The roles of vegetation in mediating changes in precipitation and runoff in the tropics

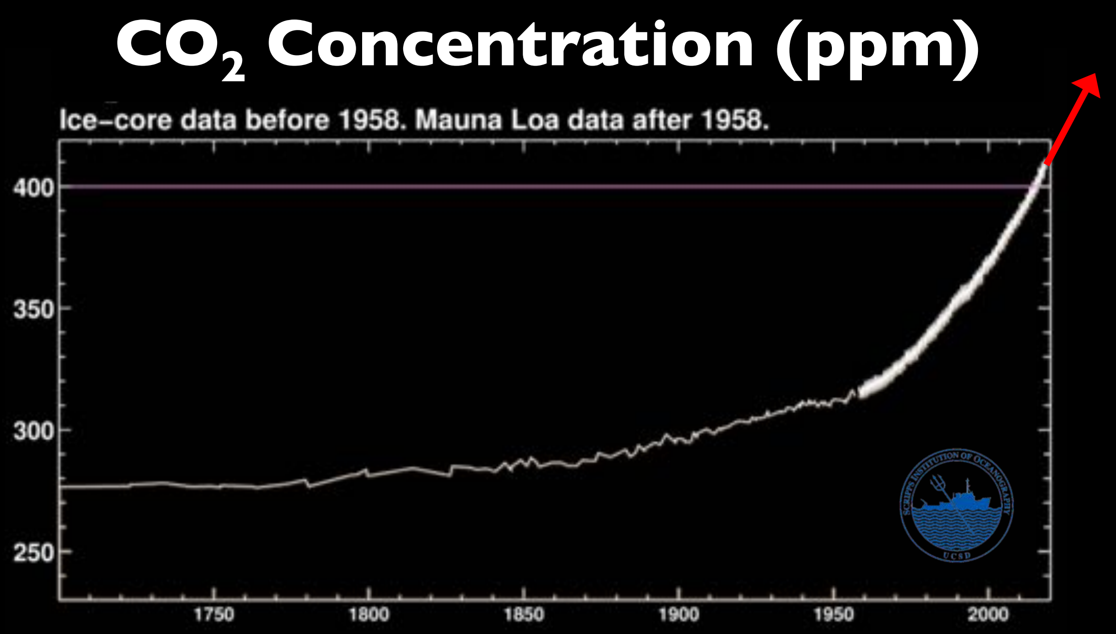
Gabriel Kooperman

University of Georgia

Forrest Hoffman (ORNL), Charles Koven (LBNL), Keith Lindsay (NCAR), Yang Chen (UCI), Megan Fowler (UCI), Baird Langenbrunner (UCI), Michael Pritchard (UCI), James Randerson (UCI), Abigail Swann (UW)

September 20, 2018

How do plant physiological responses to rising CO_2 contribute to long-term changes in the hydrological cycle?



Precipitation

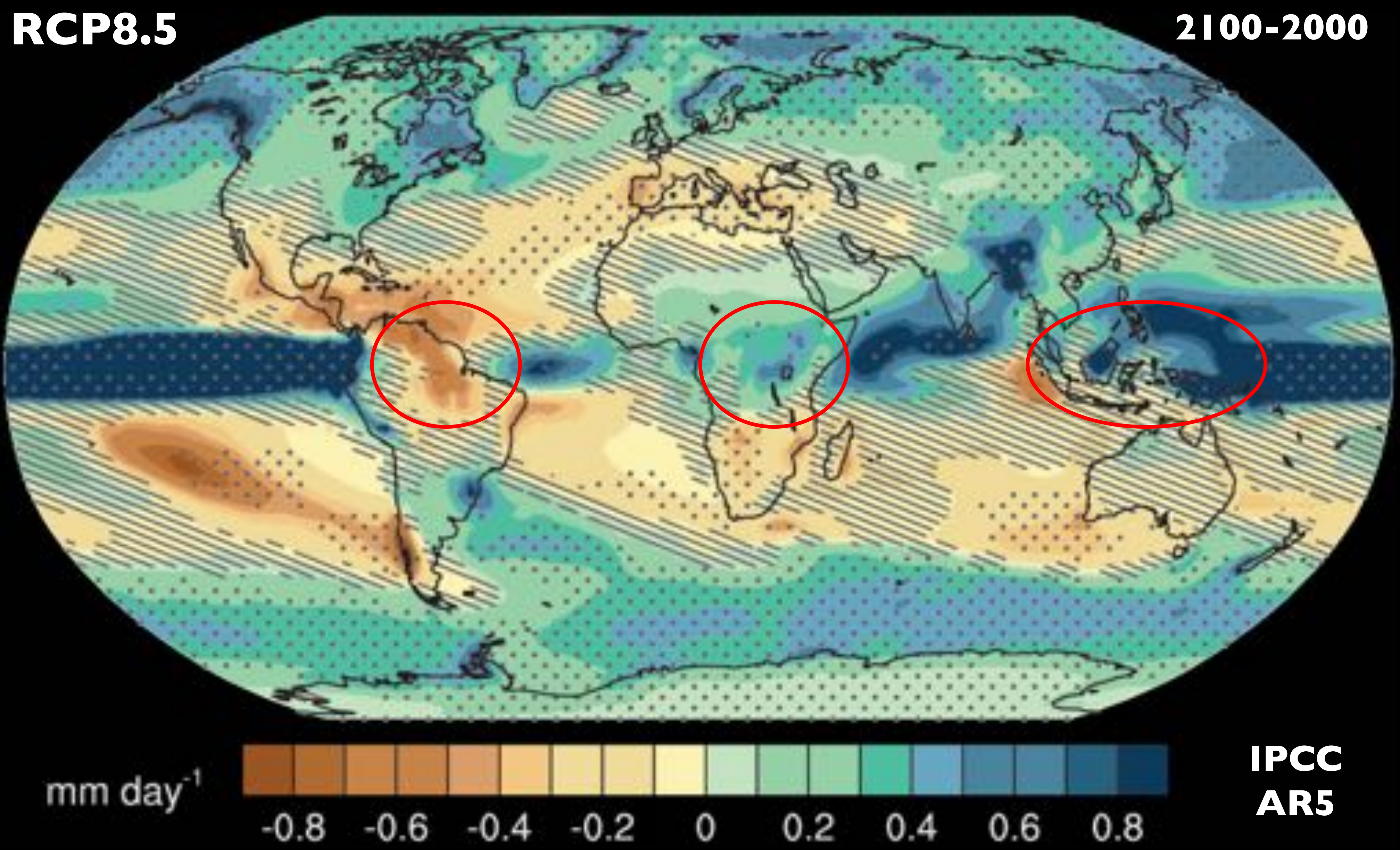
Drought

Flooding

Heat/Fire

Tropical forests are critical for carbon cycling and biodiversity, but future rainfall changes over forests have seemed uncertain

Annual Mean Precipitation Change

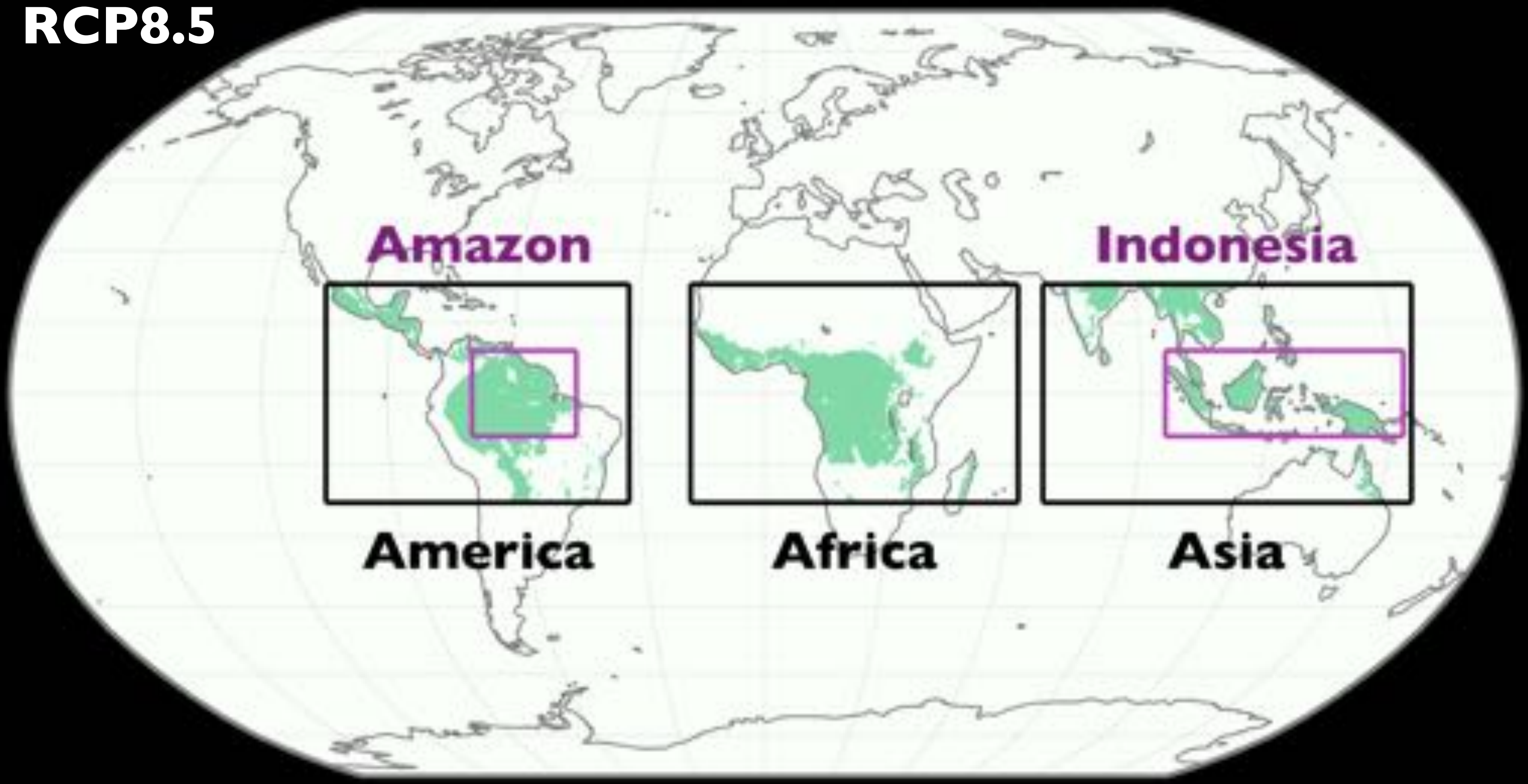


IPCC AR5

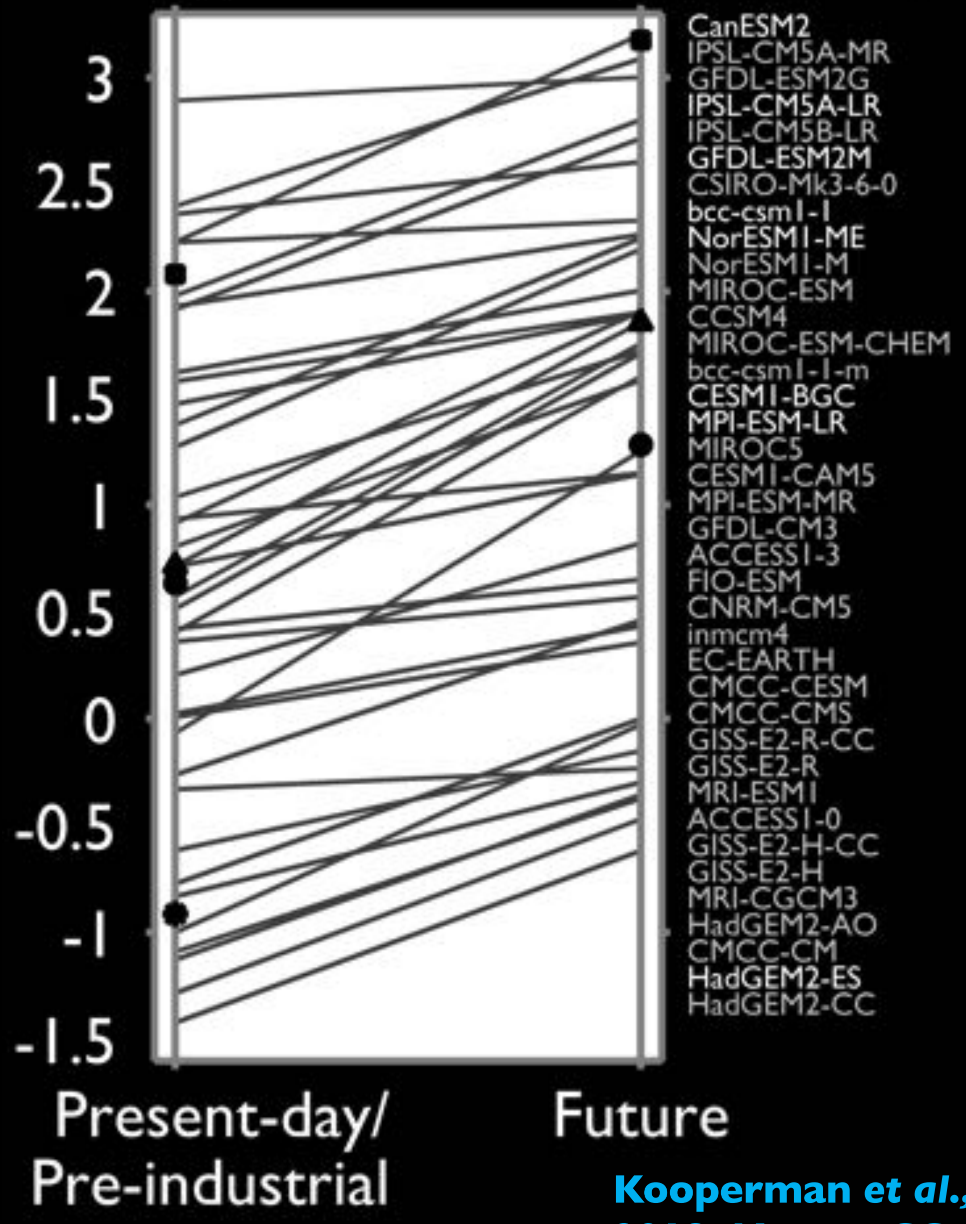
Despite this uncertainty, all modern climate models project a growing zonally asymmetric rainfall pattern across the tropics

Tropical Forest Regions

RCP8.5



Precipitation Asymmetry



Tropical Precipitation Asymmetry Index

$$I_{TPA} = (P_{Asia} + P_{Africa})/2 - P_{America}$$

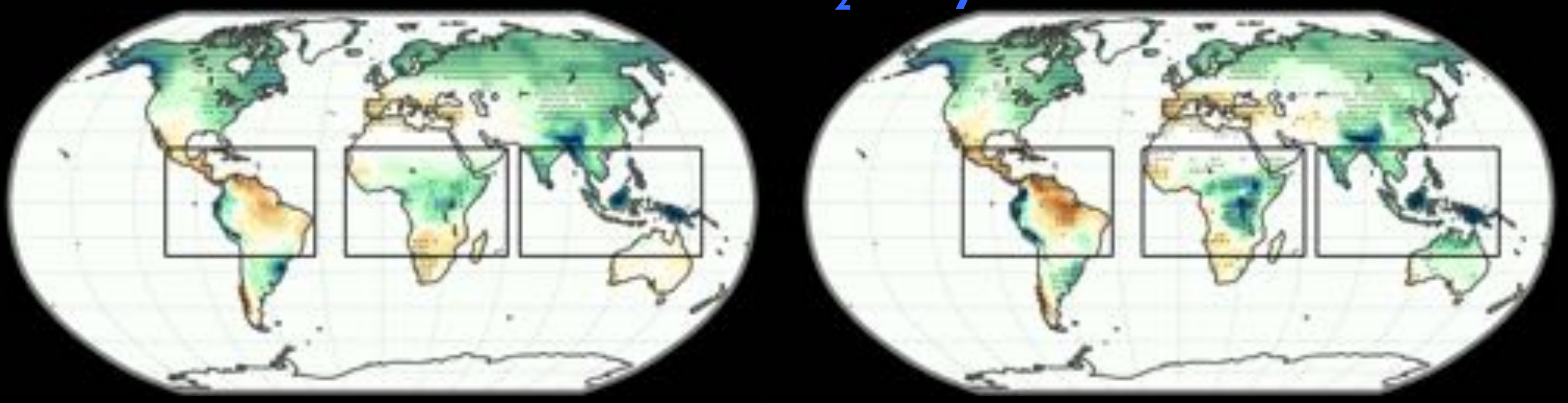
Kooperman *et al.*, 2018, Nature CC

Zonally asymmetric rainfall pattern is driven by both radiative greenhouse and plant physiological responses to increasing CO_2

Annual Mean Precipitation Change

RCP8.5

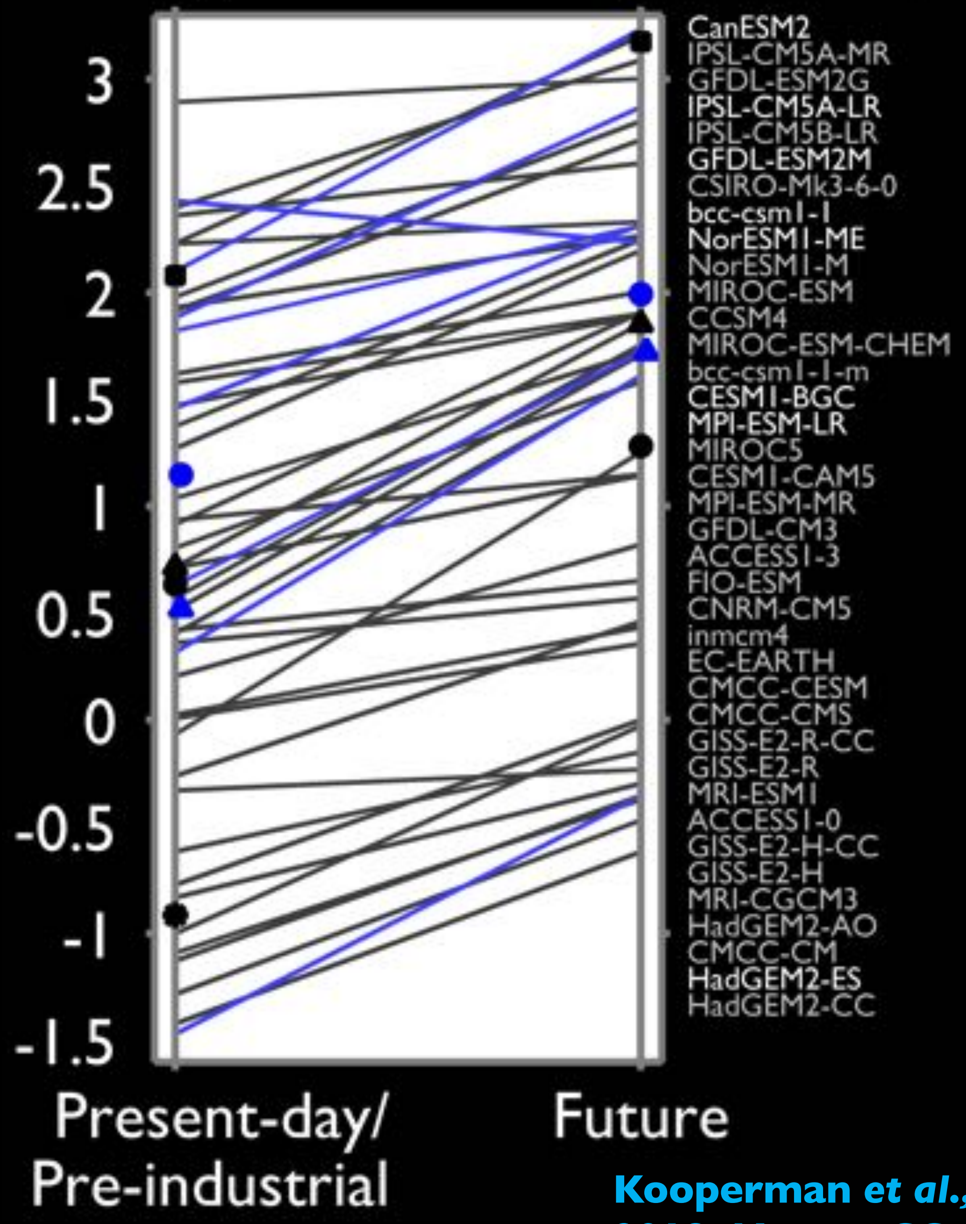
CO_2-Only



Physiological Effects of CO_2

Greenhouse Effects of CO_2

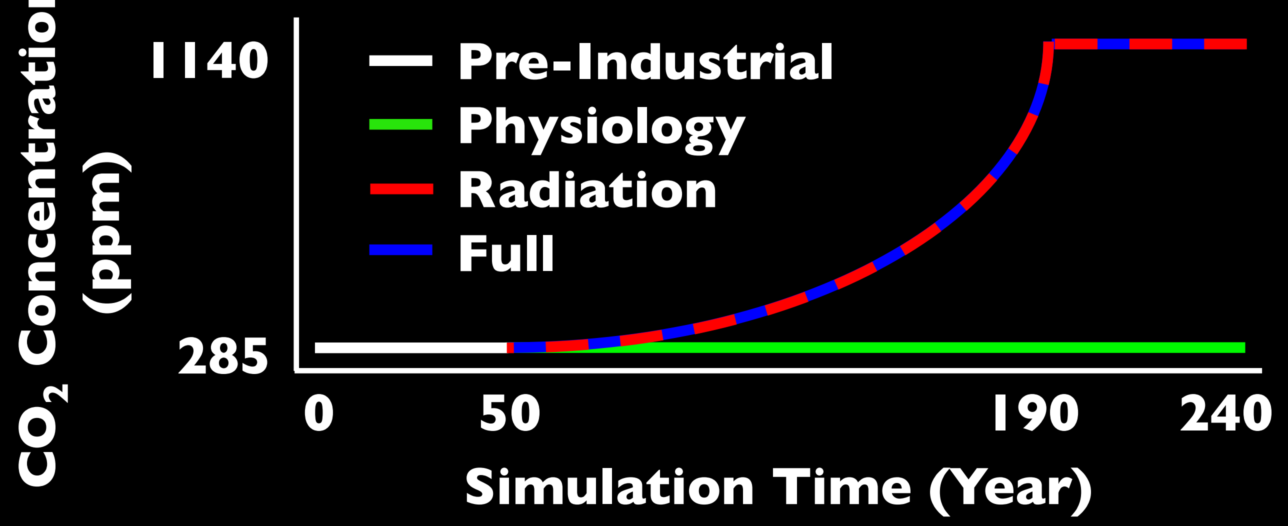
Precipitation Asymmetry



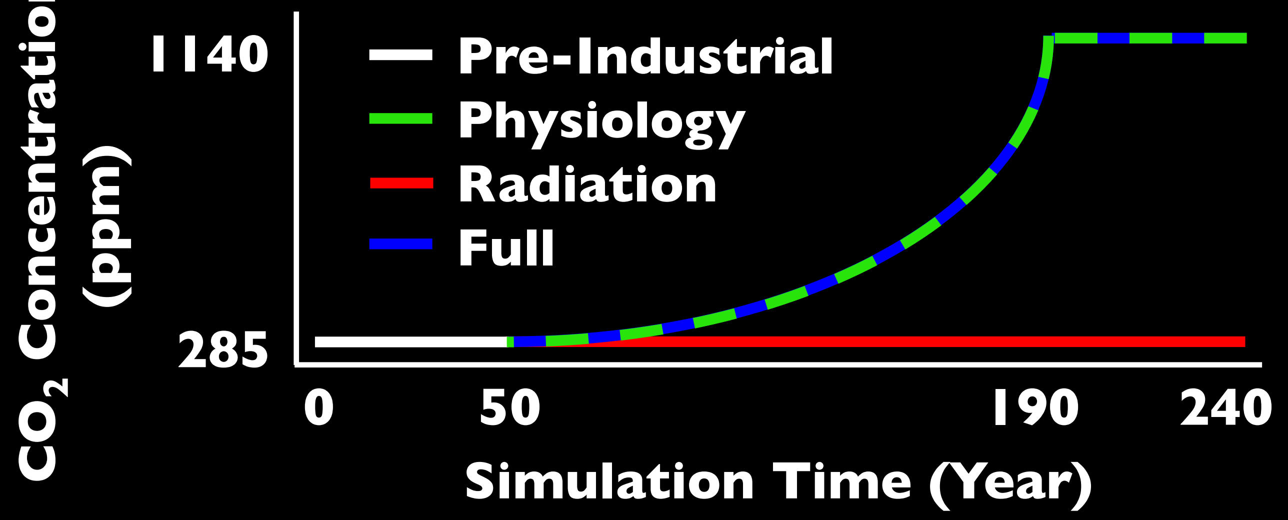
Kooperman *et al.*, 2018, Nature CC

Idealized CO_2-only forcing simulations separate the radiative-greenhouse and plant-physiology impacts of rising CO_2

