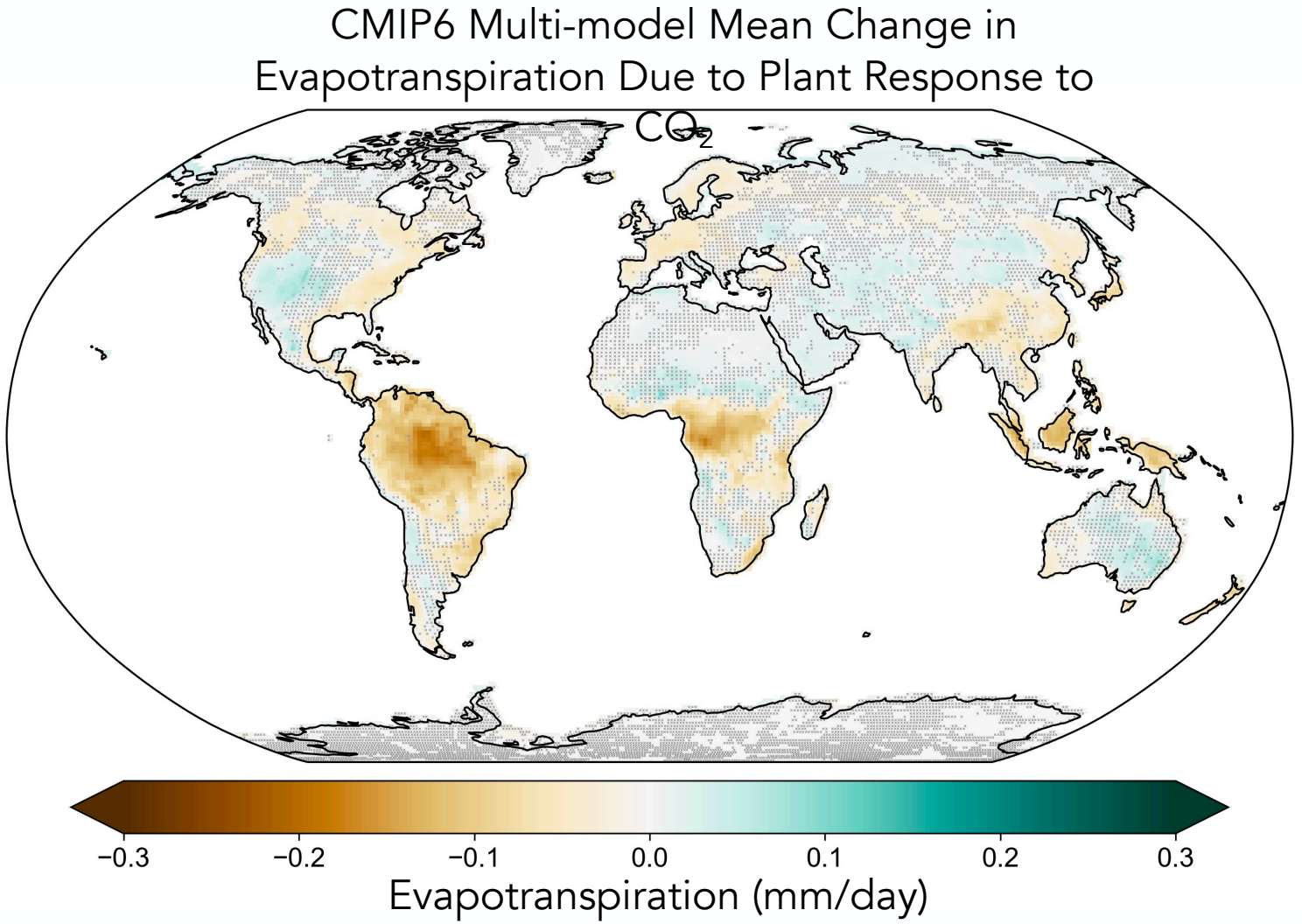
- Inter-model agreement on sign of TCR_{PHYS}
- Increasing statistical significance at higher [CO_2]
- Consistent spatial pattern

Research Question 2

What mechanisms drive plants' contribution to near-surface warming?

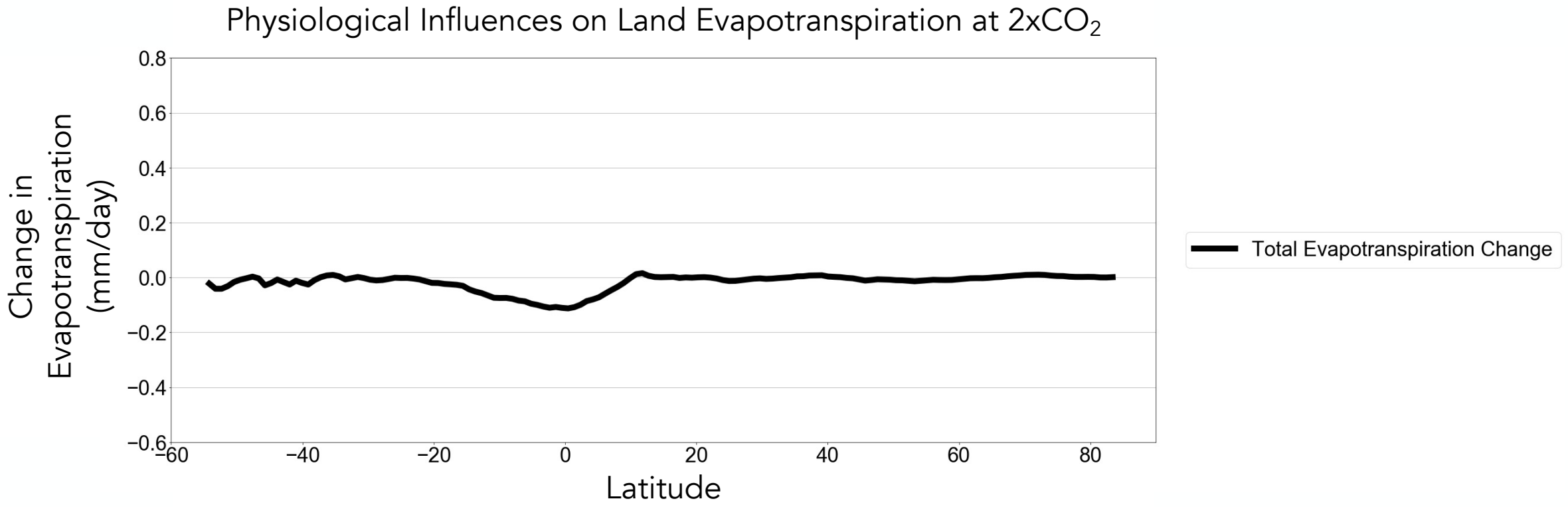
Plants warm the land surface by suppressing ET.

