Carbon–Water Cycle Interactions: How do plant physiological responses to rising CO_2 impact the water cycle and climate extremes in the tropics?

Gabriel Kooperman

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)

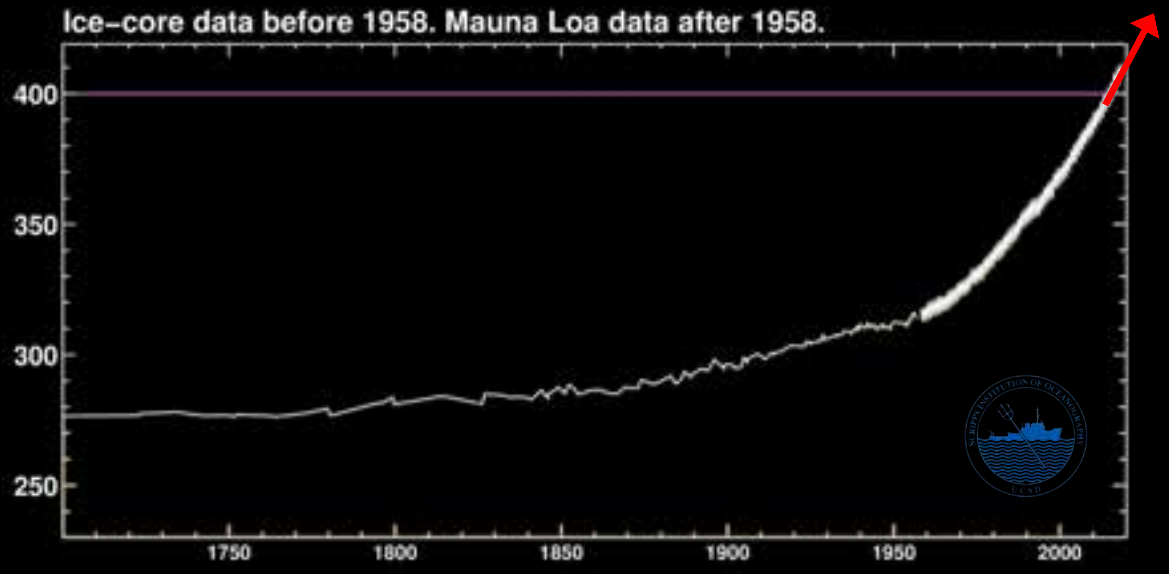
August 27, 2019

UNIVERSITY OF GEORGIA

GORDON AND BETTY MOORE FOUNDATION

How do plant physiological responses to rising CO_2 impact the water cycle and climate extremes in the tropics?

CO_2 Concentration (ppm)