Atmosphere CO_2 Radiative Forcing



Land CO_2 Physiological Forcing

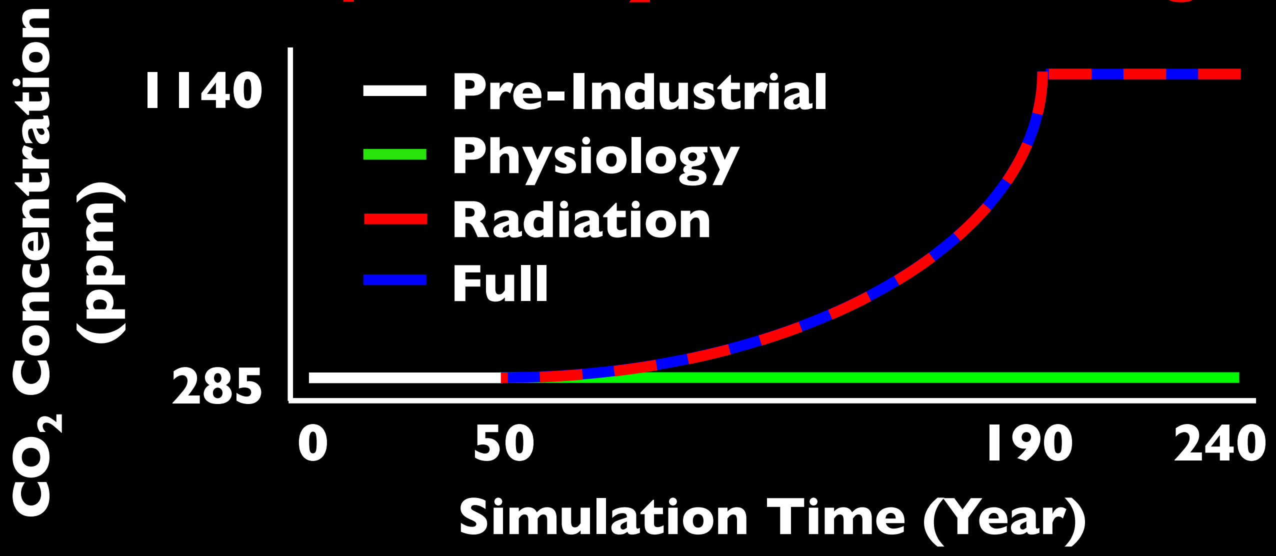


Community Earth System Model

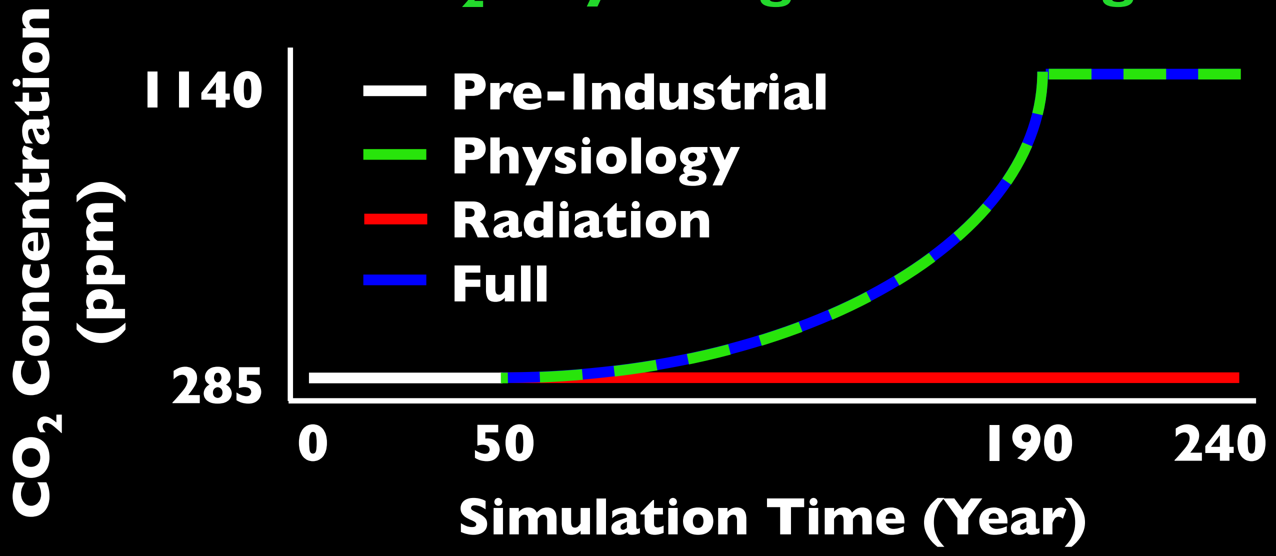
CAM	CLM
Pre-Industrial	Pre-Industrial
$4xCO_2$	$4xCO_2$
$4xCO_2$	Pre-Industrial
Pre-Industrial	$4xCO_2$

Idealized CO_2-only forcing simulations separate the radiative-greenhouse and plant-physiology impacts of rising CO_2

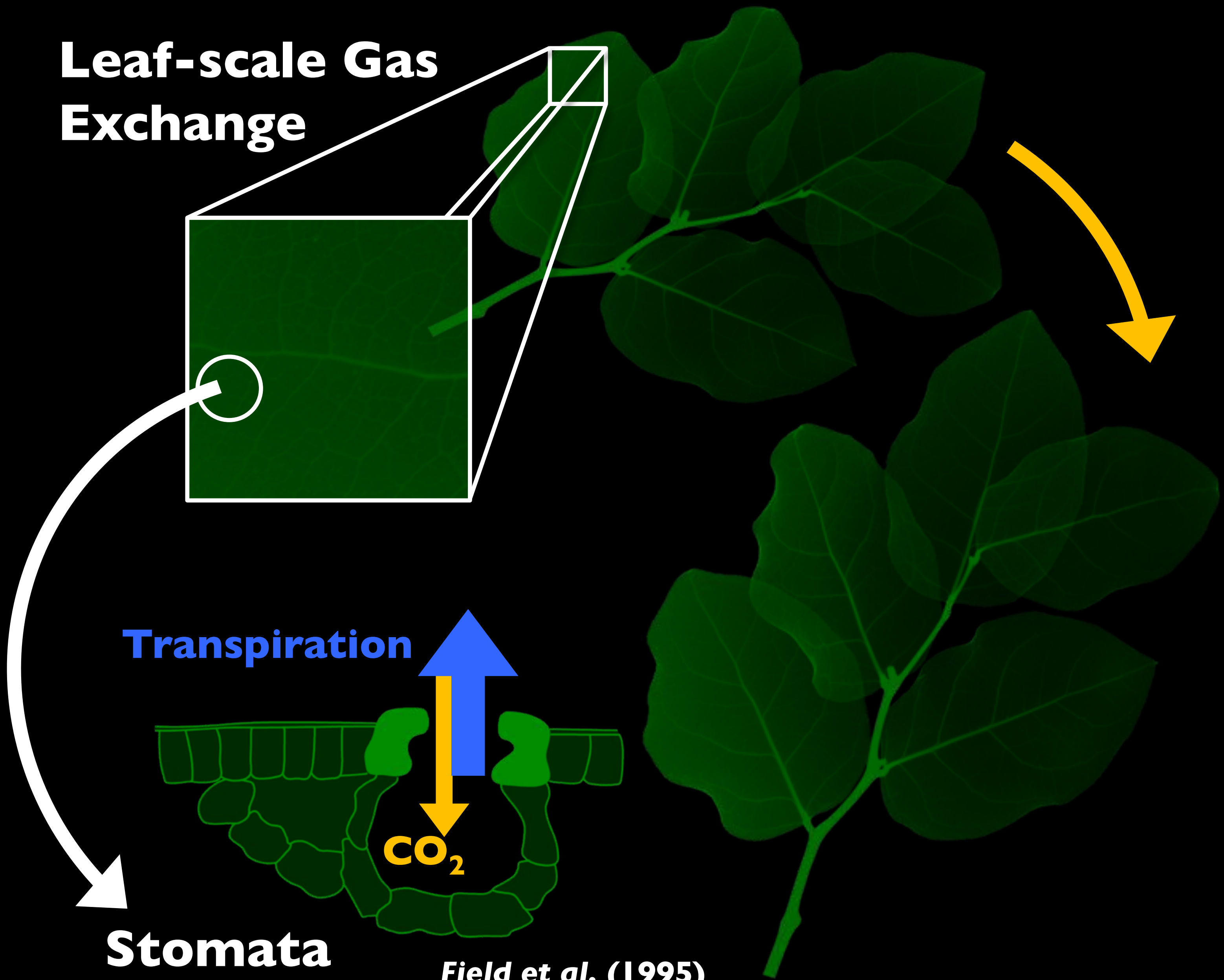
Atmosphere CO_2 Radiative Forcing



Land CO_2 Physiological Forcing



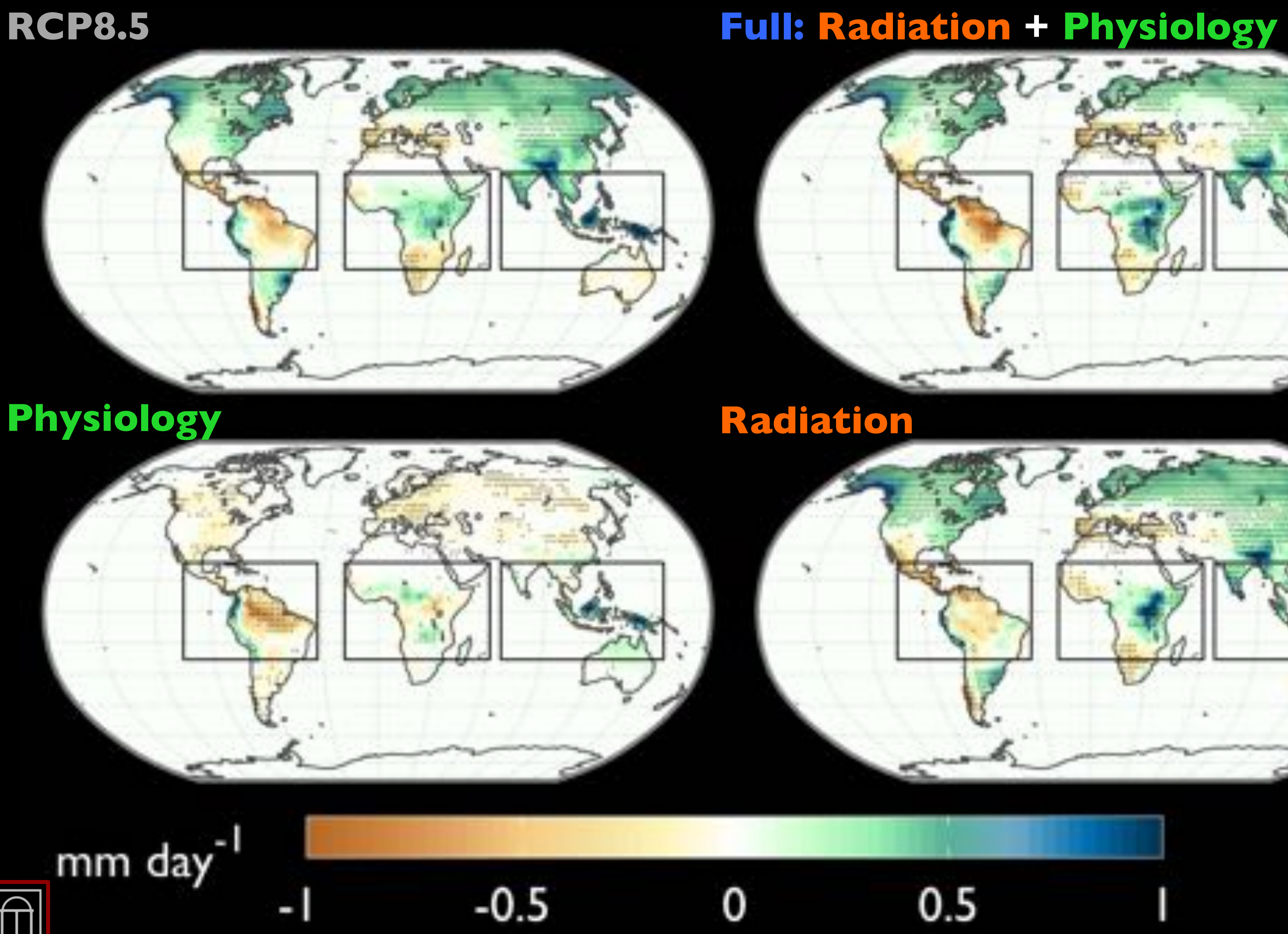
Physiology: Stomatal Conductance and Leaf Area



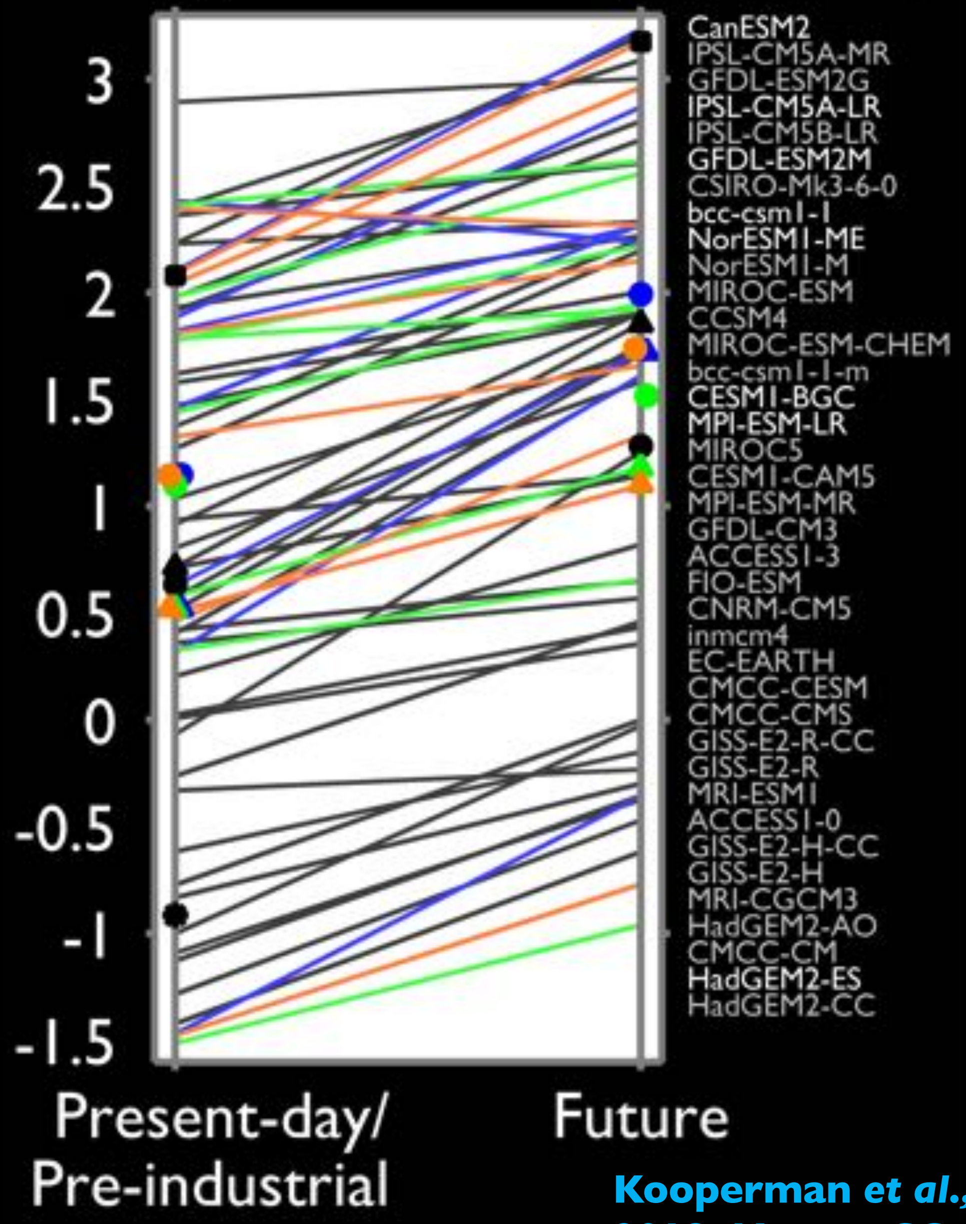
Field et al. (1995)

Zonally asymmetric rainfall pattern is driven by both radiative greenhouse and plant physiological responses to increasing CO_2

Annual Mean Precipitation Change



Precipitation Asymmetry

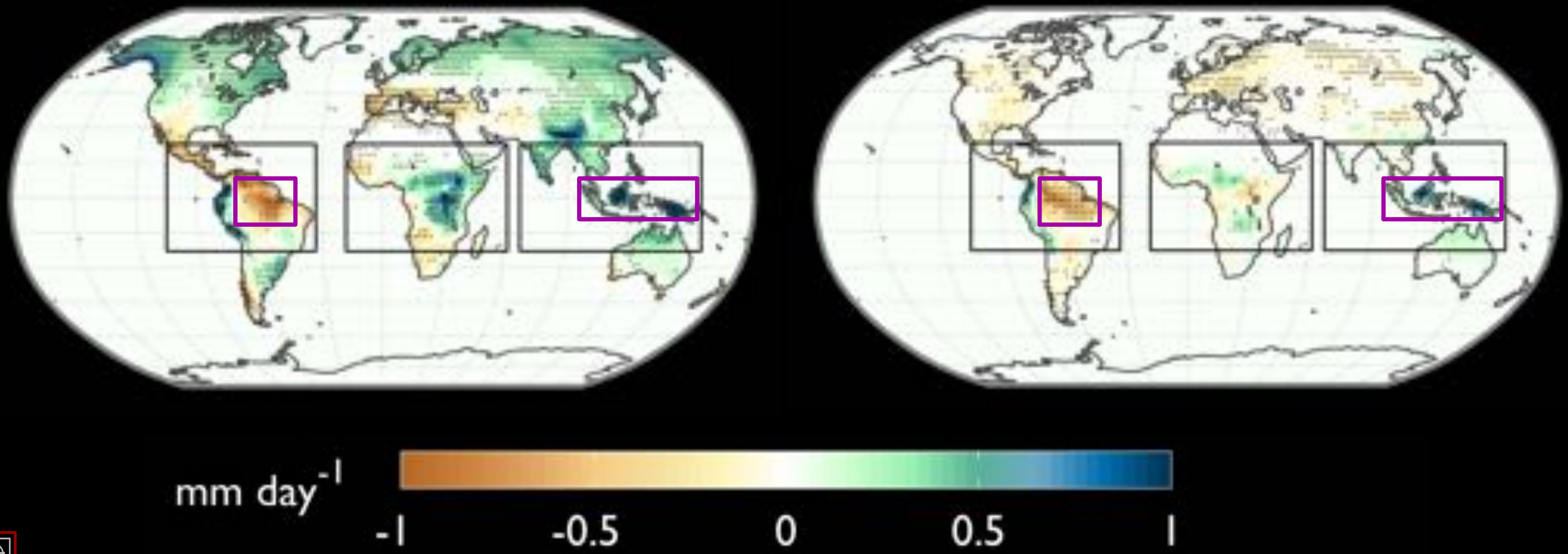


Kooperman *et al.*, 2018, Nature CC

Plant physiological responses alone are a dominant component of the overall precipitation change over dense tropical forests