- Plant responses generally decrease ET in vegetated regions, especially the tropics
- Consistent with CMIP5



Plants warm the land surface by suppressing ET.

Changes in stomatal conductance and leaf area have opposing influences on ET



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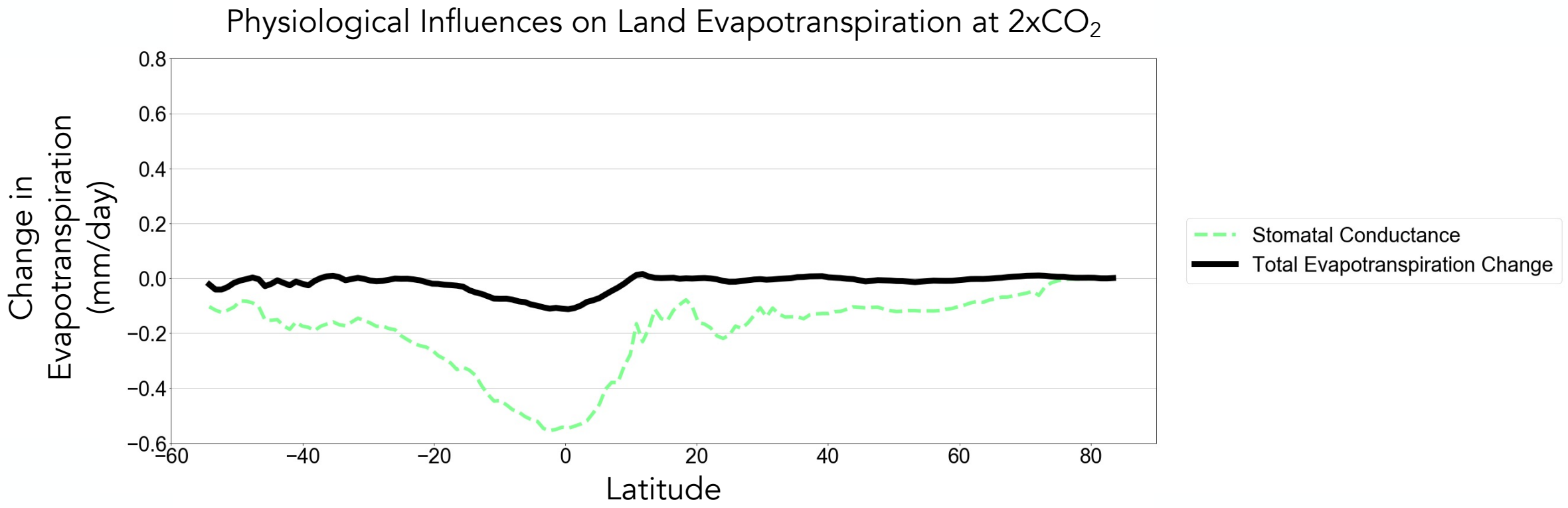

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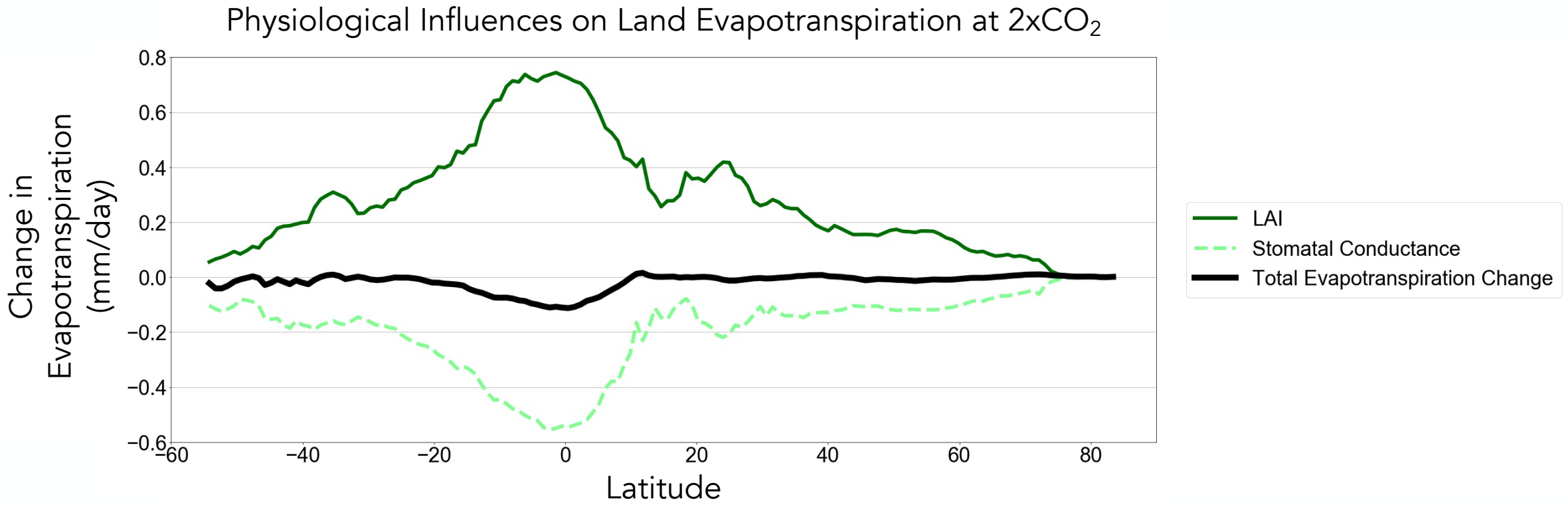

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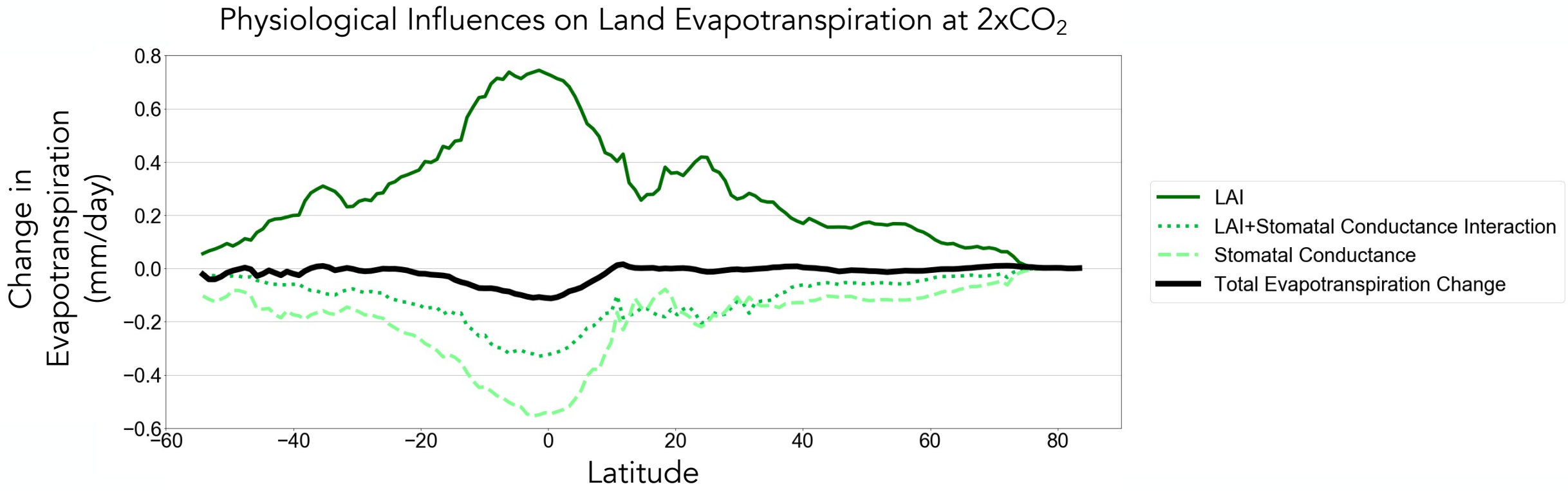
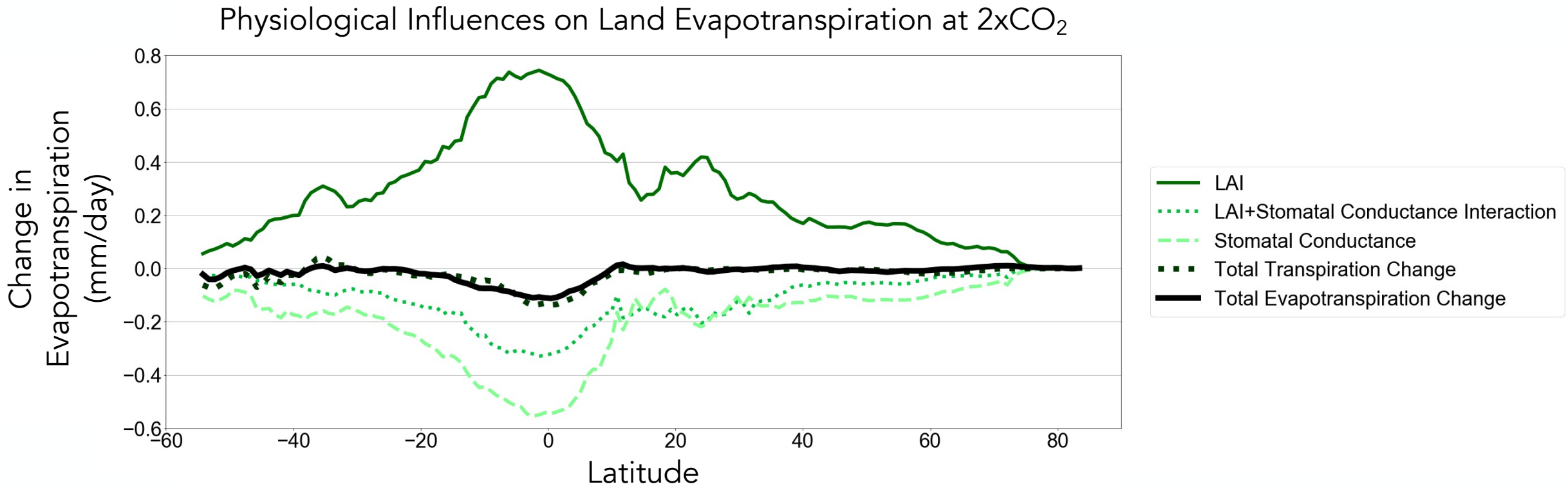