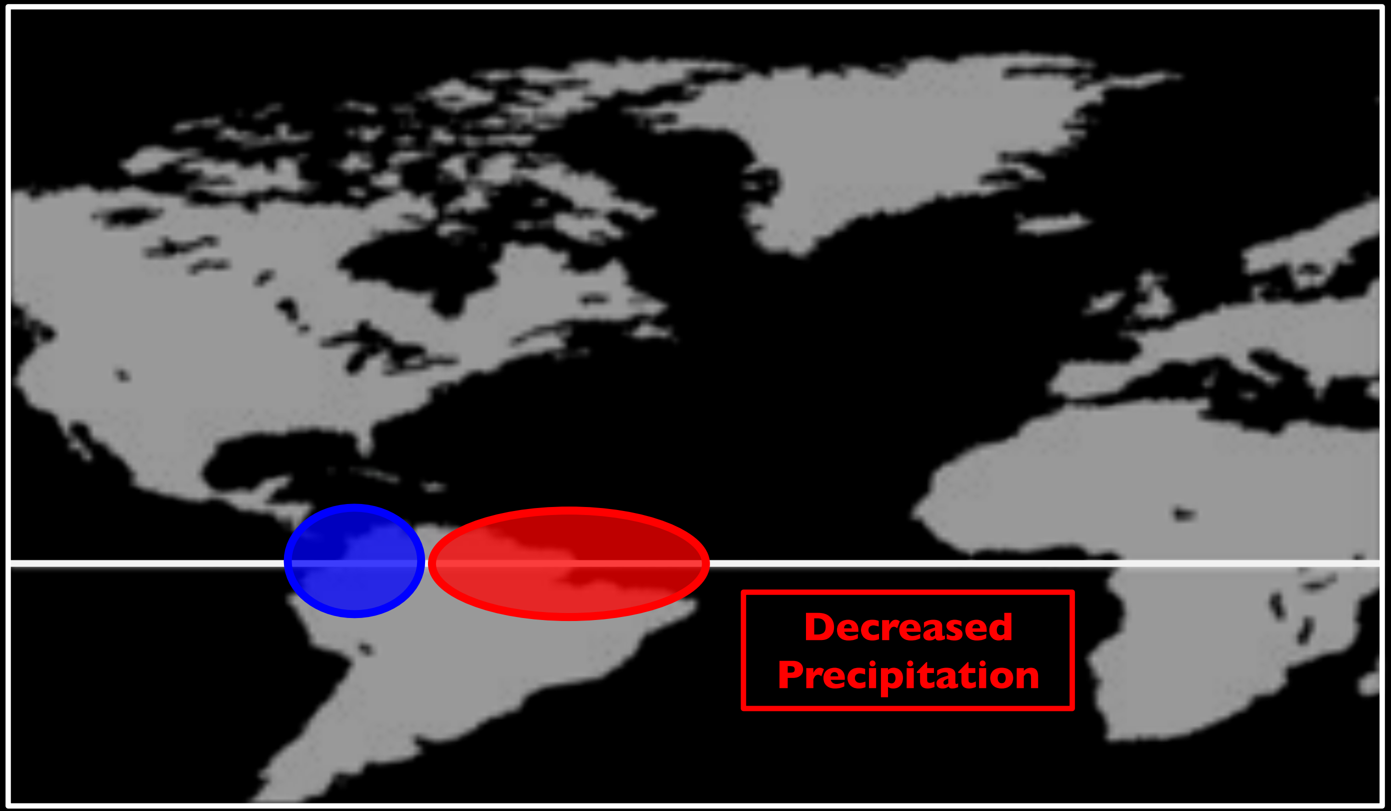
Annual Mean Precipitation Change

Full: Radiation + Physiology | Physiology

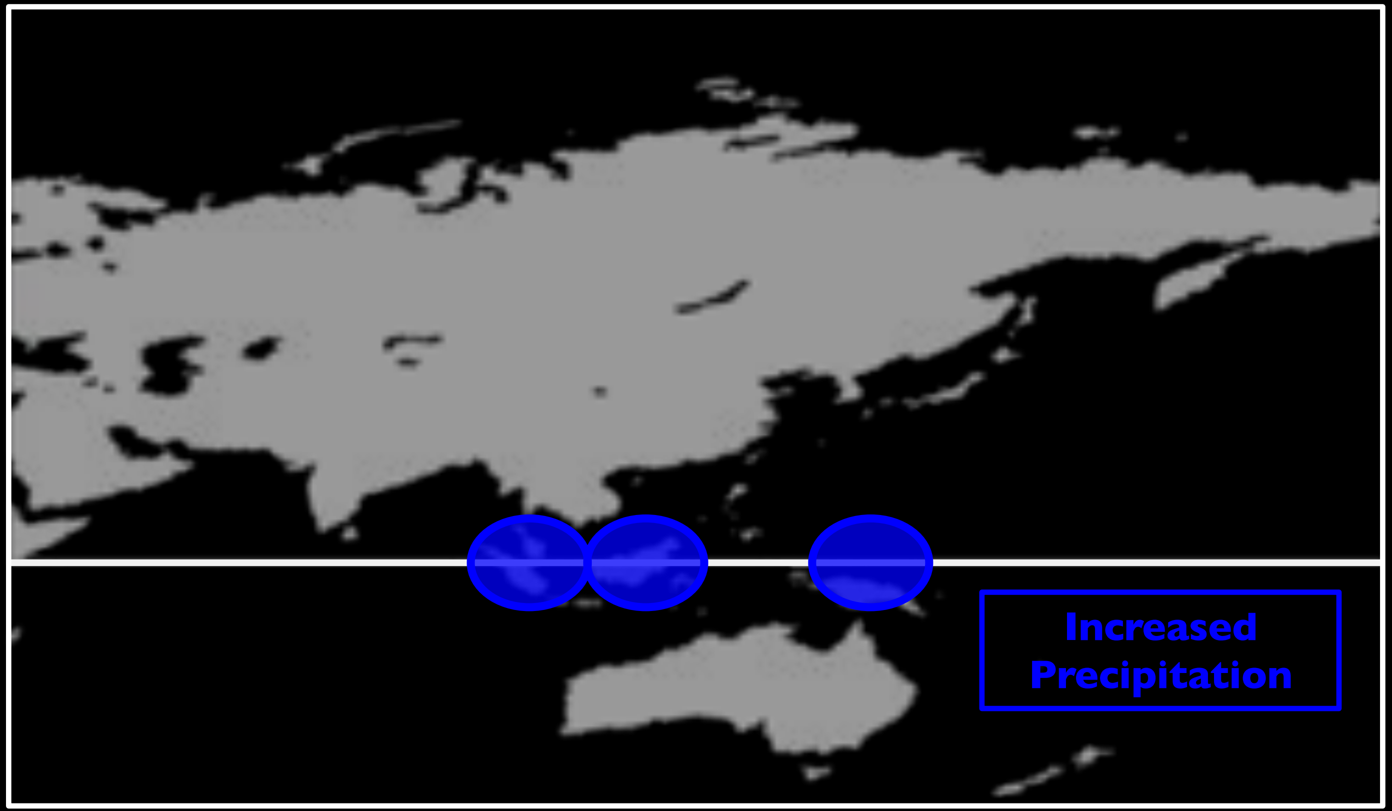


How do plant physiological responses to rising CO_2 contribute to this zonally asymmetric pattern of rainfall change?

Amazon



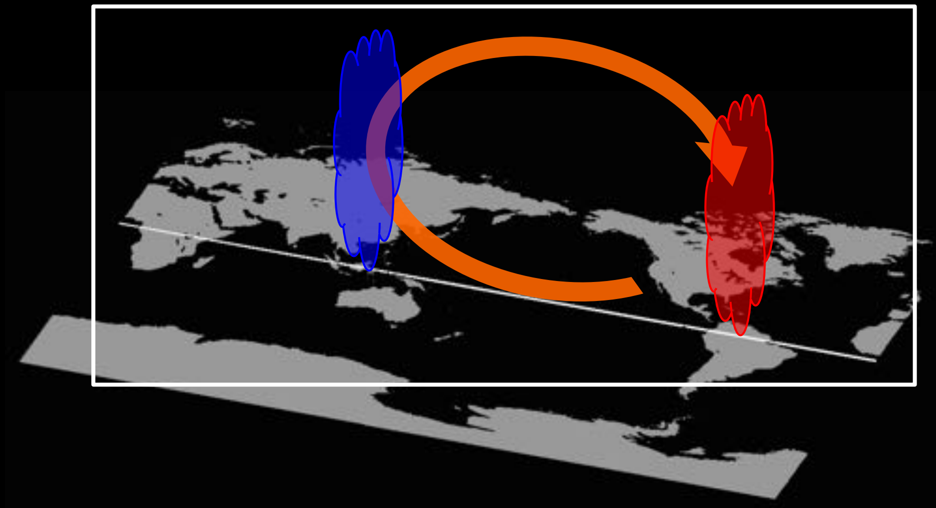
Indonesia



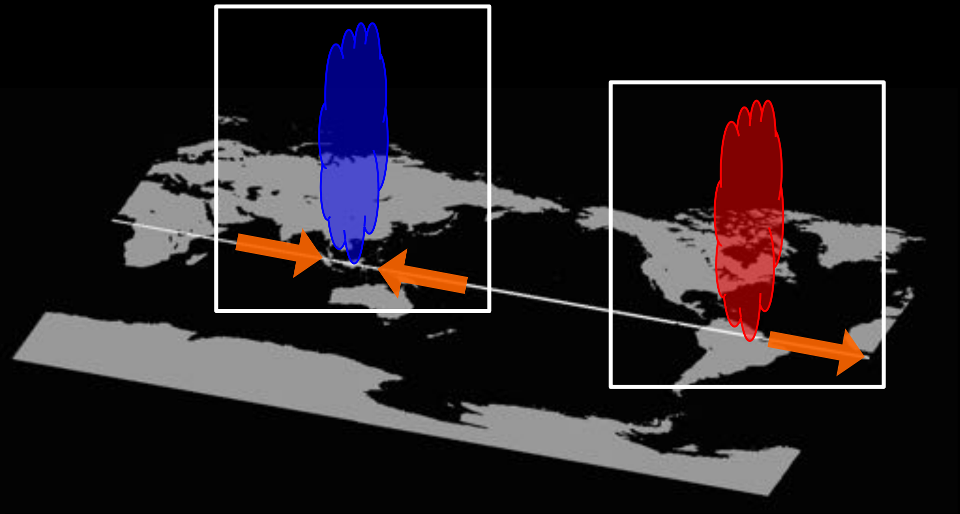
Precipitation ↑
Precipitation ↓

A new experiment with CESM tests if the pattern is driven by tropics-wide (e.g. Walker Circulation) or regional mechanisms

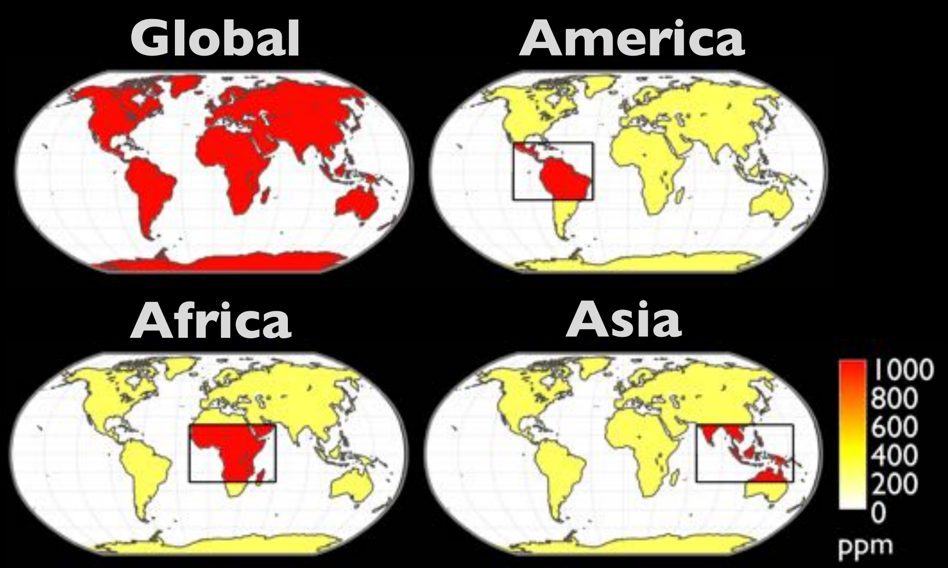
Tropics Wide Mechanism



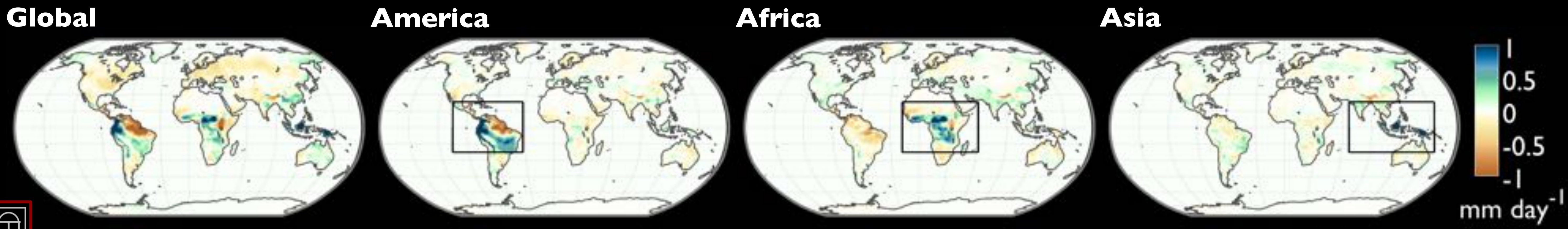
Regional Mechanisms



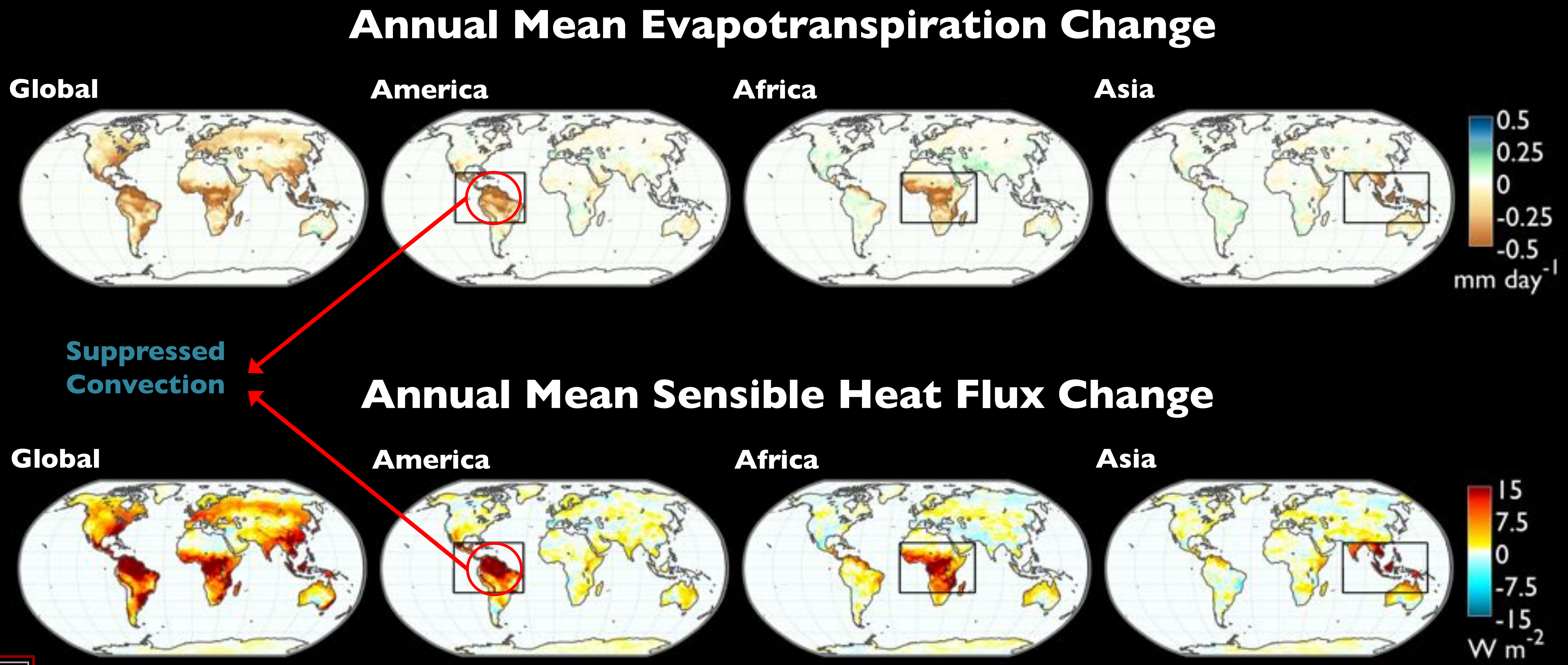
CO_2 Concentration



Annual Mean Precipitation Change



Higher CO_2 reduces stomatal conductance and transpiration, modifying surface heat fluxes and near-surface air conditions



How do plant physiological responses to rising CO_2 contribute to this zonally asymmetric pattern of rainfall change?

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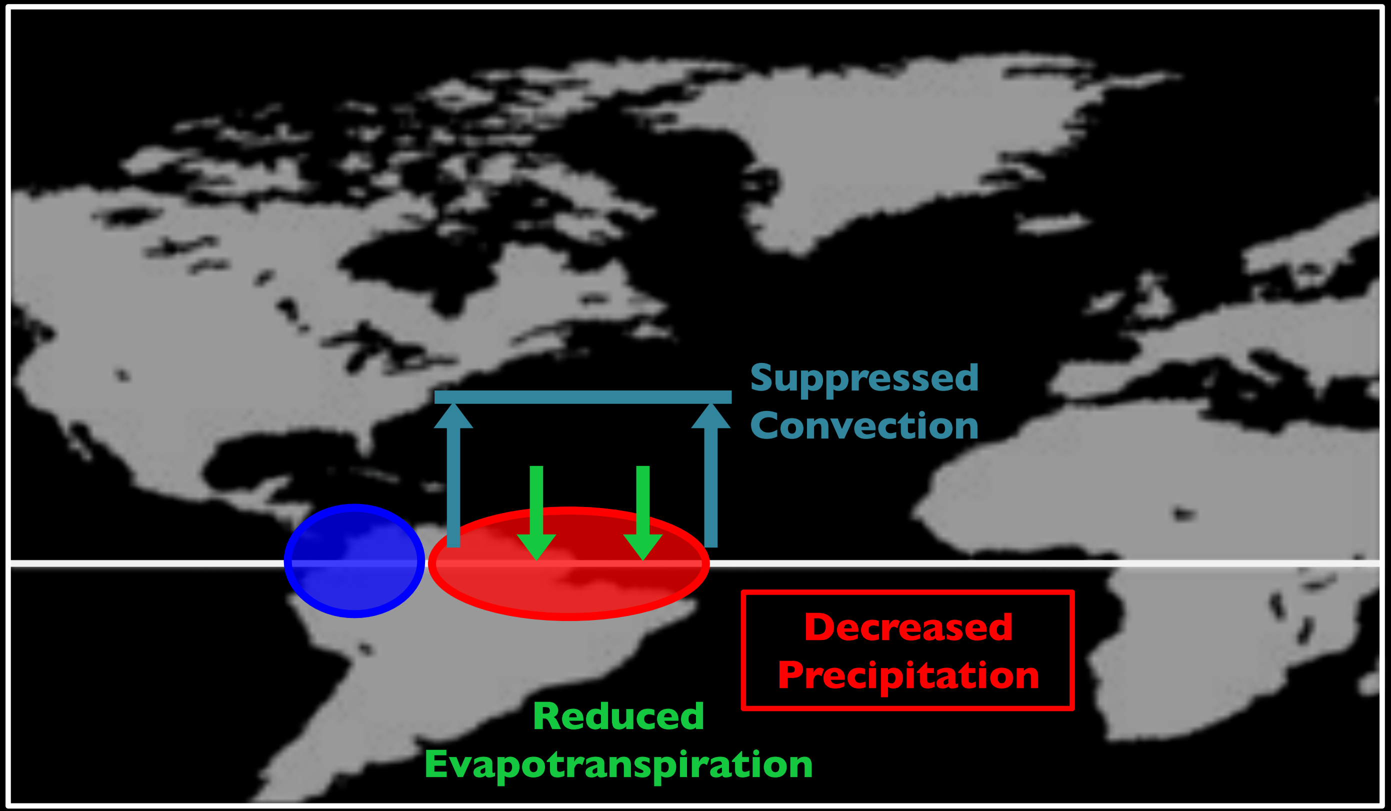
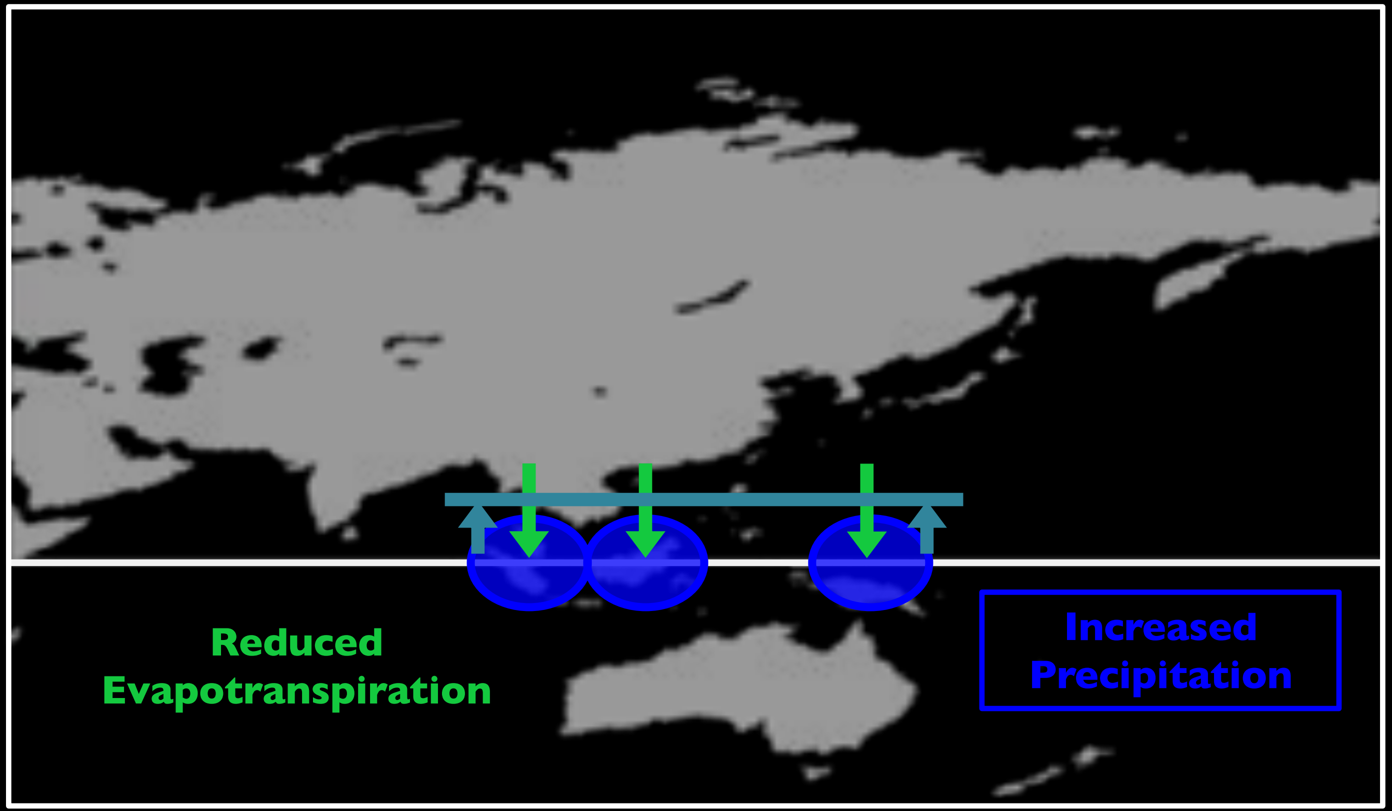