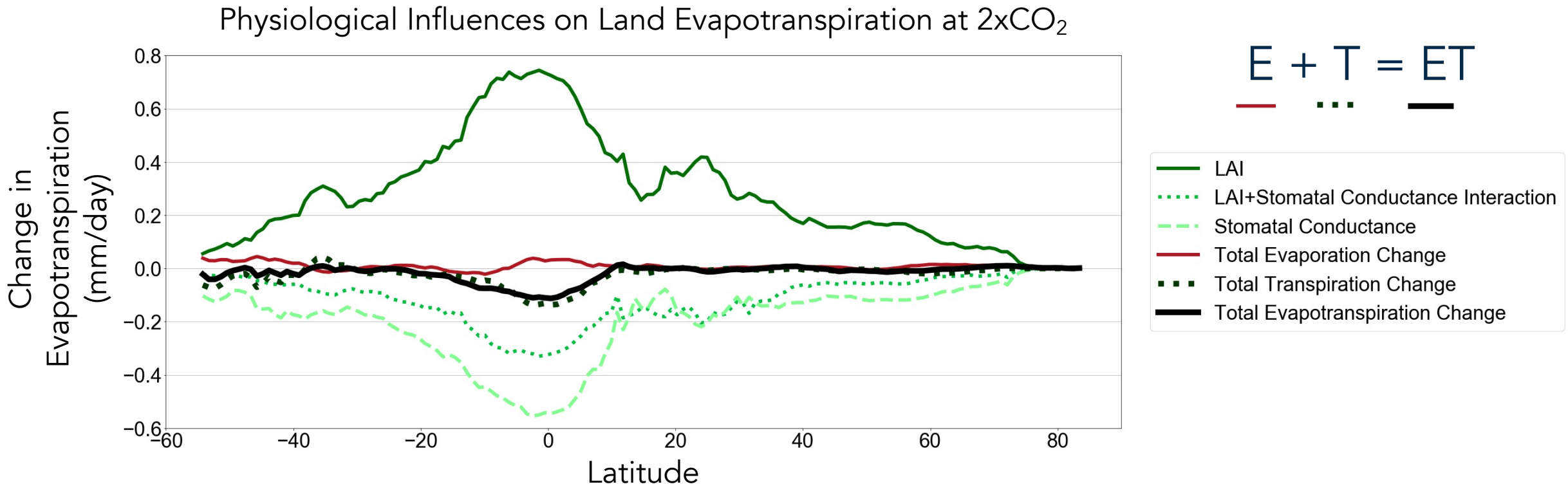
Plants warm the land surface by suppressing ET.

Stomatal conductance term dominates



Plants warm the land surface by suppressing ET.

Minimal physiologically-driven land *evaporation* change



Plants warm the land surface by increasing the net radiation absorbed *by modifying clouds.*

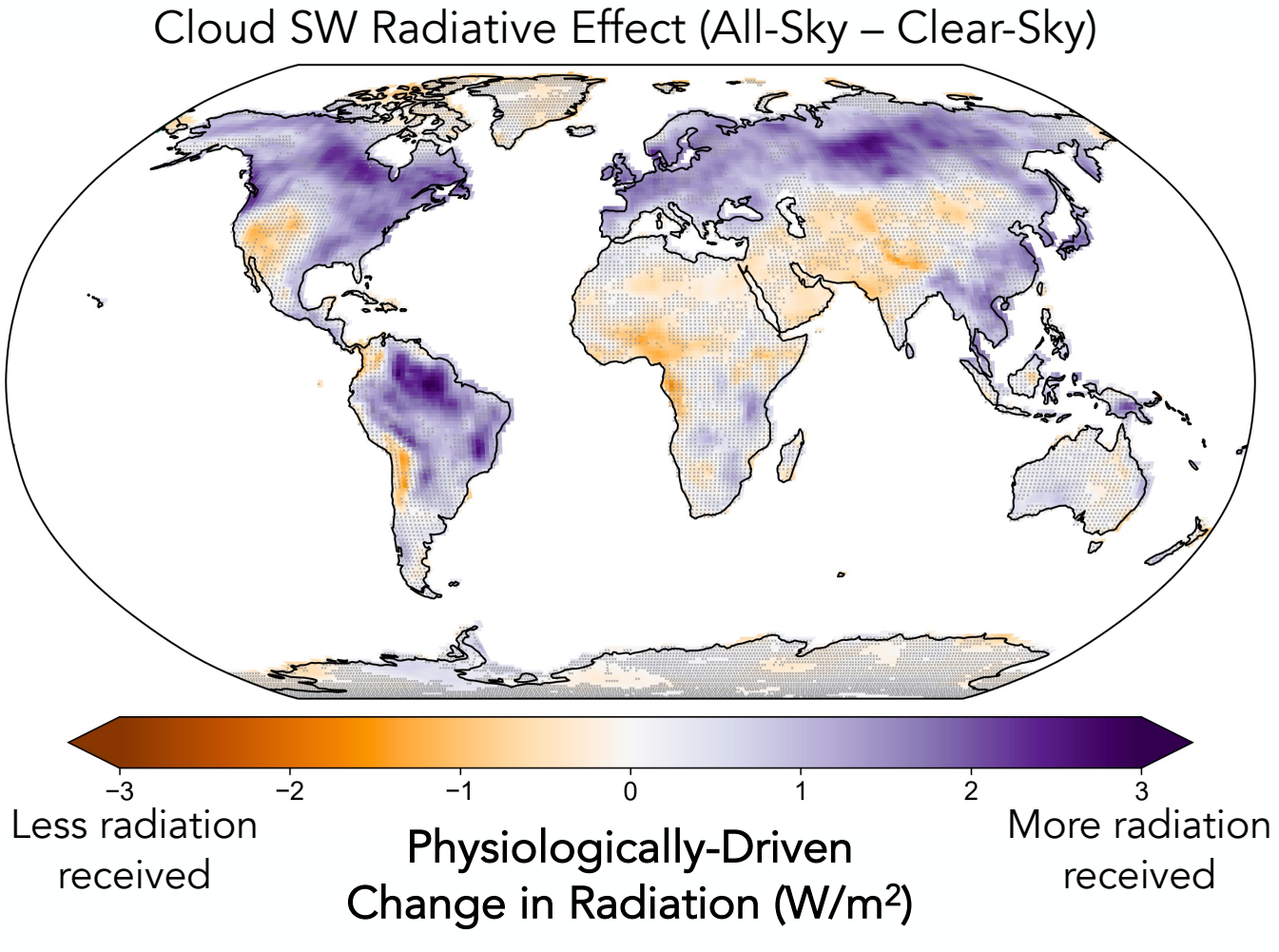
Reduced ET

Increased temp.