Indonesia

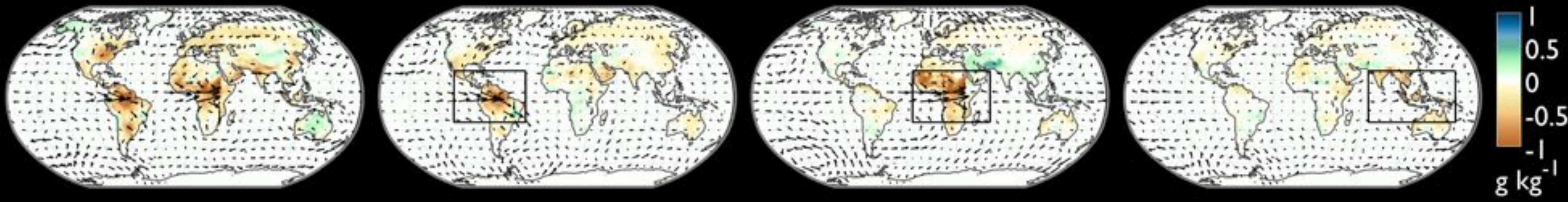


Precipitation ↑
Precipitation ↓
Evapotranspiration ↓
Condensation Level ↑

Surface flux changes drive convectively-coupled and island-like circulations over the Amazon and Indonesia, respectively

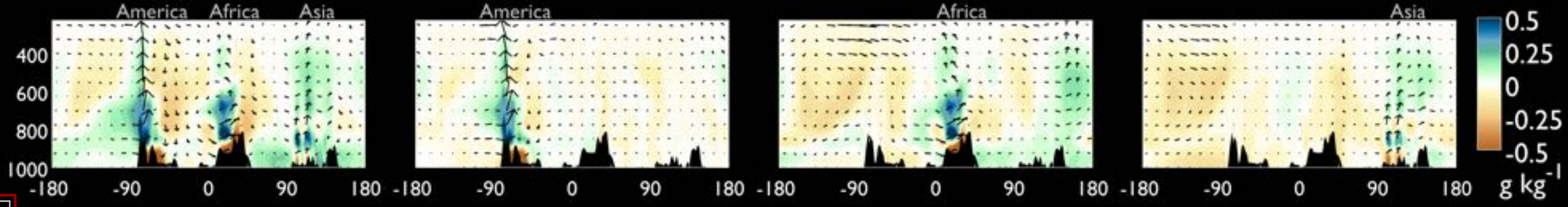
Annual Mean Surface Specific Humidity Change

Global **America** **Africa** **Asia**



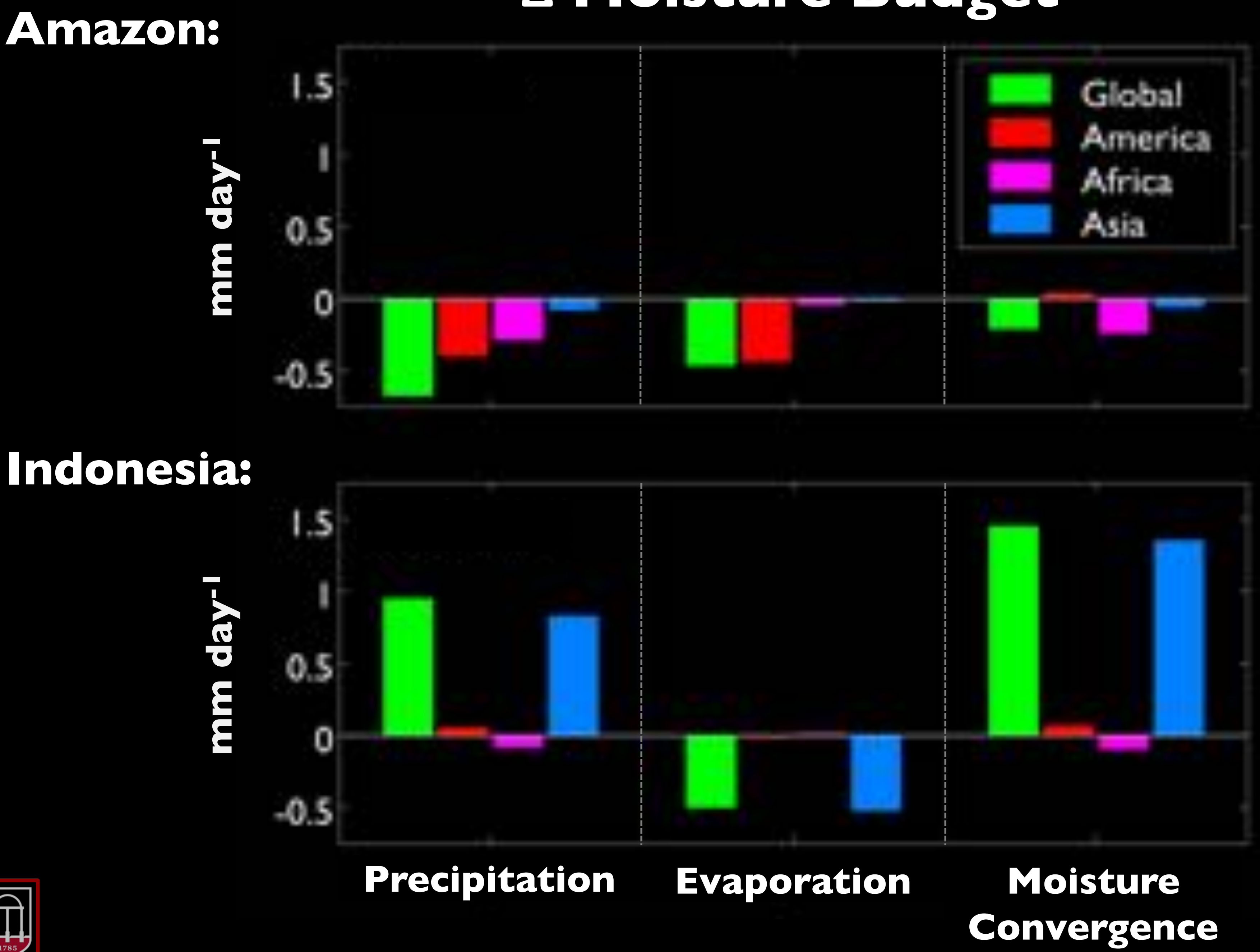
Annual Mean Tropical (5˚S - 5˚N) Specific Humidity Change

Global **America** **Africa** **Asia**



Locally and non-locally driven moisture convergences changes lead to less rainfall over the Amazon and more over Indonesia

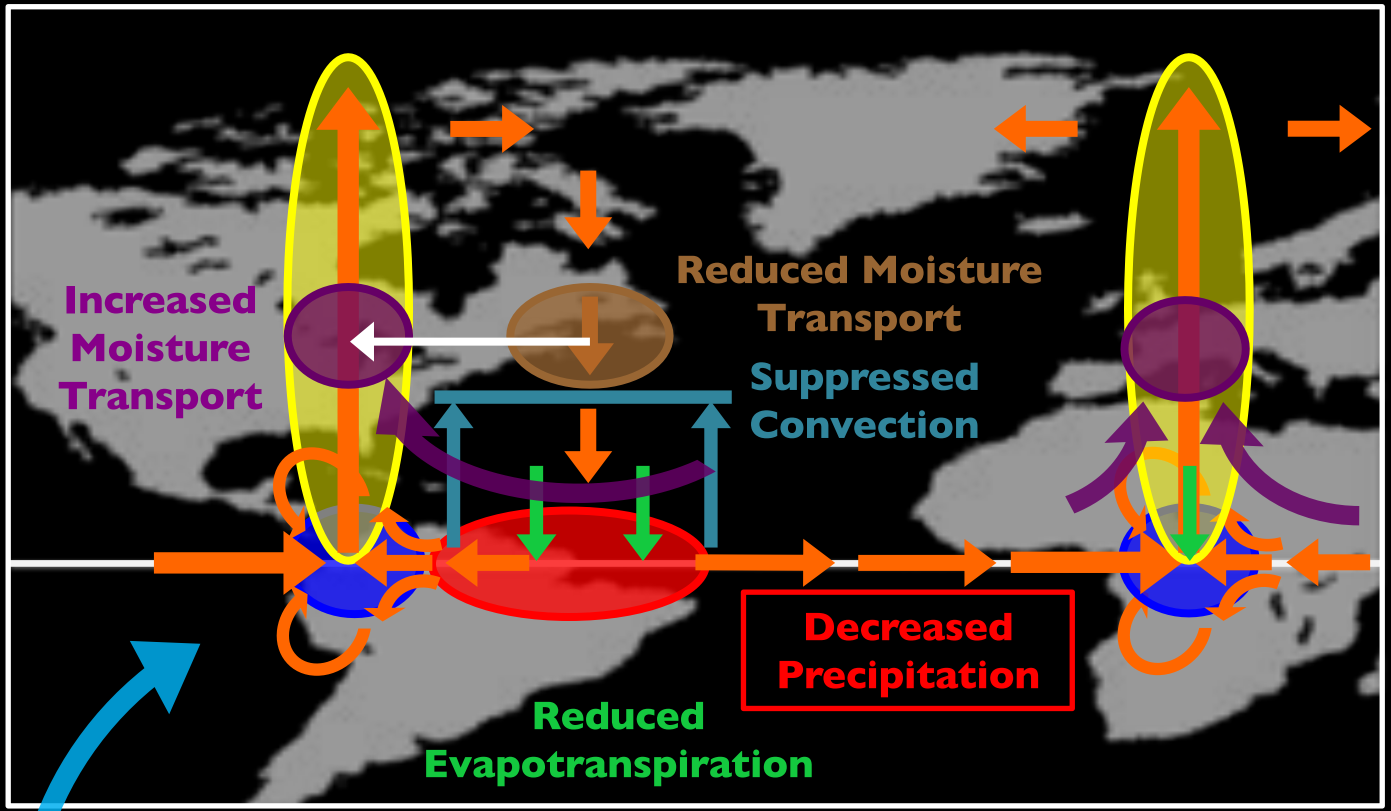
Δ Moisture Budget



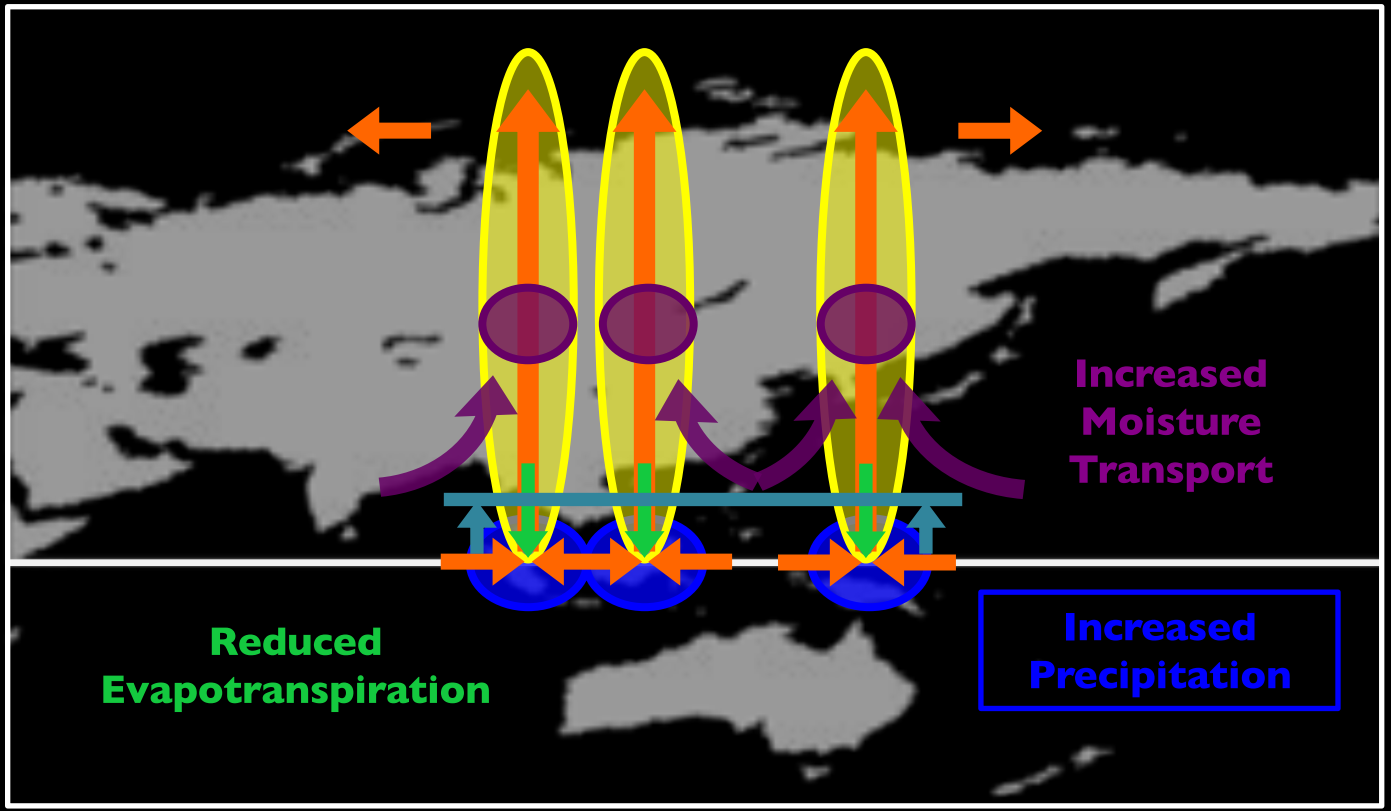
- **Precipitation reduction over the Amazon has local and non-local (Africa) influences**
- **Evapotranspiration reduction from local forcing over the Amazon and Indonesia have similar magnitudes**
- **Indonesia has a larger rise in moisture convergence than evapotranspiration reduction**
- **Circulation changes from the Africa forcing lower moisture convergence to the Amazon**

How do plant physiological responses to rising CO_2 contribute to this zonally asymmetric pattern of rainfall change?

Amazon



Indonesia



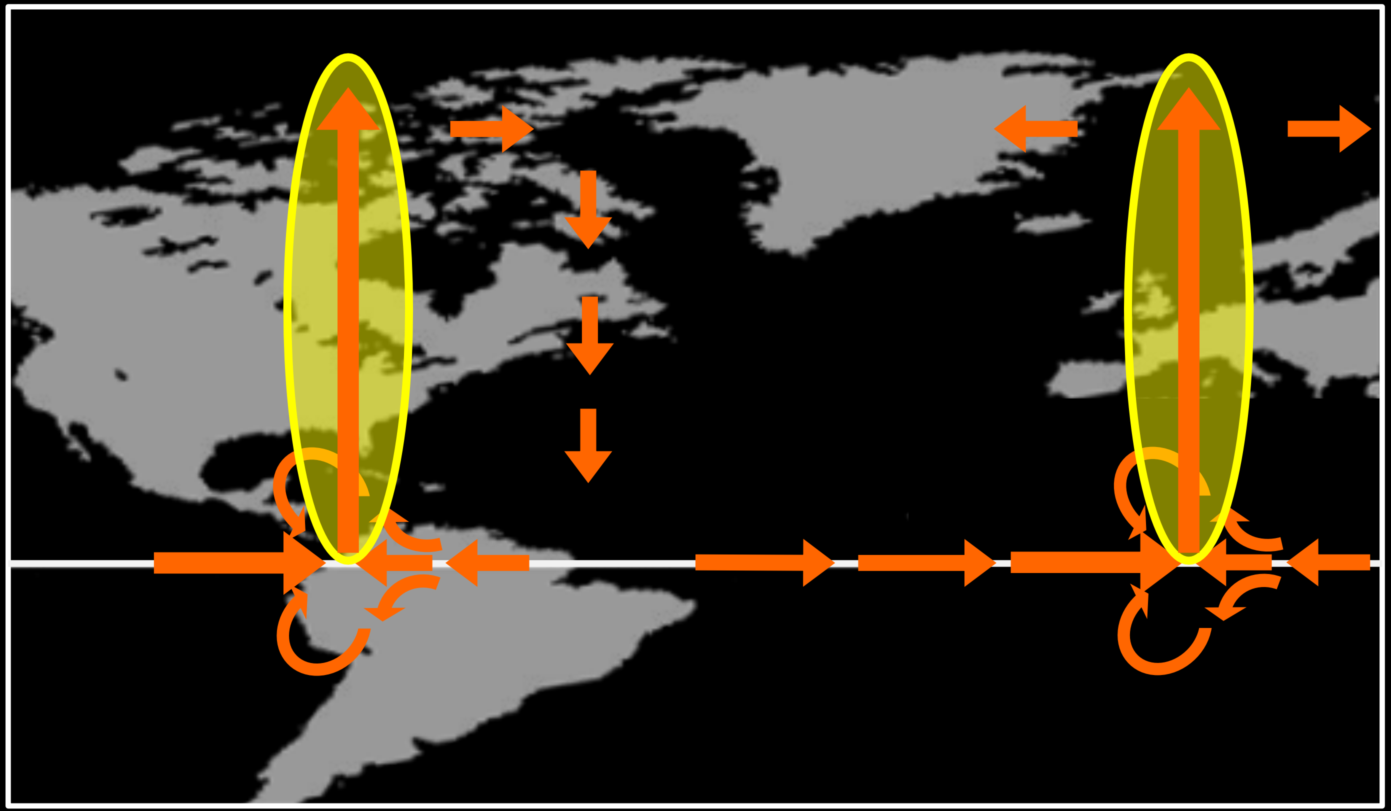
Precipitation ↑ Evapotranspiration ↓ Convective Heating ↑ Moisture Convergence ↑
Precipitation ↓ Condensation Level ↑ Circulation Anomaly ← Moisture Convergence ↓

Export of Moist Static Energy ←

Langenbrunner *et al.*, submitted 2018

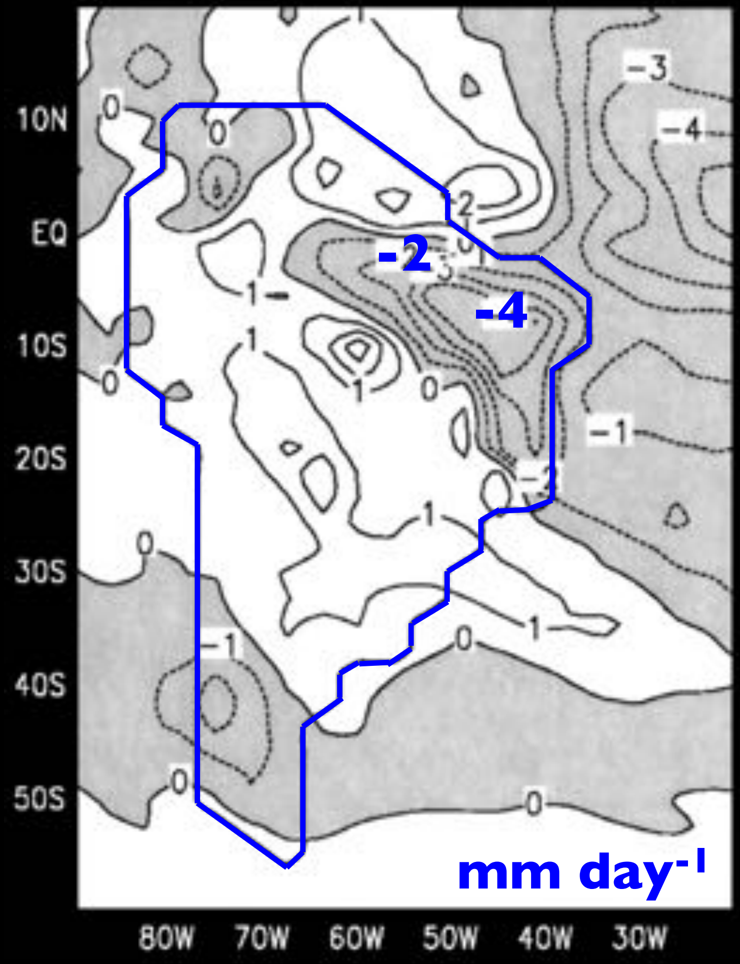
Simply the presence, proximity (~3000 km), and circulations of Africa reduce moisture flow and rainfall over the Amazon