Decrease in relative humidity

Decreased cloud cover

More SW at surface



Research Question 2

What mechanisms drive plants' contribution to land warming?

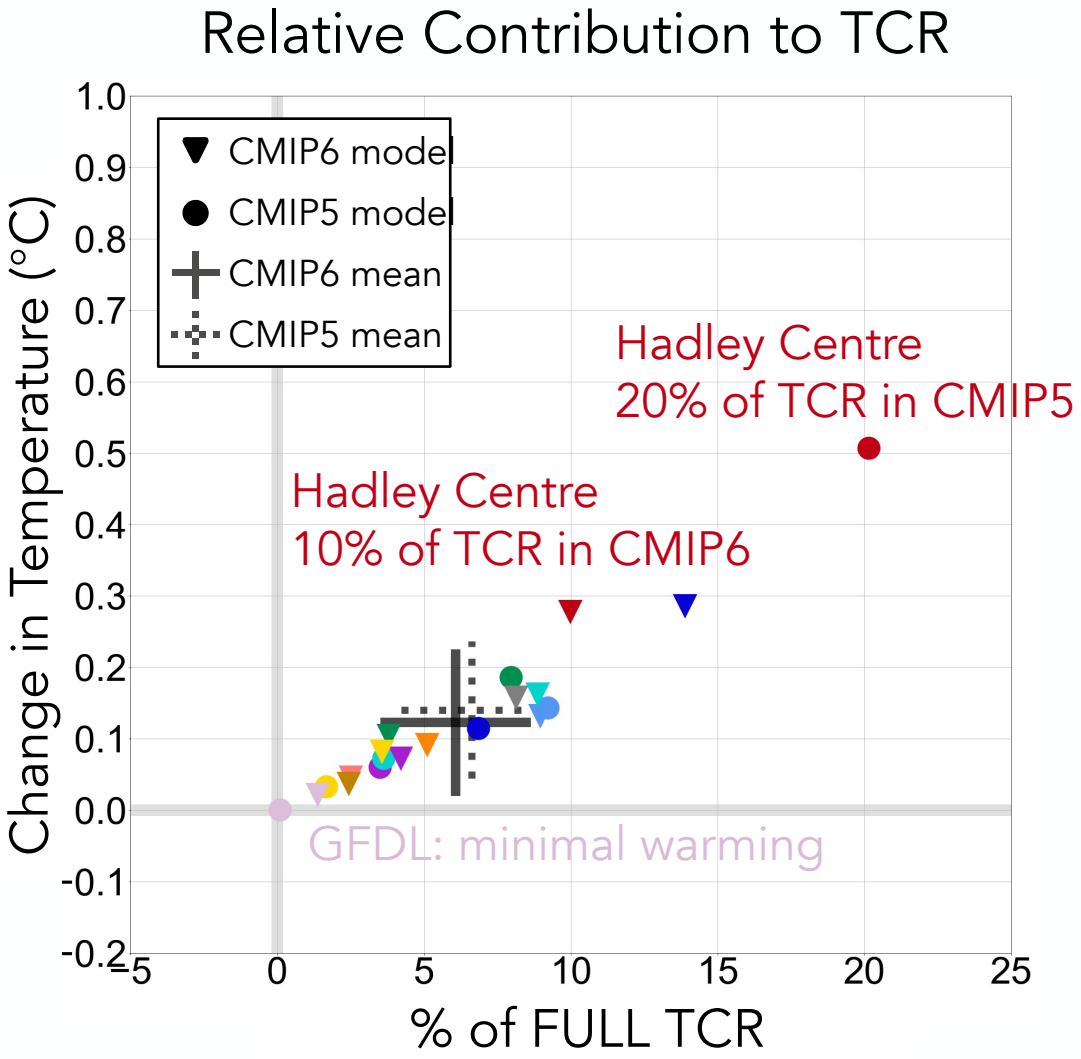
1. Suppression of evapotranspiration, which increases the surface sensible heat flux
2. Increasing the net radiation absorbed at the surface (albedo, clouds)

Research Question 3

How much do plants contribute to uncertainty in CO_2-forced warming?

Physiological responses increase uncertainty in CO_2-forced warming.

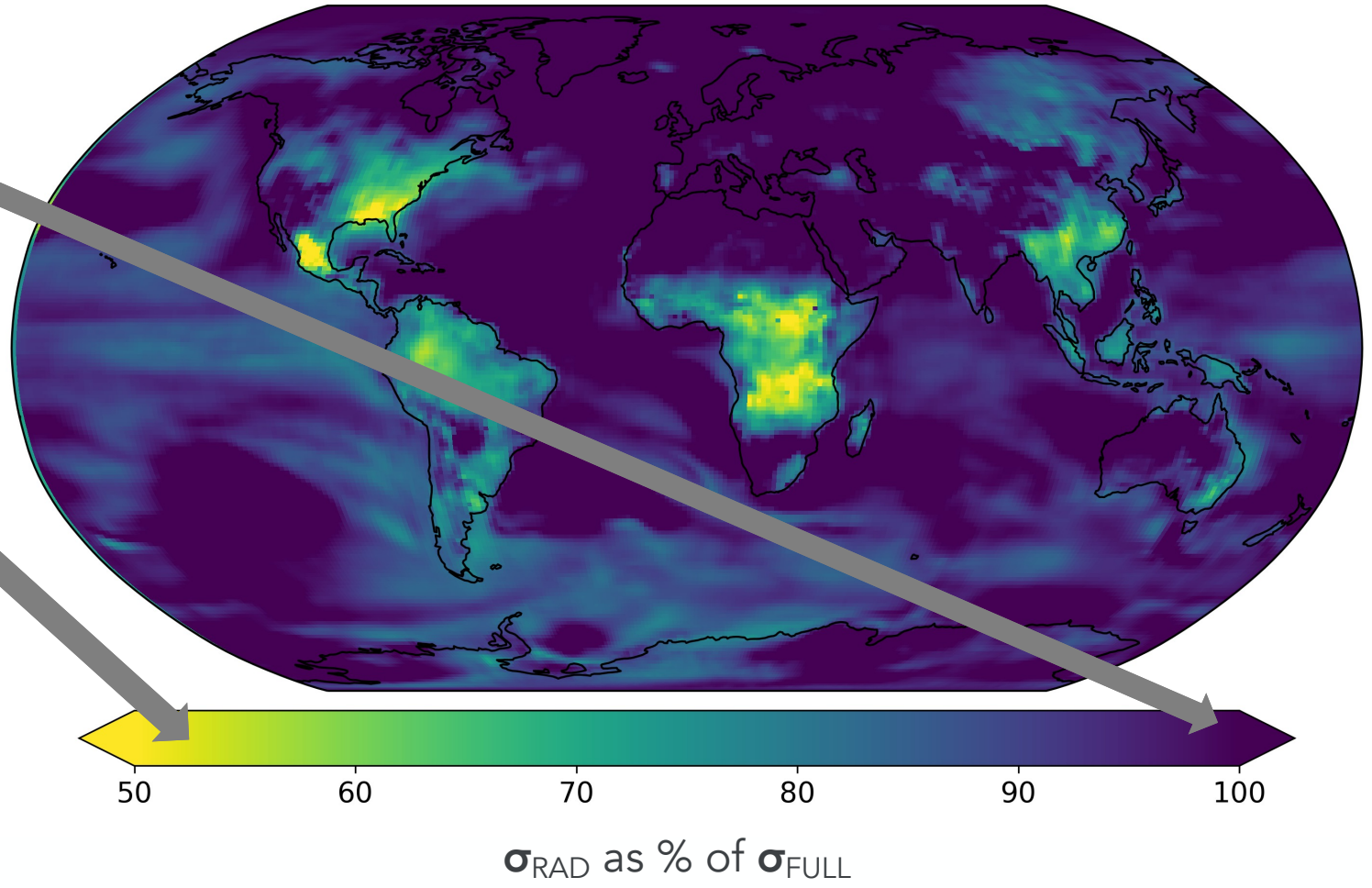
- Magnitude of global physiologically-driven warming varies significantly across models
- The physiological effect is a secondary driver of inter-model disagreement in the TCR



Physiological responses increase inter-model spread in CO_2-forced warming.

Radiation explains most of inter-model spread

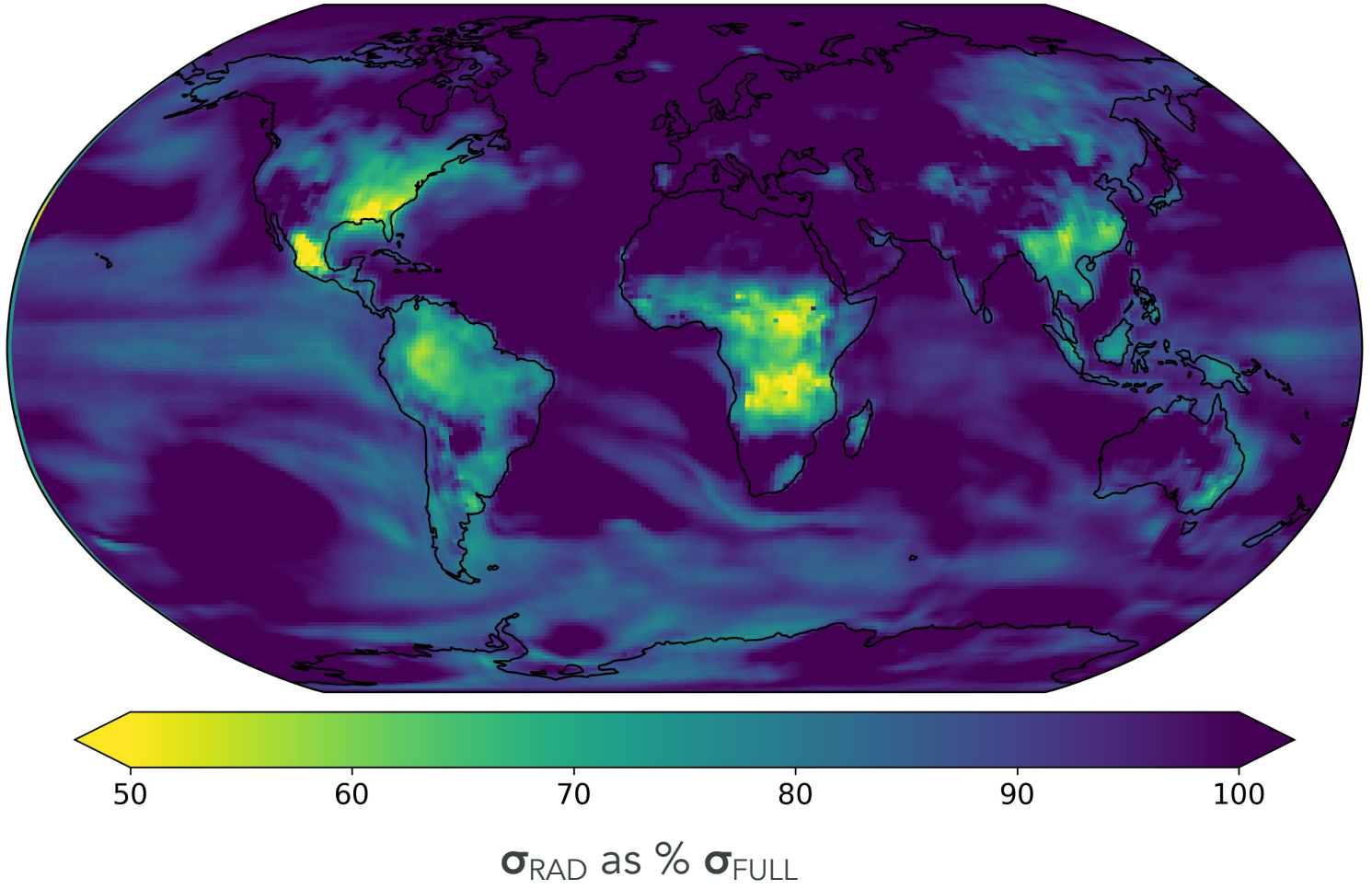
Physiology contributes 50% to inter-model spread



Physiological responses increase inter-model spread in CO_2-forced warming.