Amazon

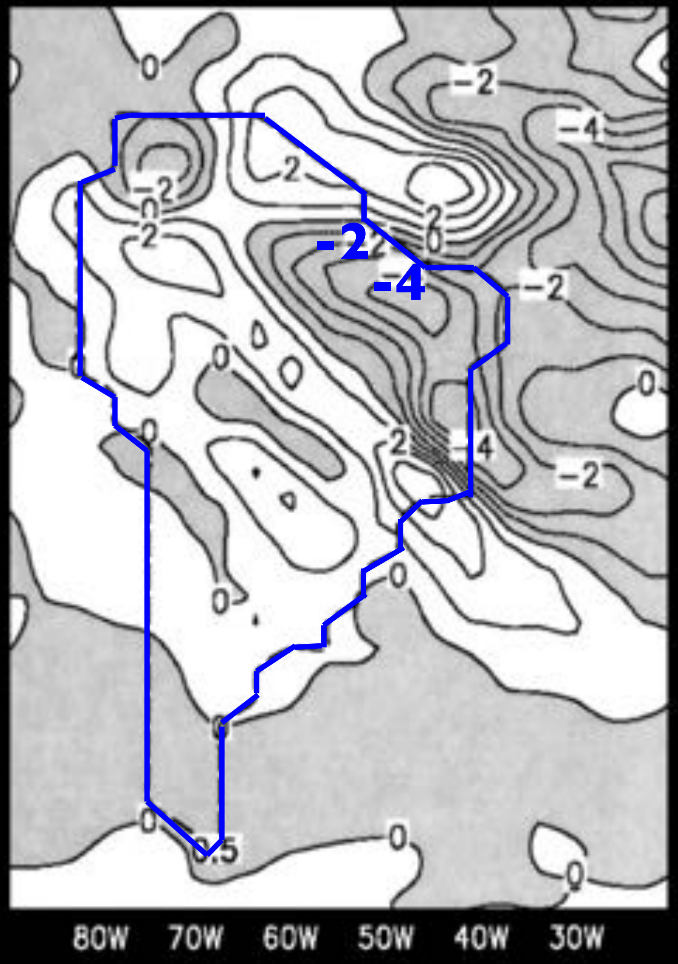


South American Rainfall
With Africa – Without Africa

Precipitation



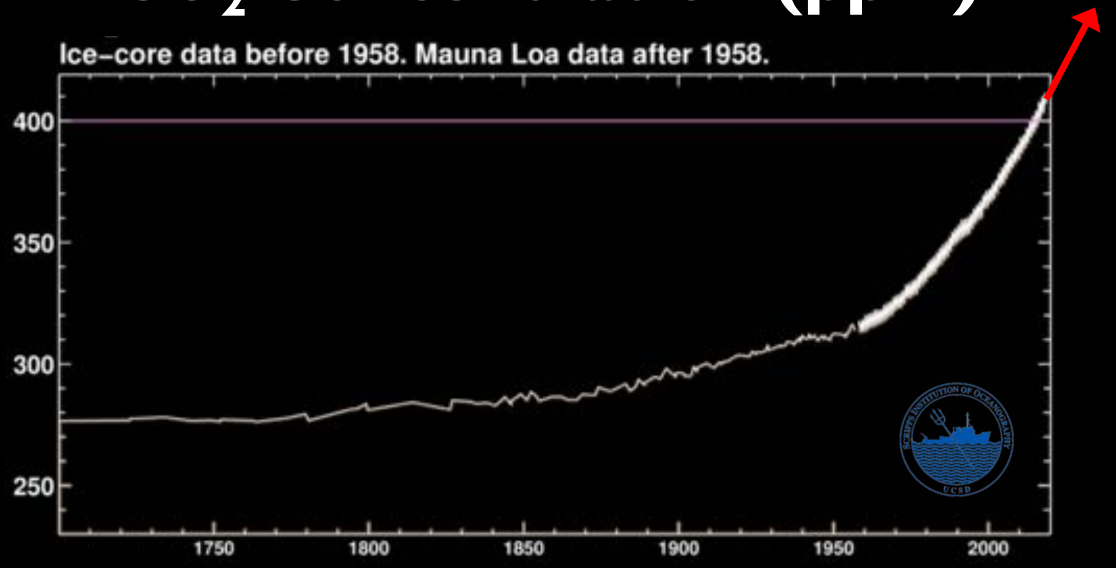
Moisture Convergence



Cook *et al.* (2004)

How do plant physiological responses to rising CO_2 contribute to long-term changes in the hydrological cycle?

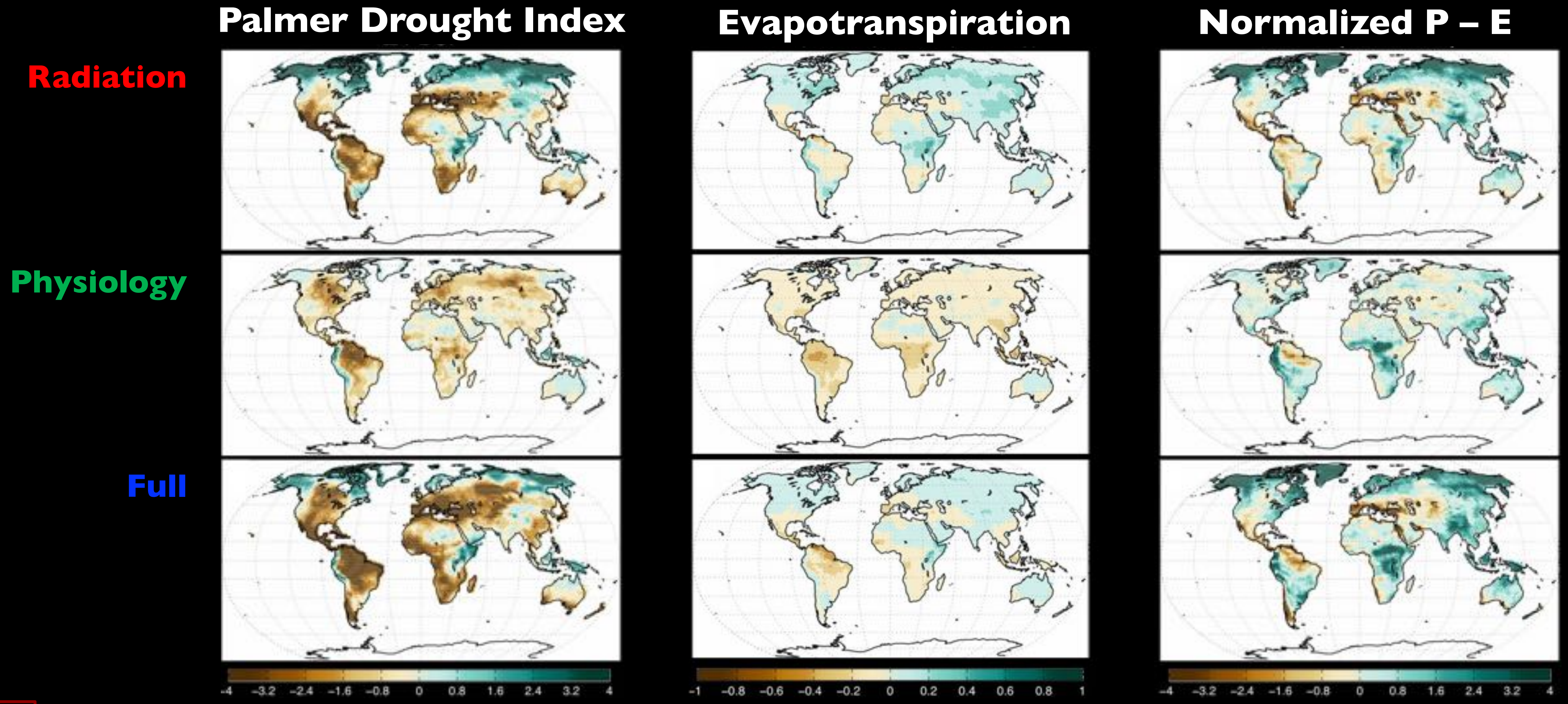
CO_2 Concentration (ppm)



Precipitation

Drought

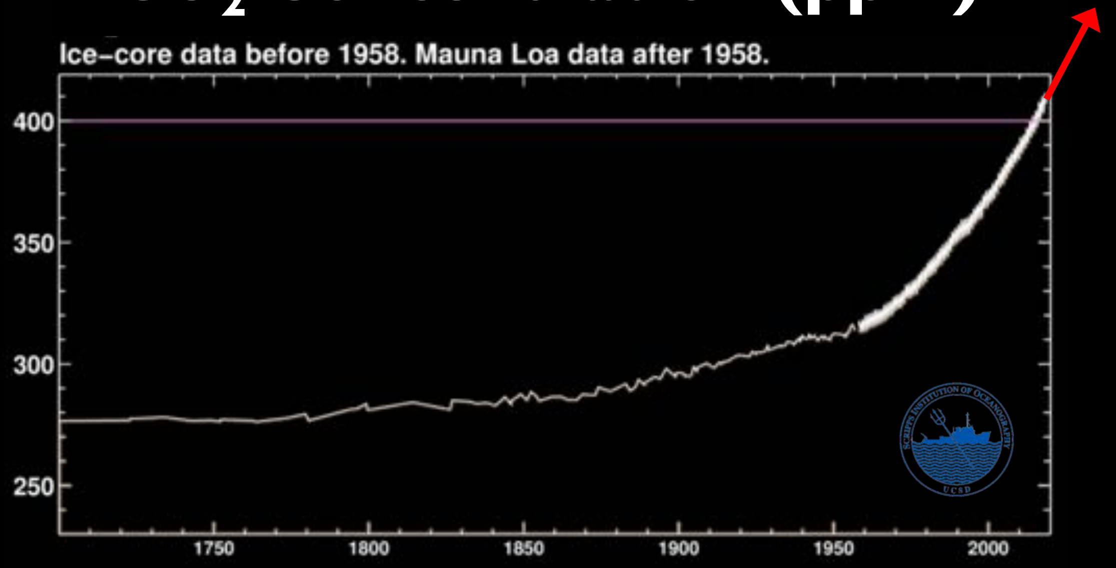
Drought assessments based on precipitation and temperature neglect the role of vegetation and project widespread increases



Swann *et al.*, 2016, PNAS

How do plant physiological responses to rising CO_2 contribute to long-term changes in the hydrological cycle?

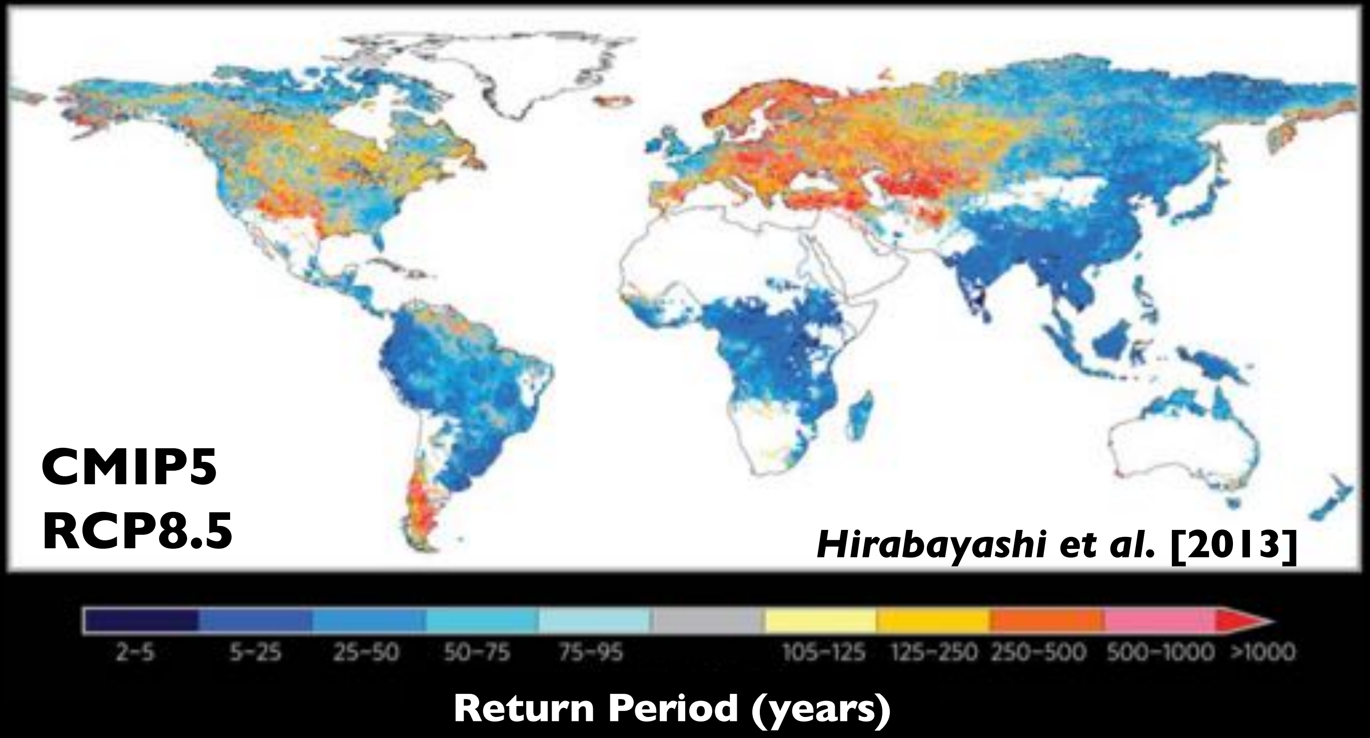
CO_2 Concentration (ppm)



Precipitation **Drought** **Flooding**

Global-scale river flooding exposure is expected to significantly increase due both climate change and population growth

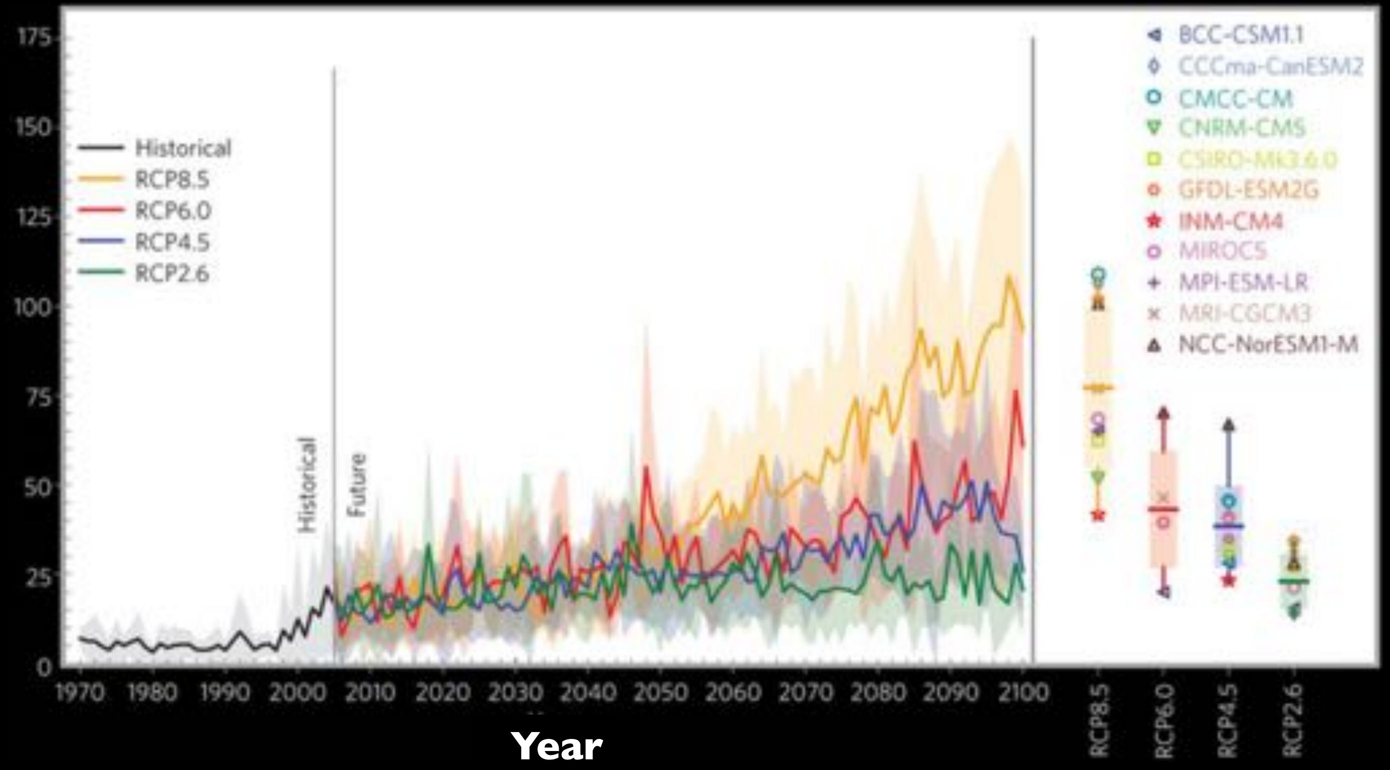
100-Year Flood Return Period Change



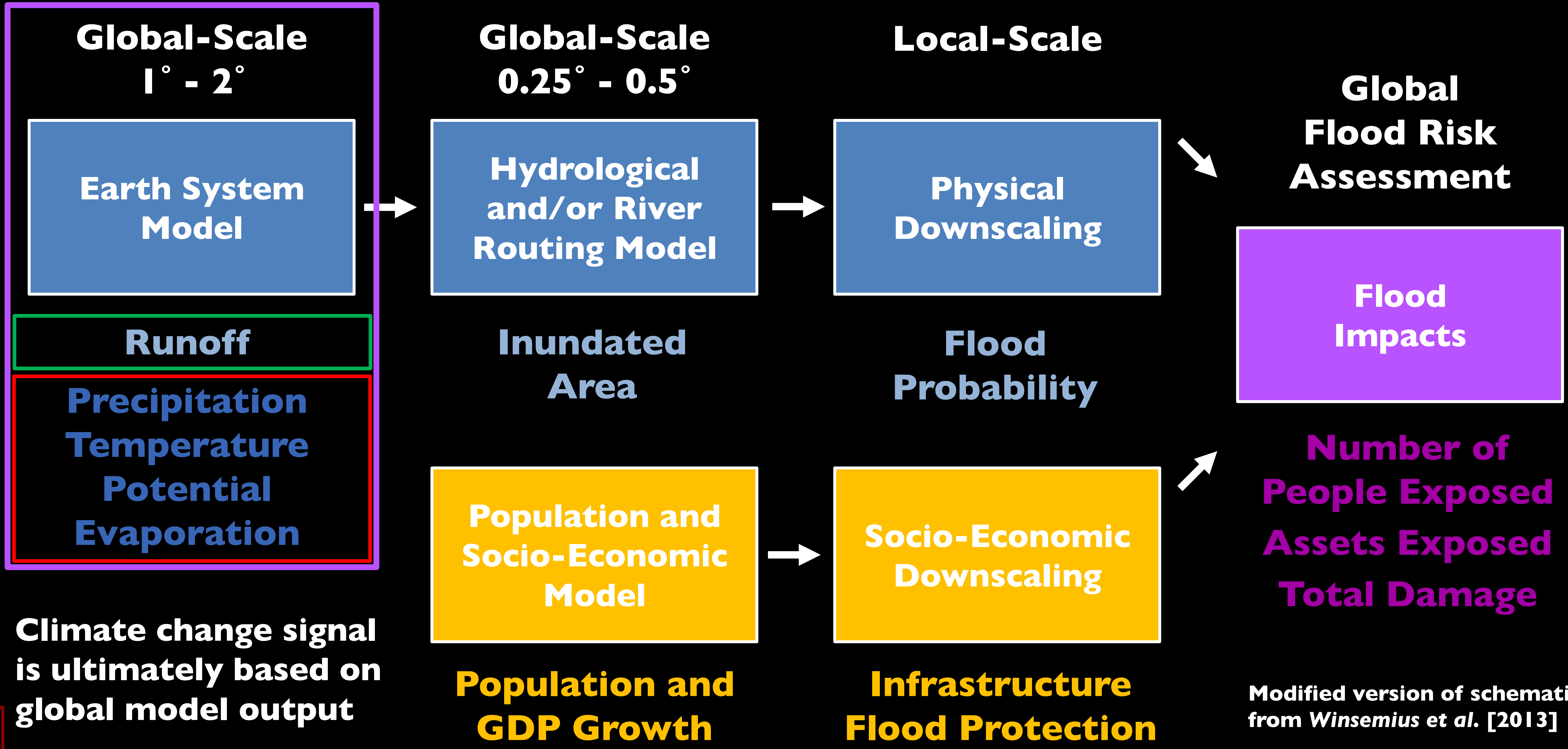
- With no population growth, up to 77 million more people could be at risk
- The number of people and property at risk is significantly higher when population growth is included

- Many recent global-scale flood assessments based on Earth system model projections
- Downscaling global runoff with CaMa-Flood model indicates a significant increase in river flood frequency and intensity

Millions of People Exposed



Global assessments based on Earth system model projections requires downscaling of either precipitation or runoff