- Globally, physiology explains about ~8% of inter-model spread
- Over non-glaciated land, physiology explains ~14%

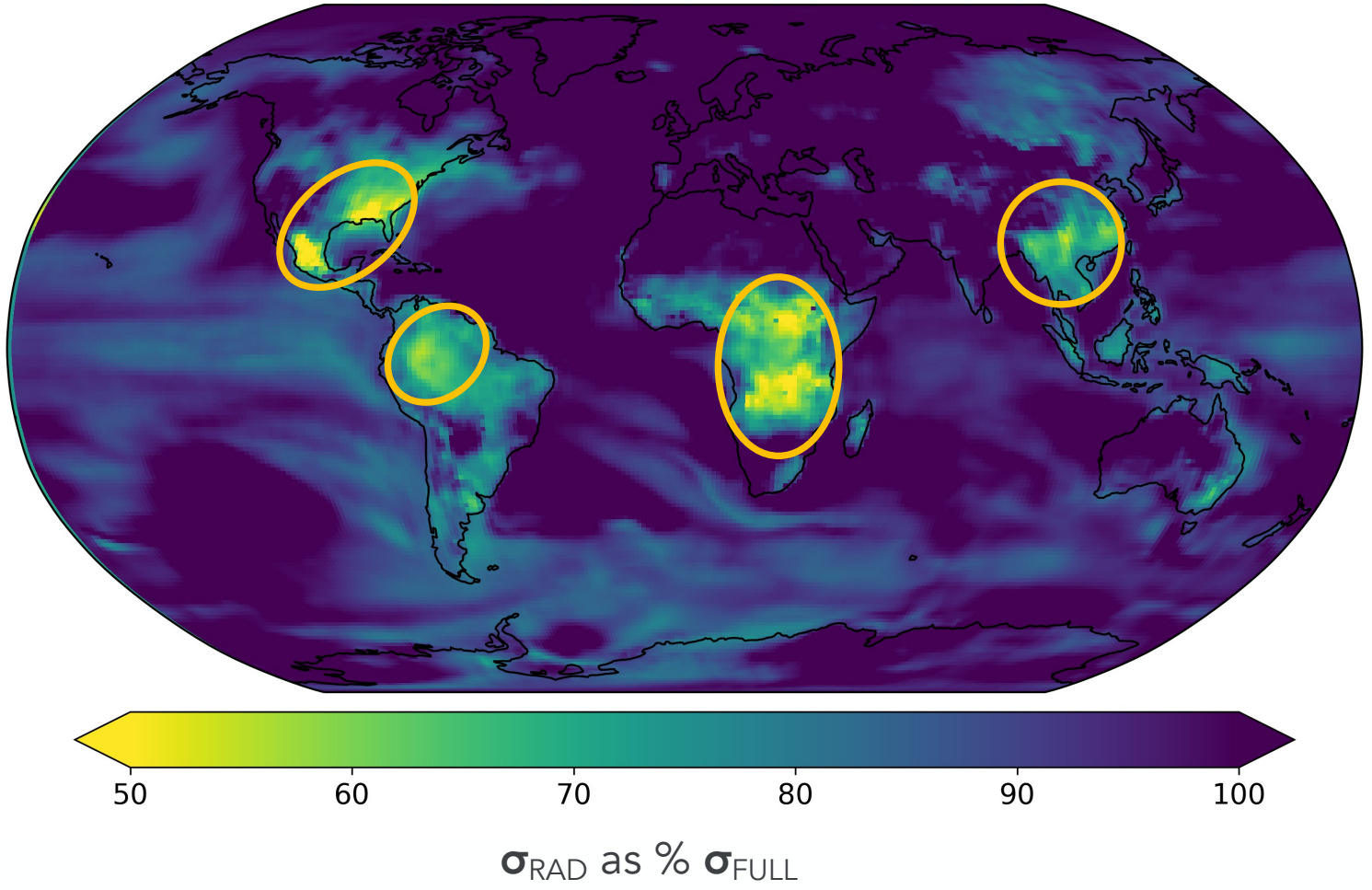
Radiation's Relative Contribution to Uncertainty in Warming at 2xCO_2



Physiological responses increase inter-model spread in CO_2-forced warming.

In some land regions, physiology contributes as much as radiative forcing to inter-model disagreement in local warming at $2xCO_2$