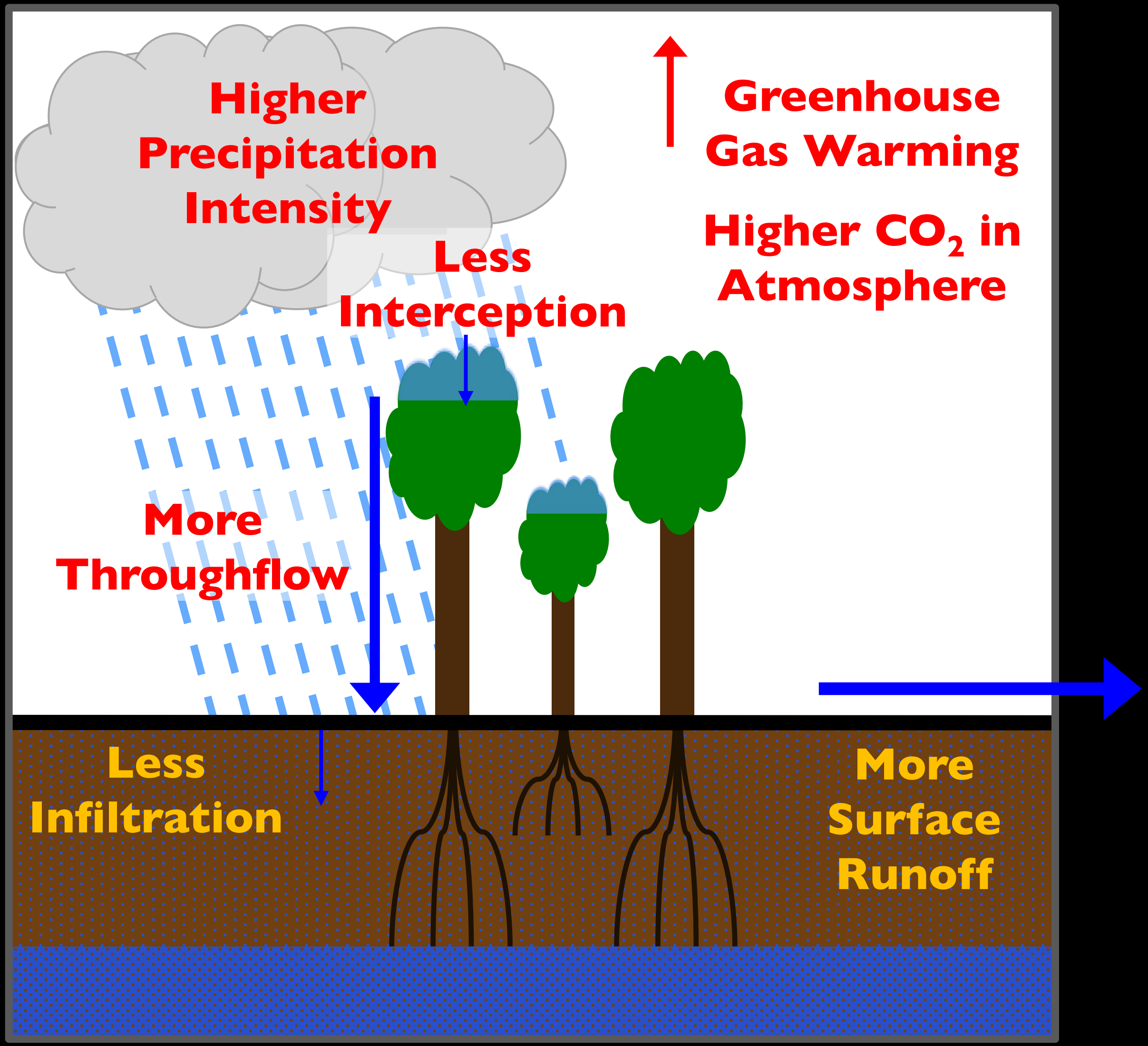


- Climate change signal is ultimately based on global model output

Modified version of schematic from *Winsemius et al.* [2013]

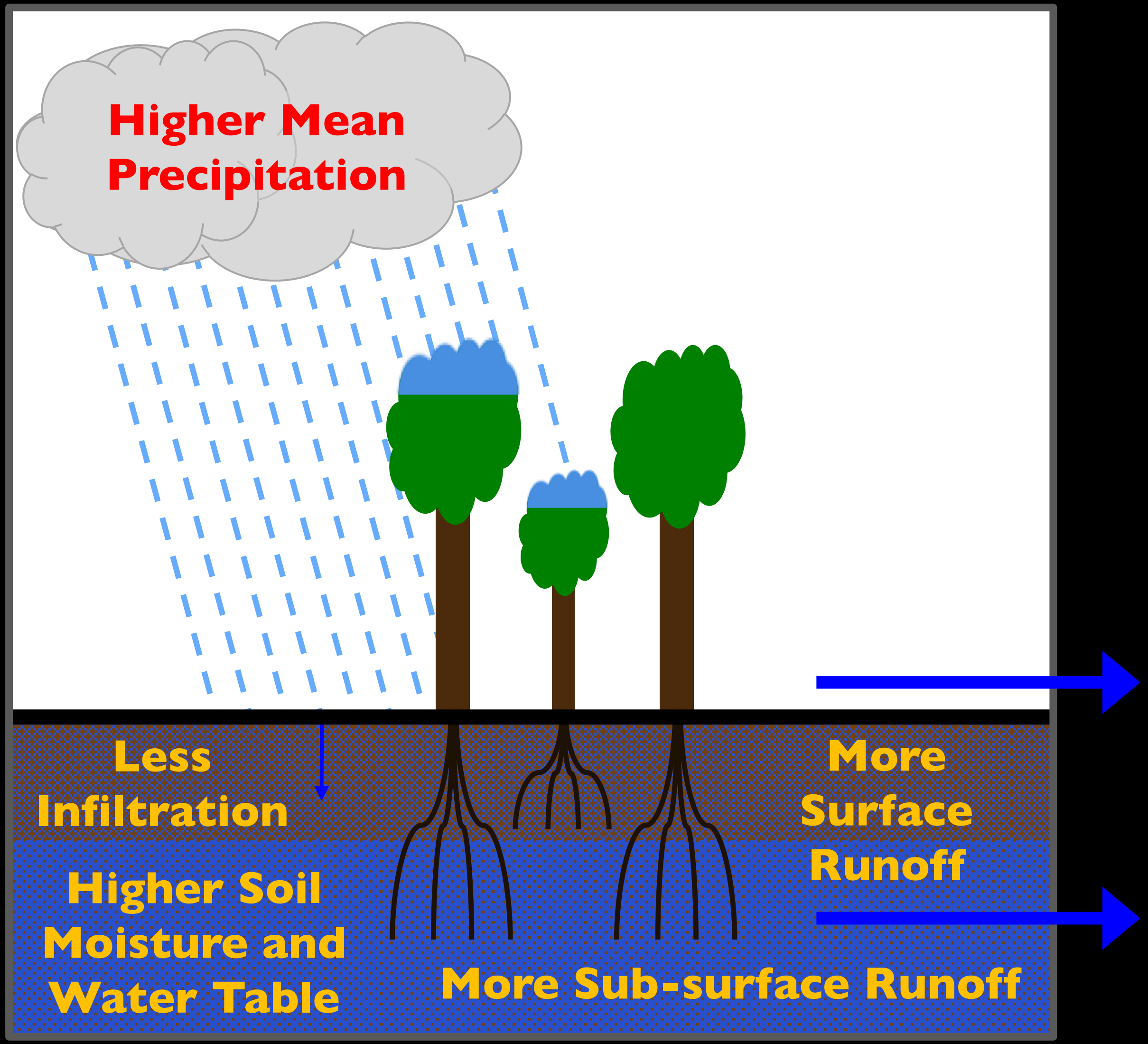
Both methods begin with global modeling results, but changes in runoff are driven by additional land-surface processes

Precipitation Intensity Change



- Precipitation intensity increase due to enhanced uplift of low-level moisture

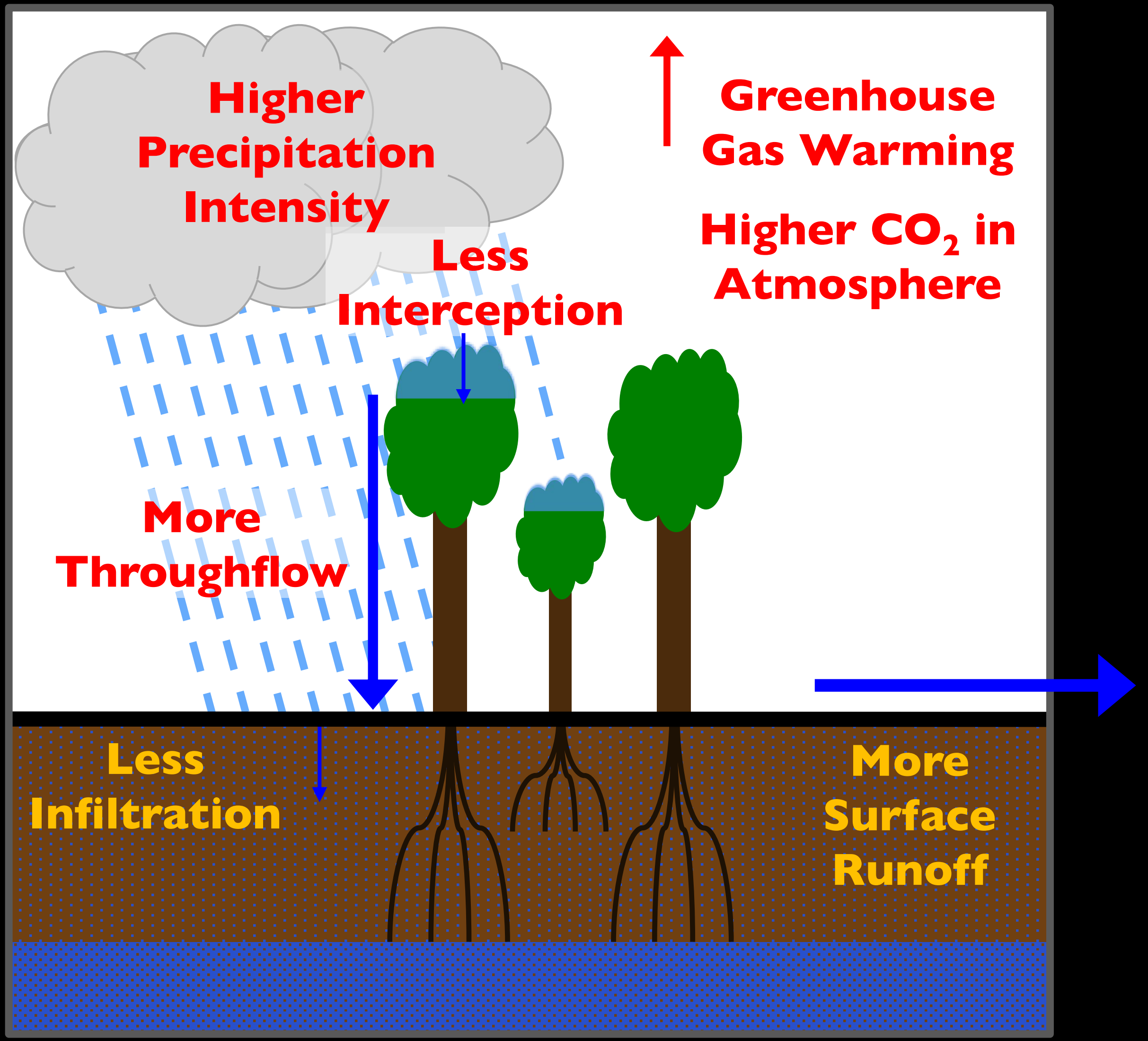
Soil Moisture Change



- Regional mean precipitation increase in some locations ("wet-get-wetter")

Both methods begin with global modeling results, but changes in runoff are driven by additional land-surface processes

Precipitation Intensity Change



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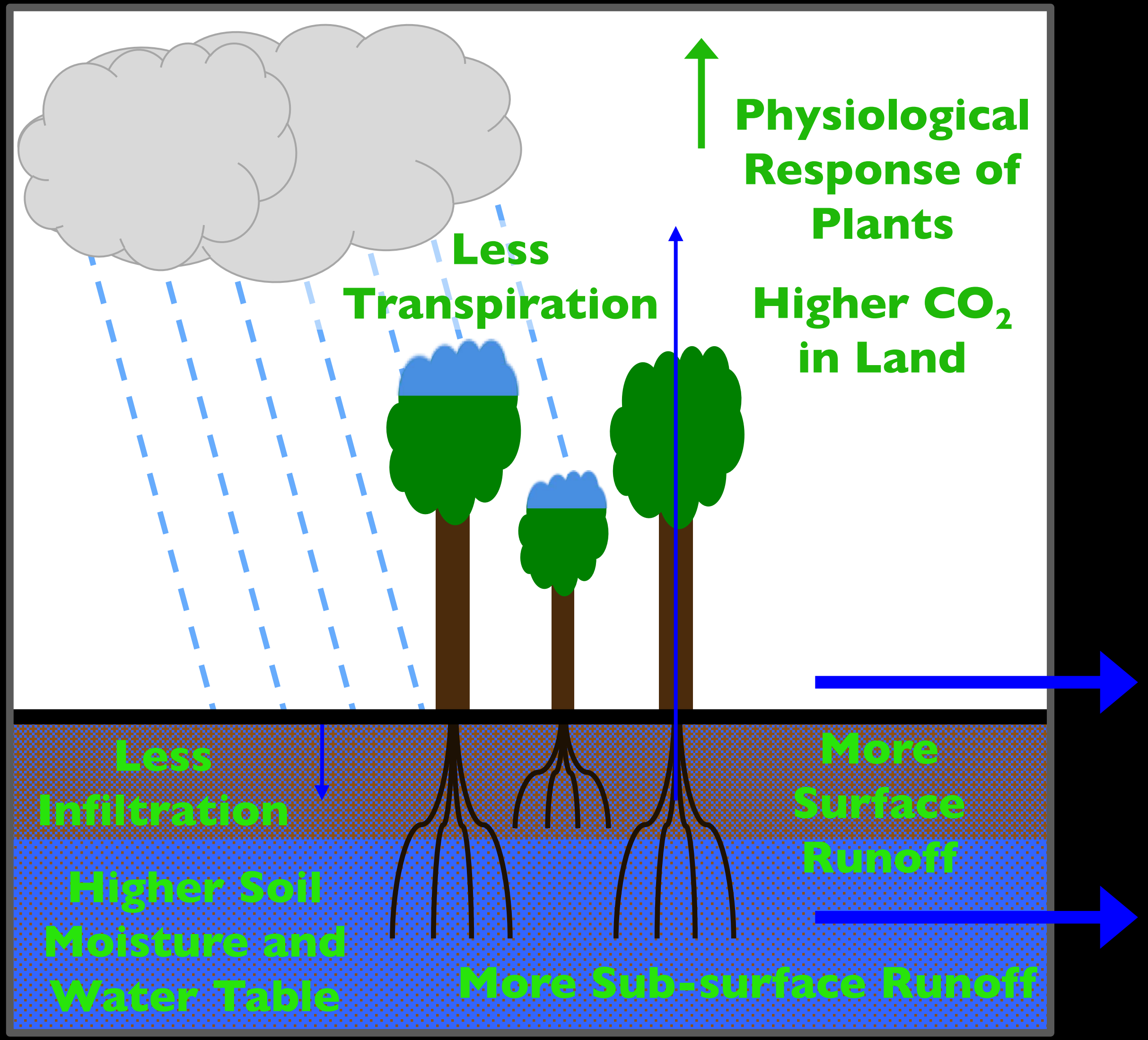
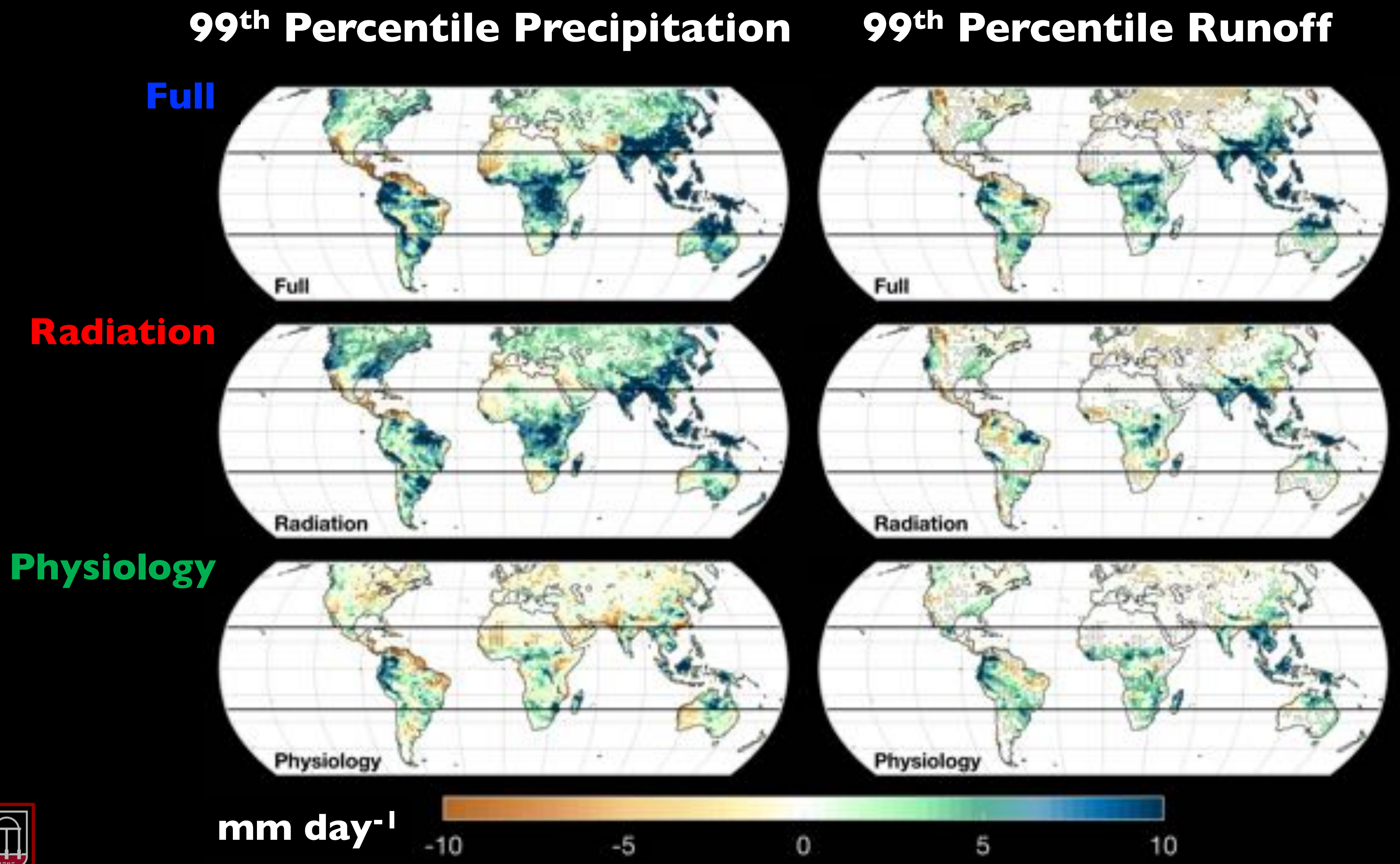
Soil Moisture Change



- Reduced stomatal conductance lowers transpiration and increases soil moisture

Rainfall intensification is primarily driven by radiative effects, but runoff intensity changes are also influenced by physiology

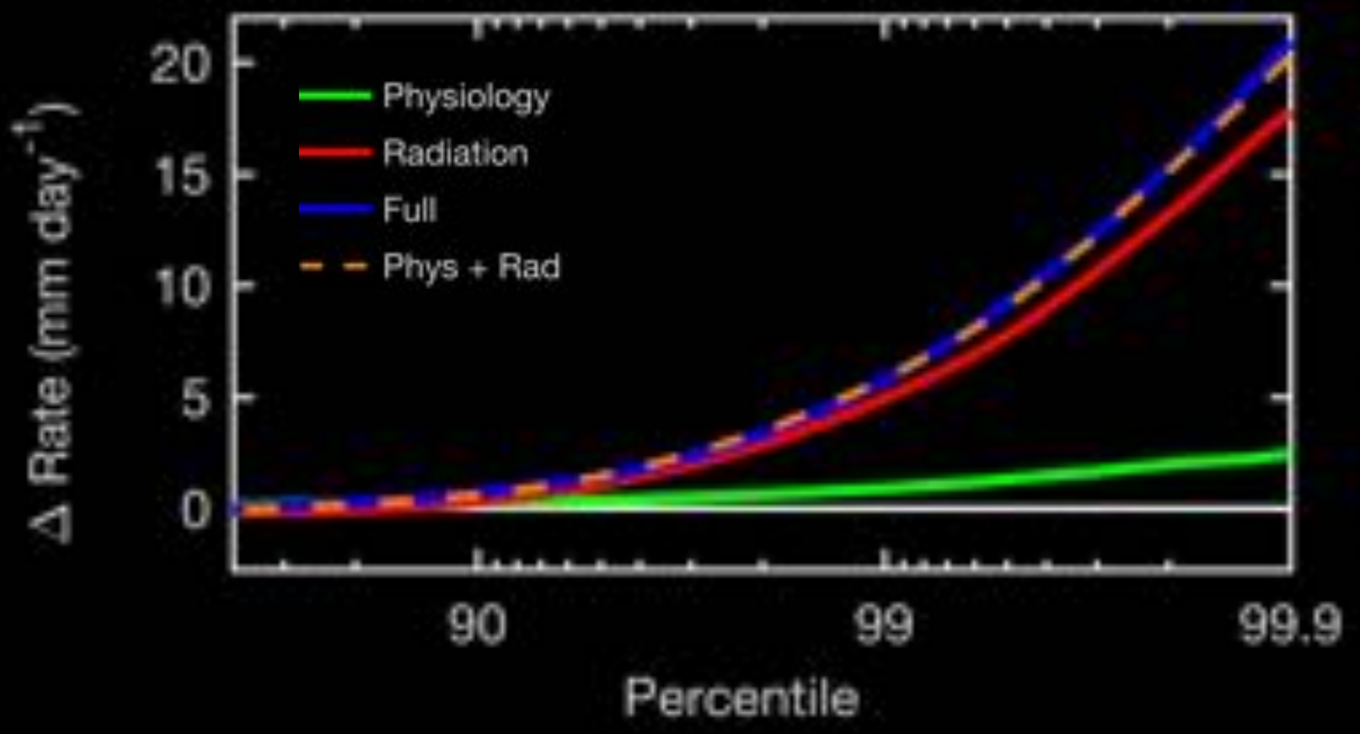


- Daily rain intensity increases across the tropics in response to increasing CO_2
- Daily runoff also increases intensity significantly due to increasing CO_2
- Rainfall intensity is primarily driven by radiative effects
- Runoff change has contributions from both radiation and physiology effects

Kooperman *et al.*, in revision 2018

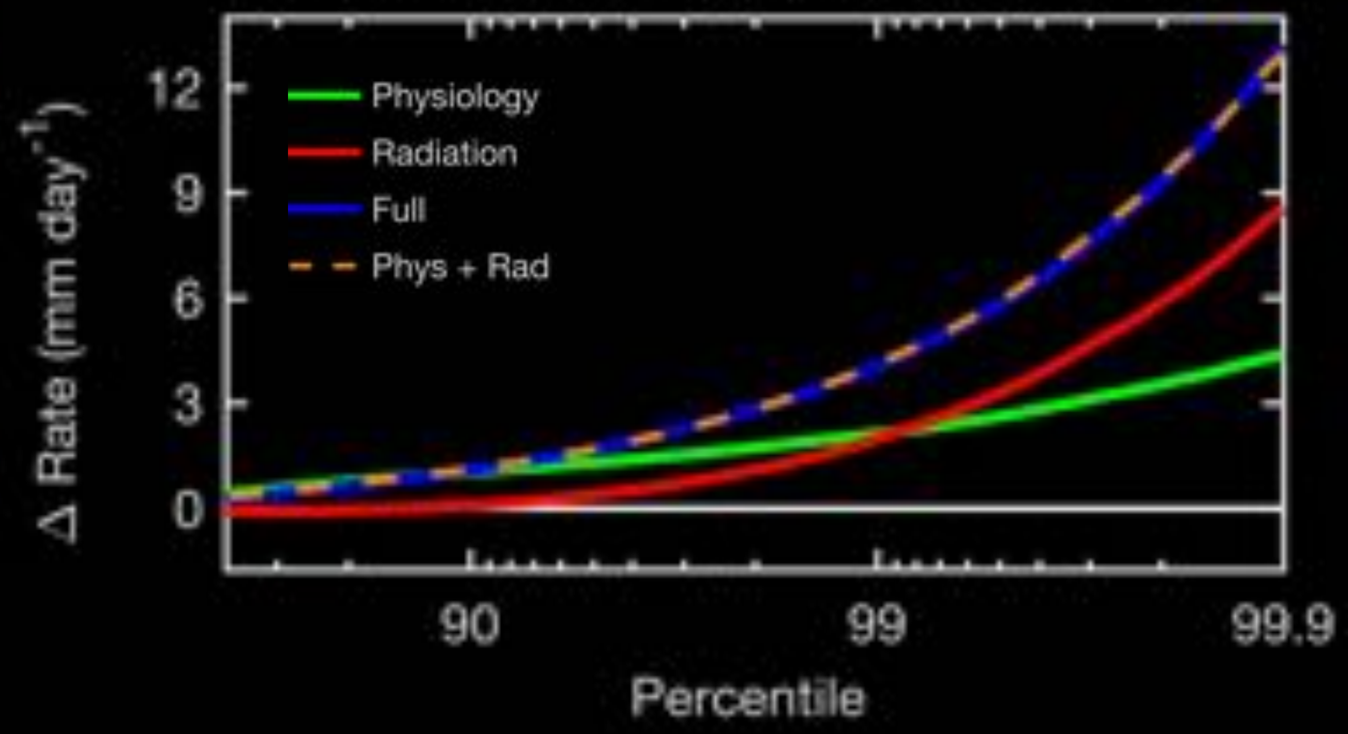
The plant-physiological response to raising CO_2 contributes as much as radiative effects to 99th percentile runoff changes

Precipitation Percentile Change



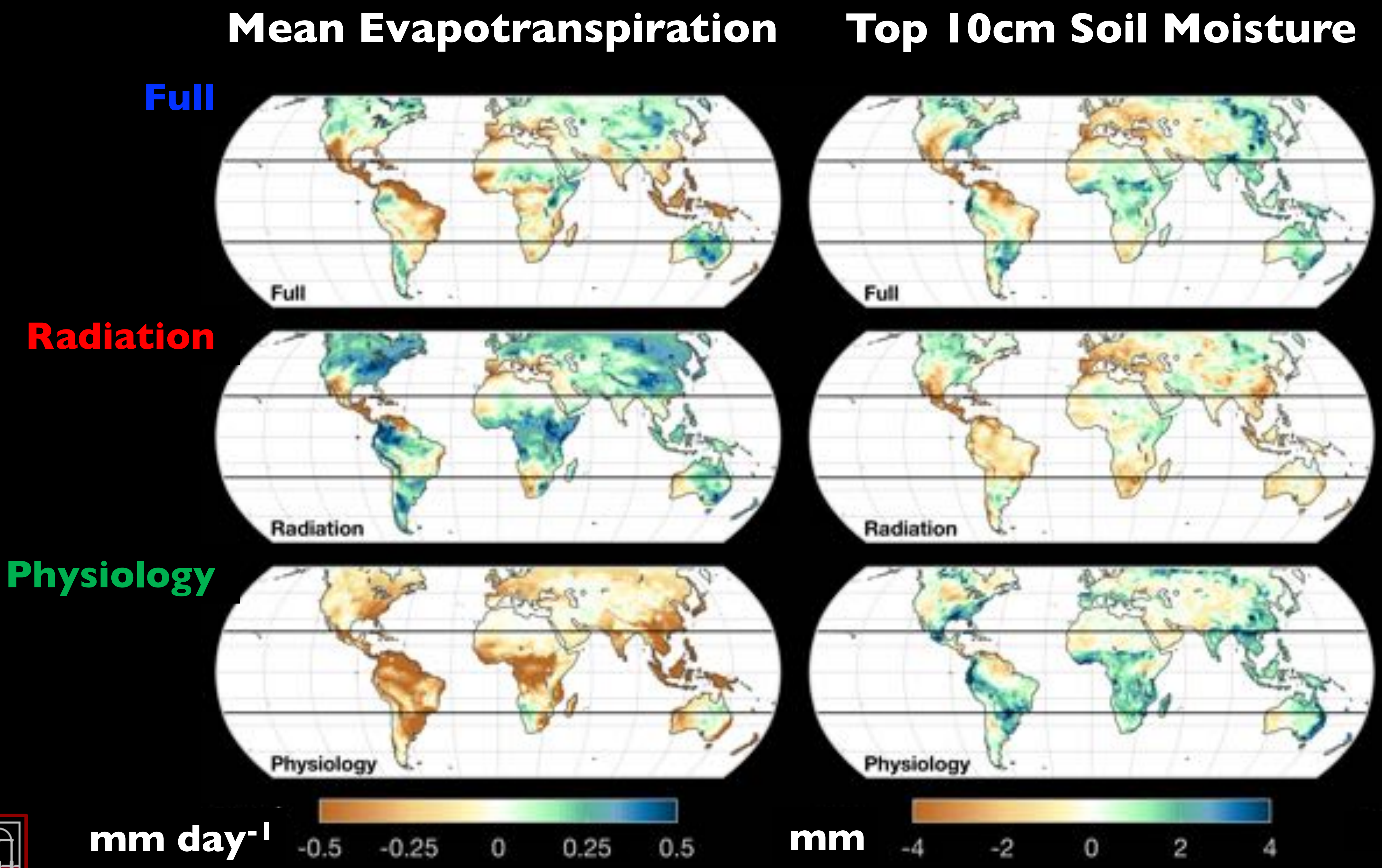
- Daily precipitation rate intensity increases across all percentile rates
- Precipitation is primarily driven by radiative effects for all percentiles
- Physiology has a small contribution

Runoff Percentile Change



- Daily runoff intensity changes are largest from physiology up to 99th percentile
- Physiology adds ⅓ to 99.9th percentile
- Full simulation is a linear combination of physiology and radiation simulations

Plant-physiological impacts of raising CO_2 are lower stomatal conductance and evaporation, and higher soil moisture



- Plant-physiology reduces stomatal conductance and transpiration
- Radiation effects raise evaporative demand and total evaporation
- Physiology effect is larger in tropics while radiation effect is larger for high-latitudes
- Physiology effect results in higher soil moisture over most tropical land

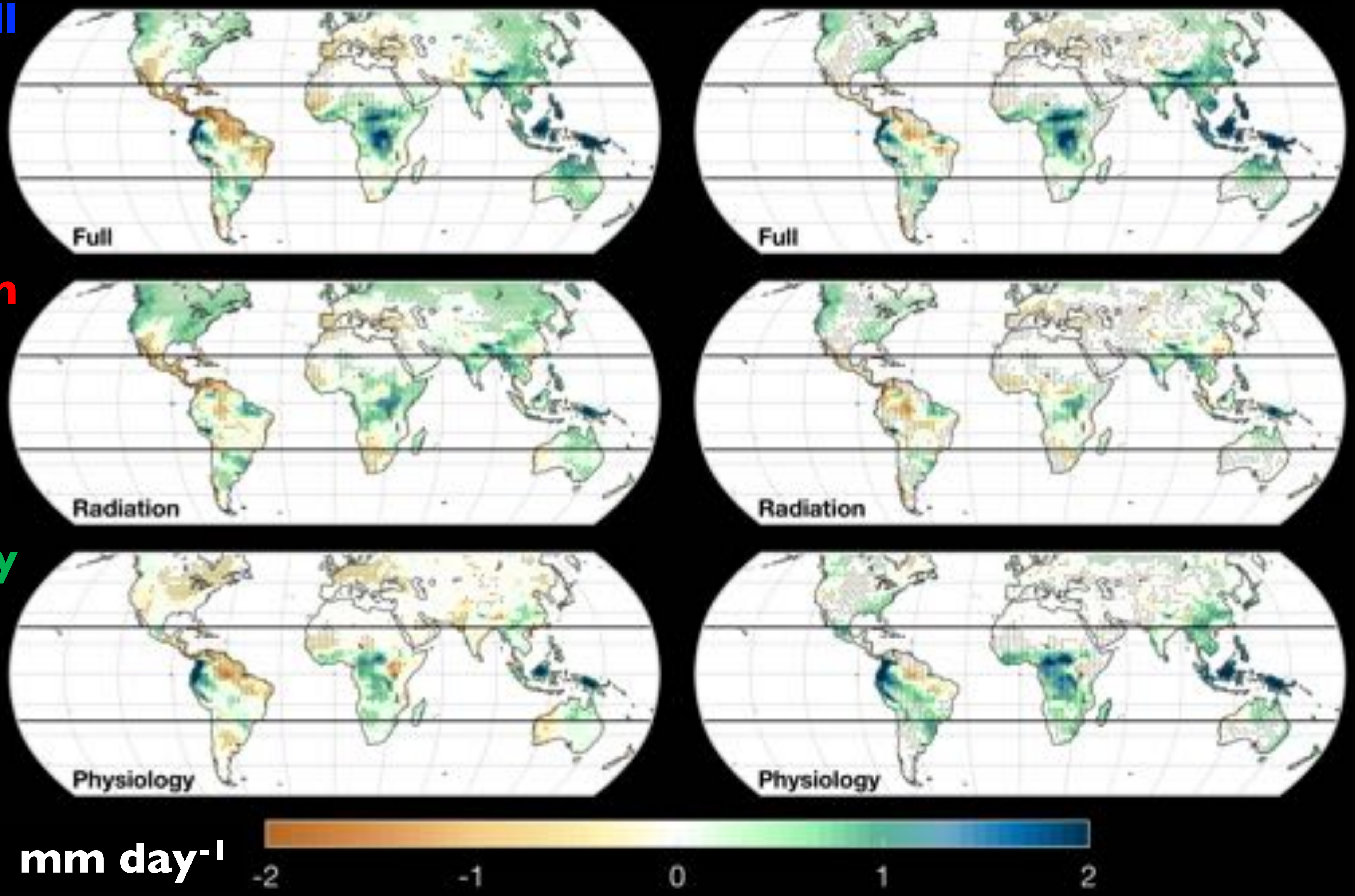
Plant-physiological and radiative effects both contribute to mean rainfall changes, but runoff is dominated by physiology

Mean Precipitation Change | **Mean Runoff Change**

Full

Radiation

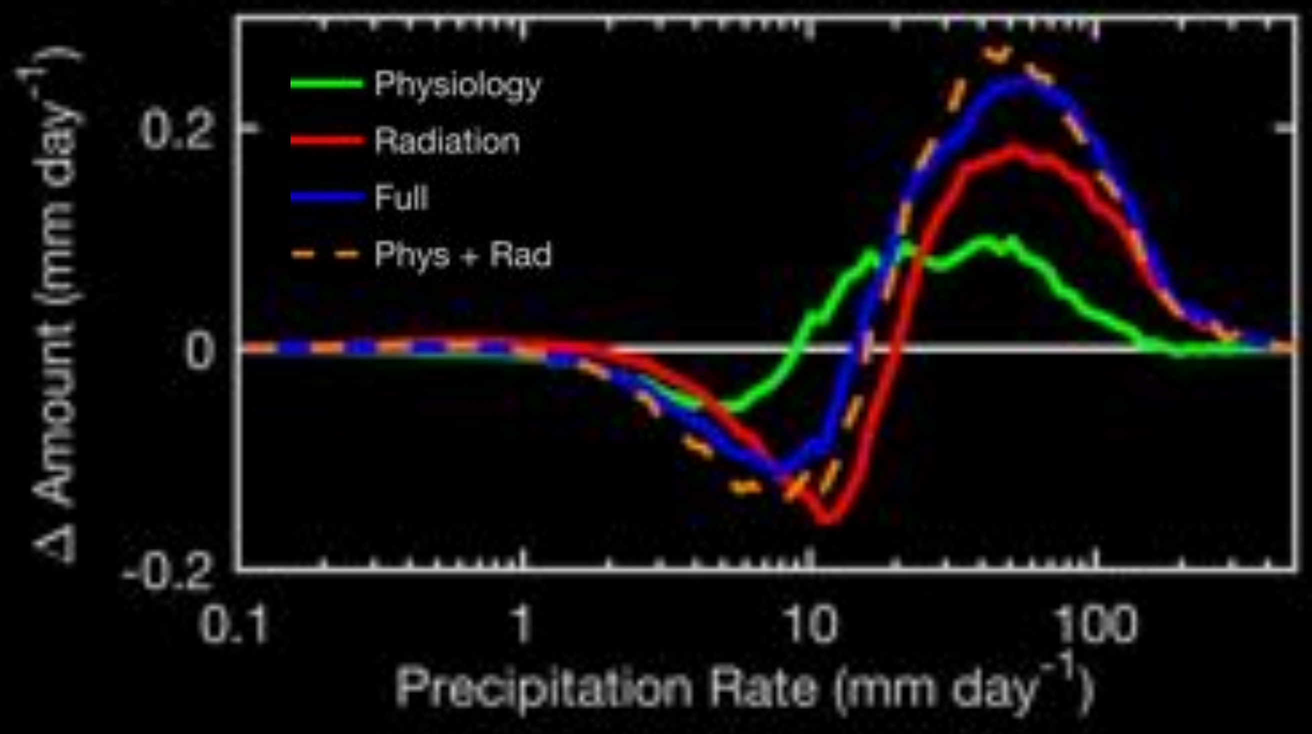
Physiology



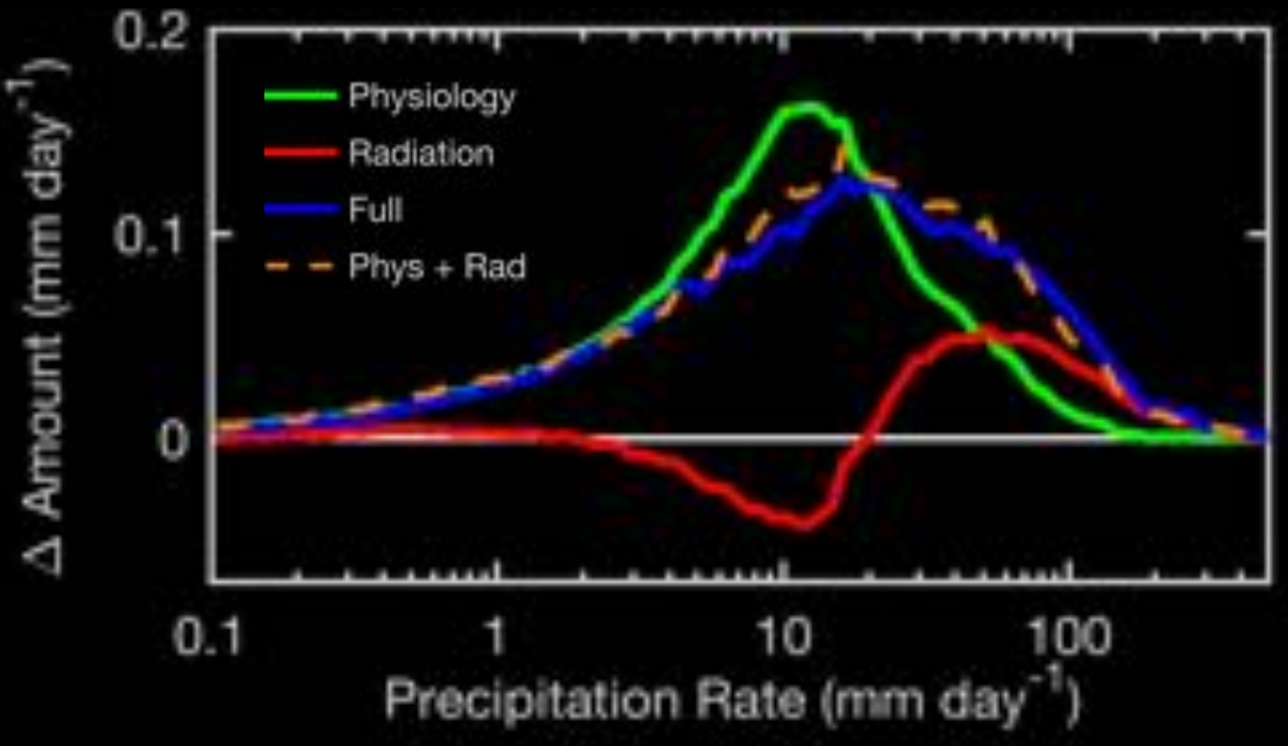
- Transpiration and soil moisture also feedback on mean precipitation
- Mean precipitation changes are from both radiation and physiology effects in the tropics
- Significant mean runoff increases across the tropics
- Runoff increases primarily due to physiology effects

Daily runoff amount increases for all precipitation rates when physiological responses to rising CO_2 are included

Precipitation Amount Distribution



Runoff Conditional Amount Distribution

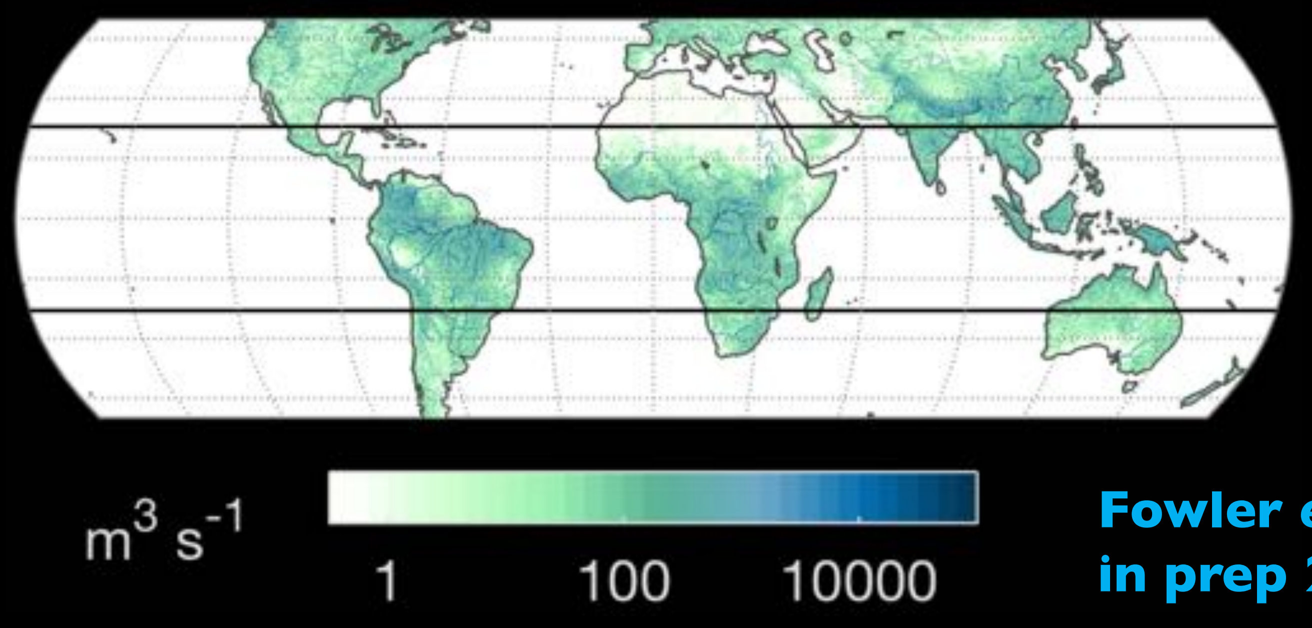


- **Accumulated precipitation amount from the highest rates increases while amount from lowest rates decreases in all cases**
- **Radiative effects have the largest impact on intensity with a strong rightward shift**