Radiation's Relative Contribution to Uncertainty in Warming at $2xCO_2$



Research Question 3

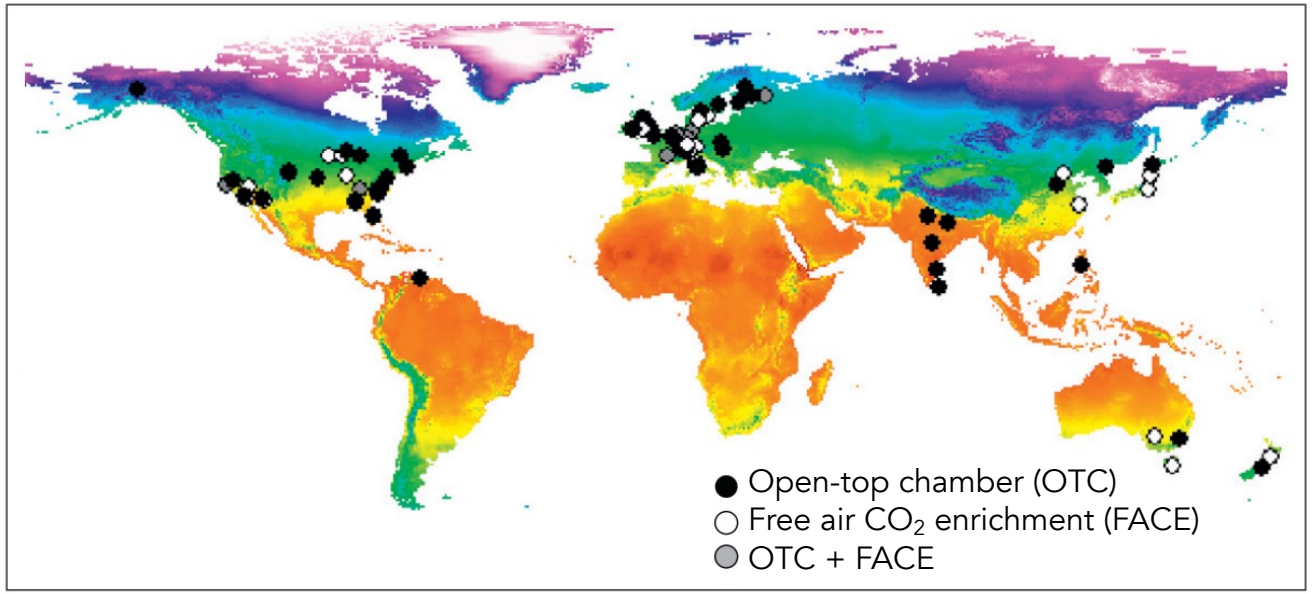
How much do plants contribute to uncertainty in CO_2-forced warming?

- Globally, plant responses to CO_2 increase inter-model spread in the TCR by about **8%**
- Plants contribute more to uncertainty in CO_2-forced warming over land (14%)
- Identified vegetated regions where physiological and radiative processes contribute equally to inter-model disagreement in CO_2-forced warming

Inter-model spread calls for more observational constraints

- Which models are more or less realistic?
- Limited FACE experiments to provide observational constraints
- ***Next step:*** evaluate model performance and develop constraints on physiologically-driven warming

Global distribution of elevated CO_2 plant/ecosystem experiments



Leakey, Bishop, and Ainsworth 2012.

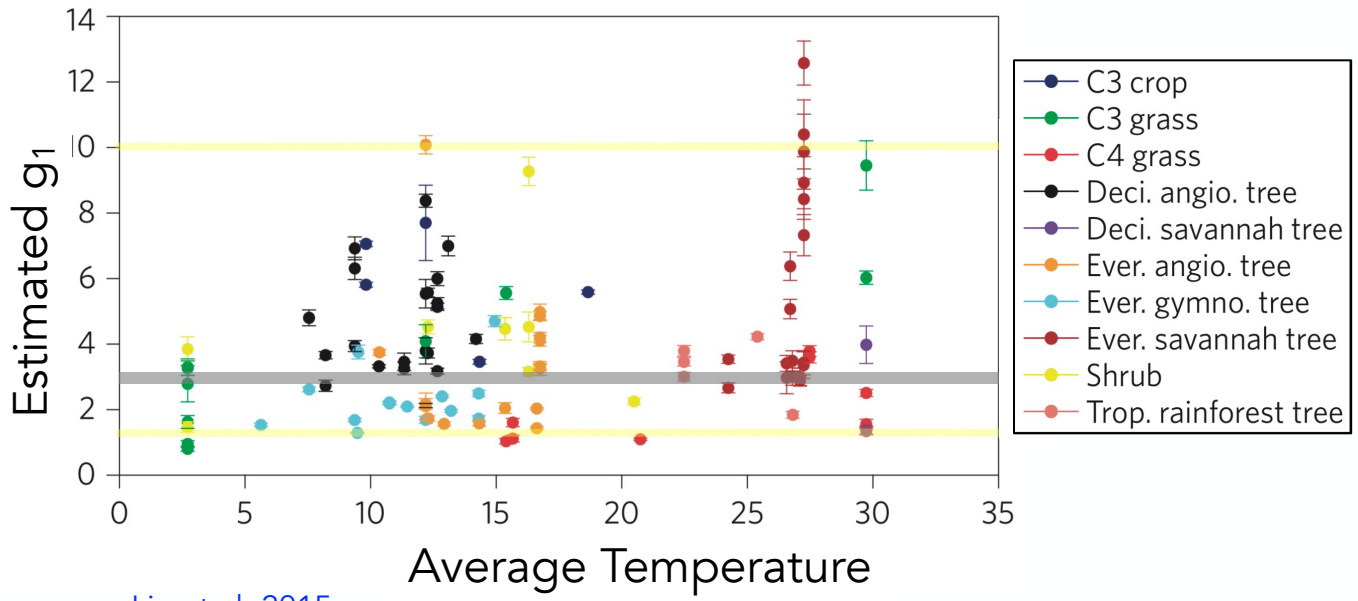
CMIP6 models may not fully probe scientific uncertainty.

- Systematic biases in stomatal conductance
  - Many models use same g1 parameter for most plant types
  - Wide variation in g1 across plant types
- Preliminary experiments in CESM2 suggest physiologically-driven warming is highly sensitive to this parameter

$$\Delta g_s \propto g_1 \left(\Delta \frac{Photosynthesis}{VPD\ [CO_2]} \right)$$

Stomatal conductance

stomatal slope



Lin et al. 2015

Carbon cycle uncertainty not limited to the carbon cycle

Models agree more on the magnitude of radiatively forced warming than we thought!

Carbon cycle uncertainty not limited to the carbon cycle

We need to better understand land surface processes, which are especially difficult to constrain

Further motivation for observational constraints on how stomatal conductance, leaf area, and evapotranspiration should respond to increasing atmospheric CO_2 concentrations

Conclusions

Take home Points

- Plant physiological responses to CO_2 account for a small but significant fraction (6.1%) of the TCR
- Plants influence the TCR through both partitioning of turbulent fluxes and radiative changes
- Uncertainty surrounding plant physiological responses increases inter-model disagreement in CO_2-forced warming, especially over land

Implications

→ Carbon cycle processes embedded in global climate sensitivity metrics

→ The physiological effect makes CO_2 different from other GHGs

→ Carbon cycle uncertainty not limited to the carbon cycle