- **Radiative effects on runoff have a similar right shift for runoff intensity changes**
- **But the influence of physiology increases runoff from all precipitation rates (same rain rates produce more extreme runoff)**

Downscaling pre-industrial CESM runoff with the CaMa-Flood model captures streamflow though major river systems

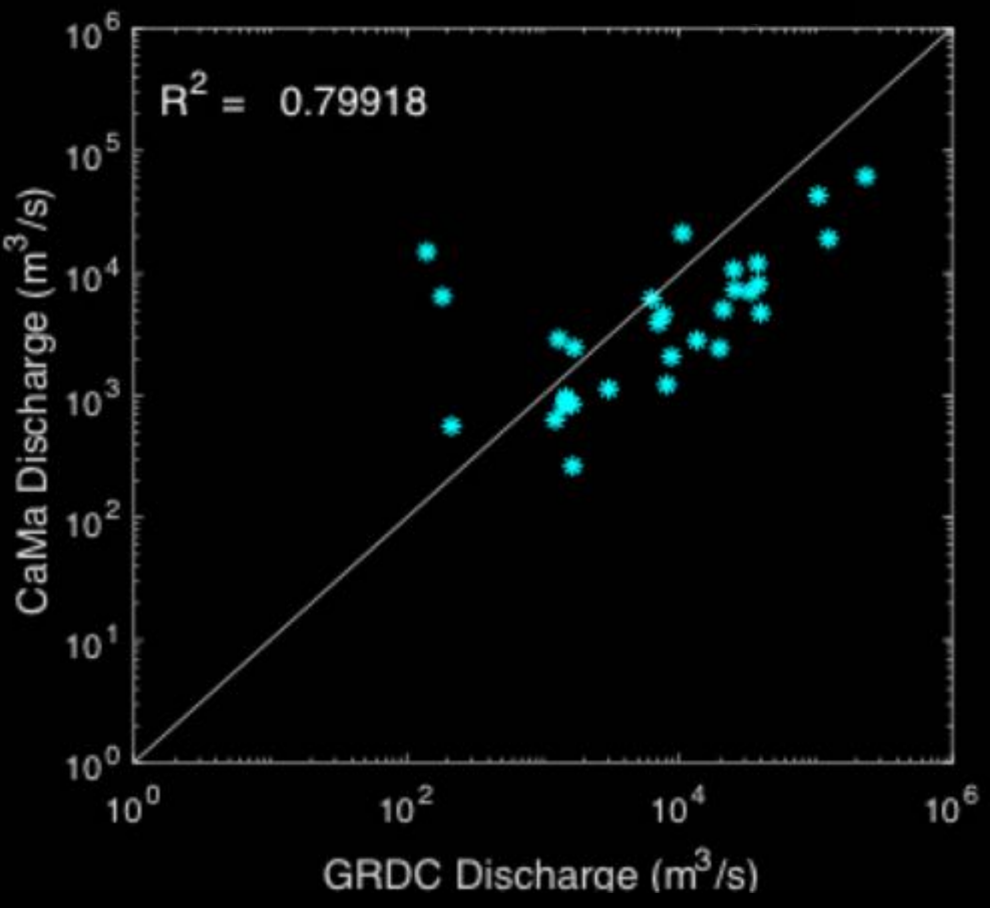
99th Percentile Pre-Industrial Discharge



Fowler *et al.*, in prep 2018

- The Catchment-based Macroscale Floodplain Model is used to downscale CESM runoff for global flood statistics
- The model represents continental-scale river flow and floodplain dynamics at ¼° (e.g., river discharge and inundation) in major river basins of the world

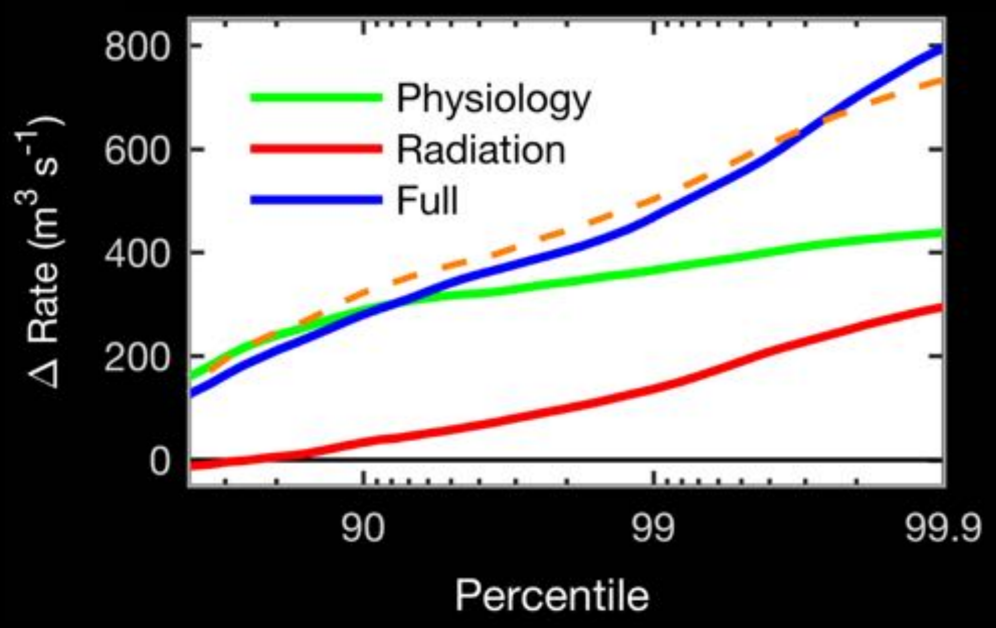
Annual Max Discharge



- The CaMa-Flood Model captures the order of magnitude of river discharge reasonably well under pre-industrial conditions relative to Global Runoff Data Centre station data

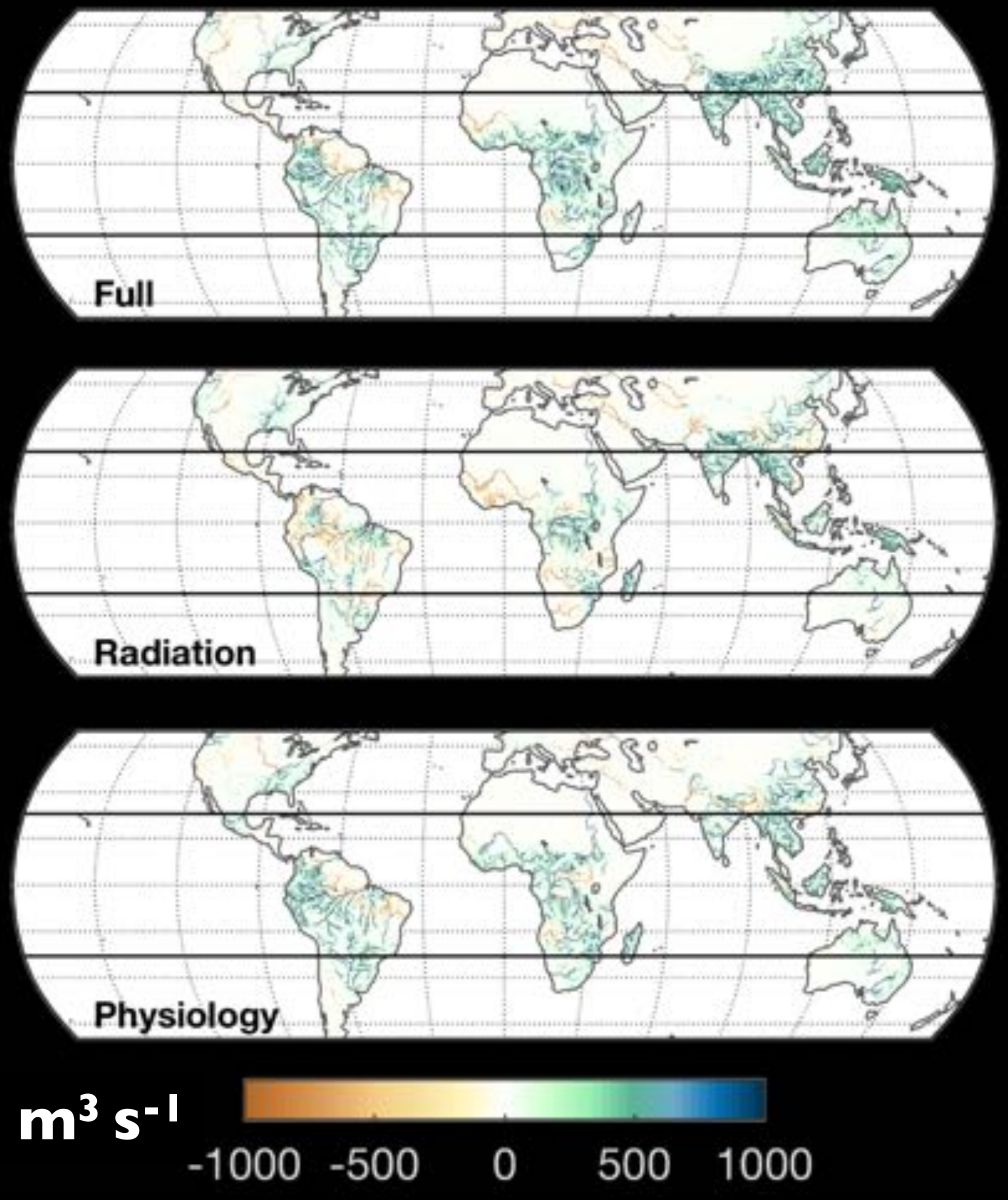
Changes in downscaled river discharge recreate the patterns of runoff change and contributions from physiological processes

Discharge Percentiles



- When runoff is aggregated downstream, physiological effects are the dominant component of discharge changes across the tropics

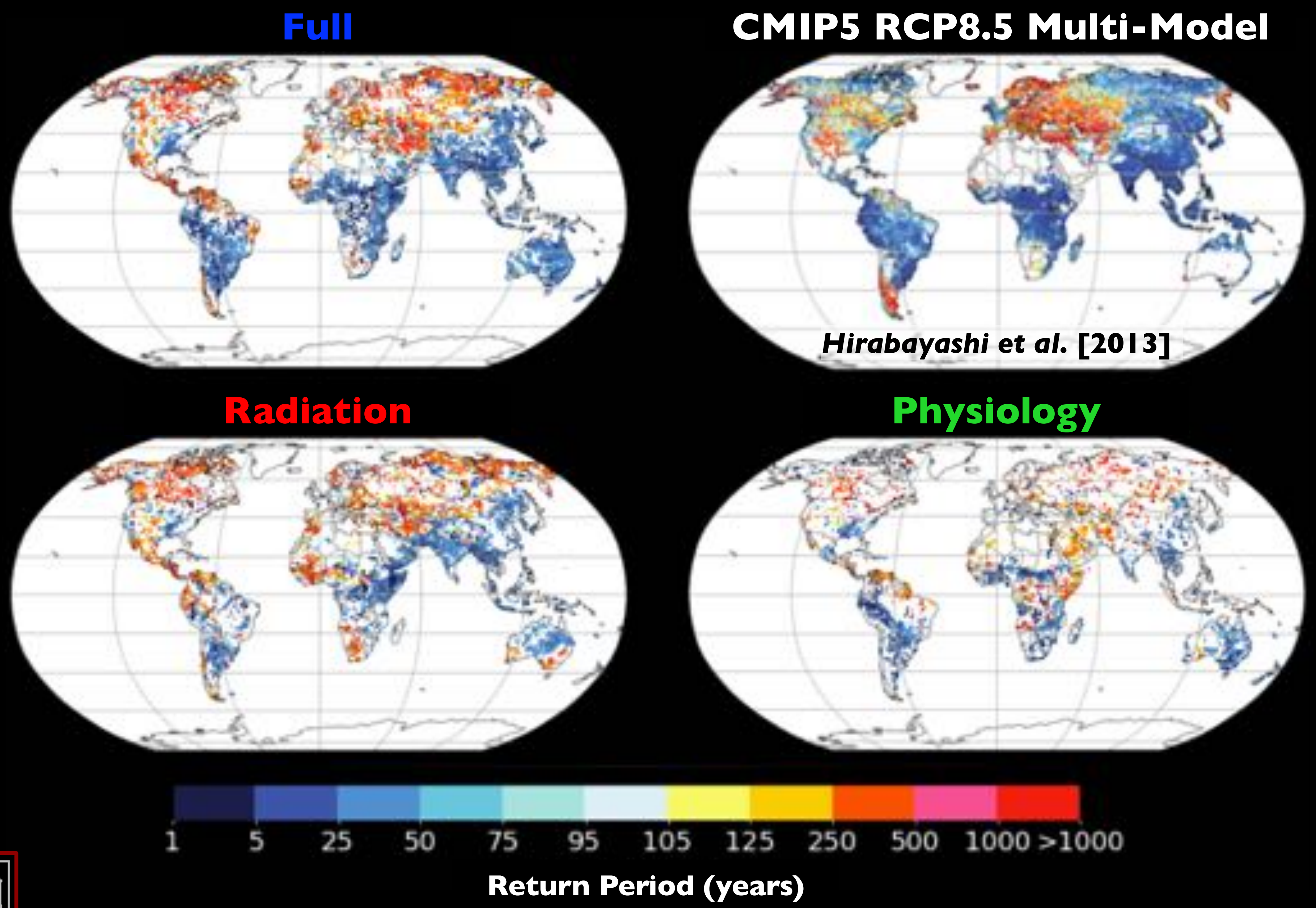
99^{th} Percentile Discharge



- The increases in 99^{th} percentile river discharge across tropical land reflect the runoff pattern
- Regional impacts from physiology and radiation are also similar
- This implies the climate change signal in studies that downscale runoff offline is mostly due to the ESM results

Idealized CO_2-only forcing captures RCP8.5 multi-model mean pattern of change from, with significant increases in the topics

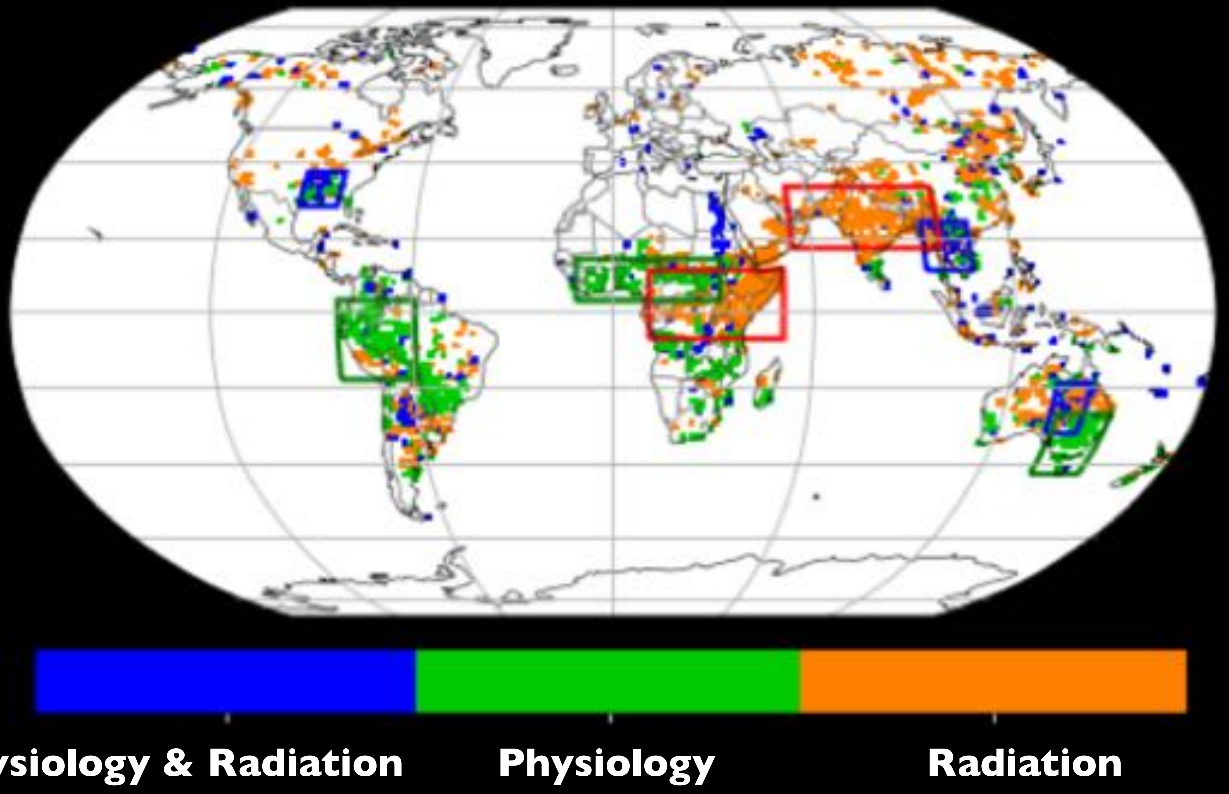
100-Year Flood Return Period Change



- Downscaling CESM runoff from the Full simulation captures the same flood return pattern as the CMIP5 Multi-Model Mean
- 1000-member bootstrap test shows a statistical significant flood increase across parts of the topics at 95% confidence level
- Comparing Full, Radiation, and Physiology simulations, identifies which mechanism has the dominant control on future flood frequency in different regions

Regions where runoff changes are driven by both radiation and physiology are likely to have the most flood related impacts

Dominant Component of Full Change



- **Radiation:** large rainfall changes
- **Physiology:** large soil moisture changes
- **Both:** large rain and soil moisture changes

Regional Average Percent Changes

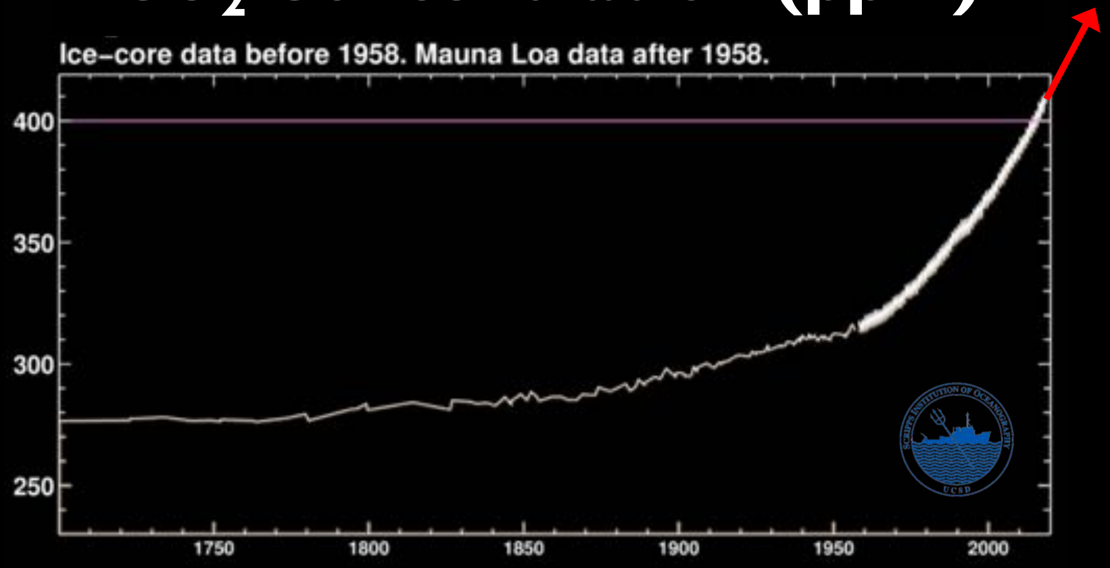
	PHYS - CTRL		RAD - CTRL		FULL - CTRL	
	India	Horn of Africa	India	Horn of Africa	India	Horn of Africa
Rain	1.9	-5.9	19.0	25.9	21.0	24.0
Soil Moist.	1.5	0.1	1.7	6.0	2.5	8.0
Runoff	21.7	29.8	34.7	46.0	56.5	79.2

	PHYS - CTRL			RAD - CTRL			FULL - CTRL		
	West Amazon	Sahel	SE Aust.	West Amazon	Sahel	SE Aust.	West Amazon	Sahel	SE Aust.
Rain	12.3	12.5	5.5	-1.2	-1.2	12.0	16.5	21.1	12.3
Soil Moist.	10.1	9.2	12.4	-4.6	-4.7	-2.8	7.1	9.2	6.2
Runoff	27.5	19.7	57.2	-2.8	9.5	2.1	49.1	34.4	64.3

	PHYS - CTRL		RAD - CTRL		FULL - CTRL	
	SE U.S.	SE Asia	SE U.S.	SE Asia	SE U.S.	SE Asia
Rain	-2.6	7.8	18.8	25.2	10.7	26.6
Soil Moist.	9.3	4.8	4.1	1.9	9.1	4.6
Runoff	104.9	75.9	92.8	79.7	132.7	107.5

How do plant physiological responses to rising CO_2 contribute to long-term changes in the hydrological cycle?

CO_2 Concentration (ppm)



Precipitation

Drought

Flooding

Heat/Fire

Conclusions

Rainfall and Drought

- Nearly all CMIP5 models predict a strengthening zonal precipitation asymmetry across tropical forests
- Physiology is a primary driver of increases in rain over Asian forests and decreases over the Amazon
- CESM simulations demonstrate that regional dynamic responses mostly drive of this pattern of change
- Results suggest that the Amazon will be more prone to drought and fire risk than other tropical forests
- Asian forests will receive more rain, which may increase flooding events

Runoff and Flooding

- Plant-physiology effects contribute as much as radiative effects to 99th percentile and one-third to 99.9th percentile runoff changes
- Plant-physiology influences runoff through both direct effects on soil moisture as well as feedbacks on mean precipitation changes
- Regions where an intensification of rainfall and plant-physiology both to contribute runoff changes are at most risk for future flooding
- Many of these regions are in lower income and highly populated areas, leading to disproportionate impacts