Precipitation

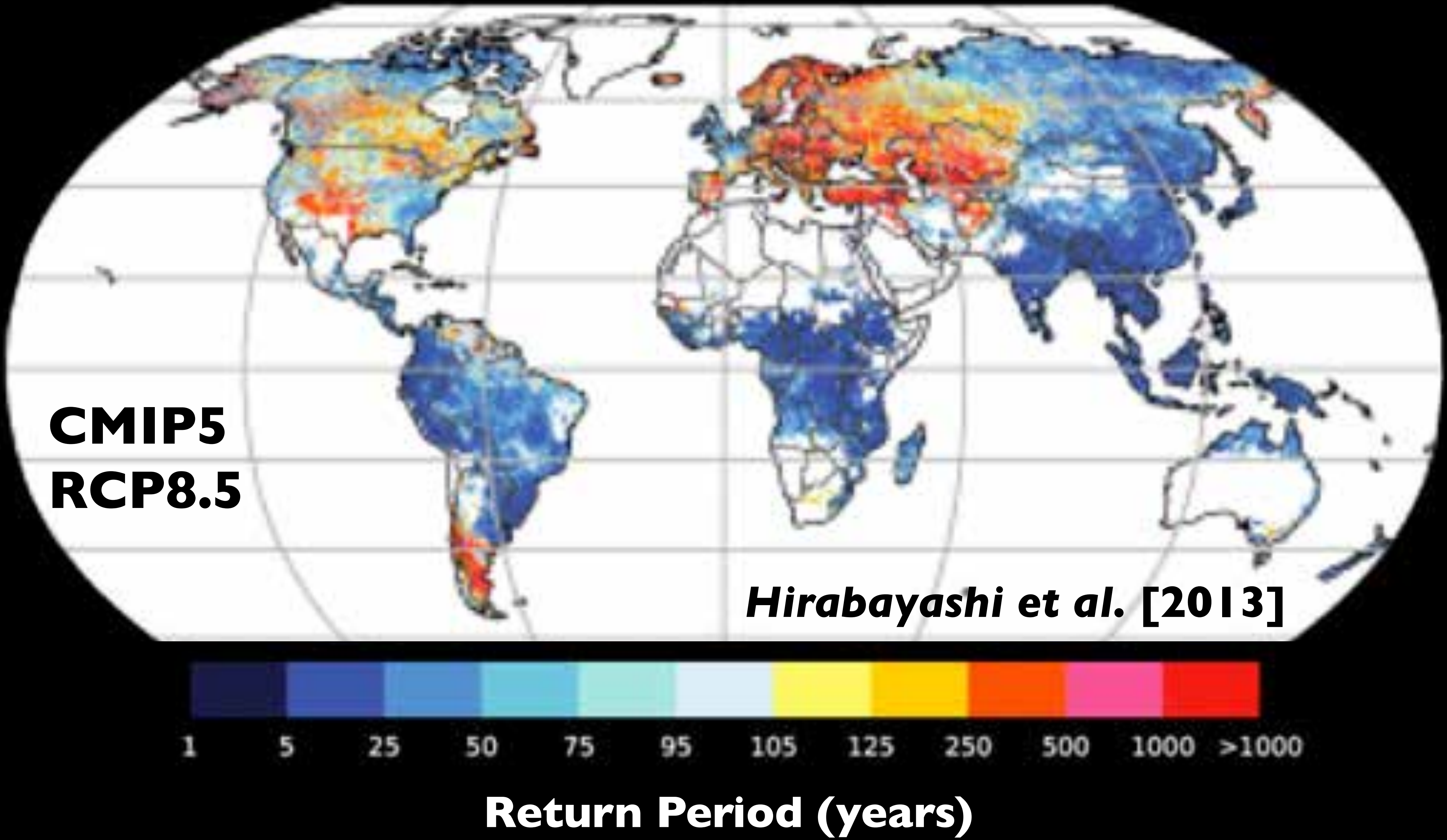
Flooding

Drought

Heat/Fire

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

Future Return Period of 20th Century 100-Year Flood



- **Many recent flood studies based on ESM projections**
- **Downscaling global runoff with CaMa-Flood model shows a large increase in the frequency of extreme river flooding**

Global assessments based on ESM results require downscaling of rainfall or runoff (prior to E3SM with MOSART-Inundation)

Global-Scale
1° - 2°

Earth System Model

Runoff

Precipitation
Temperature
Potential Evaporation

→

Global-Scale
0.25° - 0.5°

Hydrological and/or River Routing Model

Inundated Area

Population and Socio-Economic Model

Population and GDP Growth

→

Local-Scale

Physical Downscaling

Flood Probability

Socio-Economic Downscaling

Infrastructure Flood Protection

→

Global Flood Risk Assessment

Flood Impacts

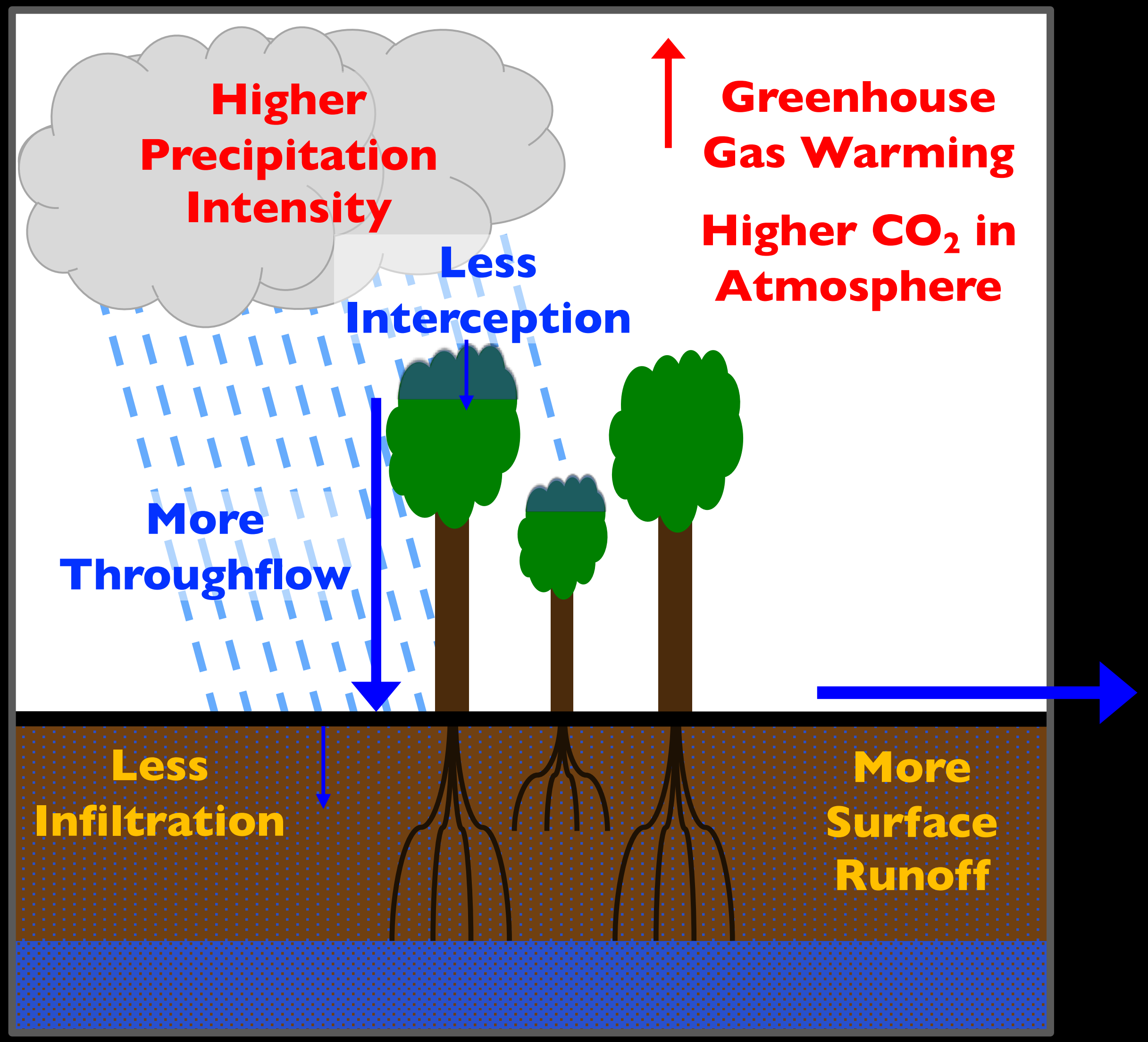
Number of People Exposed
Assets Exposed
Total Damage

- **Climate change signal is ultimately based on global model output**

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

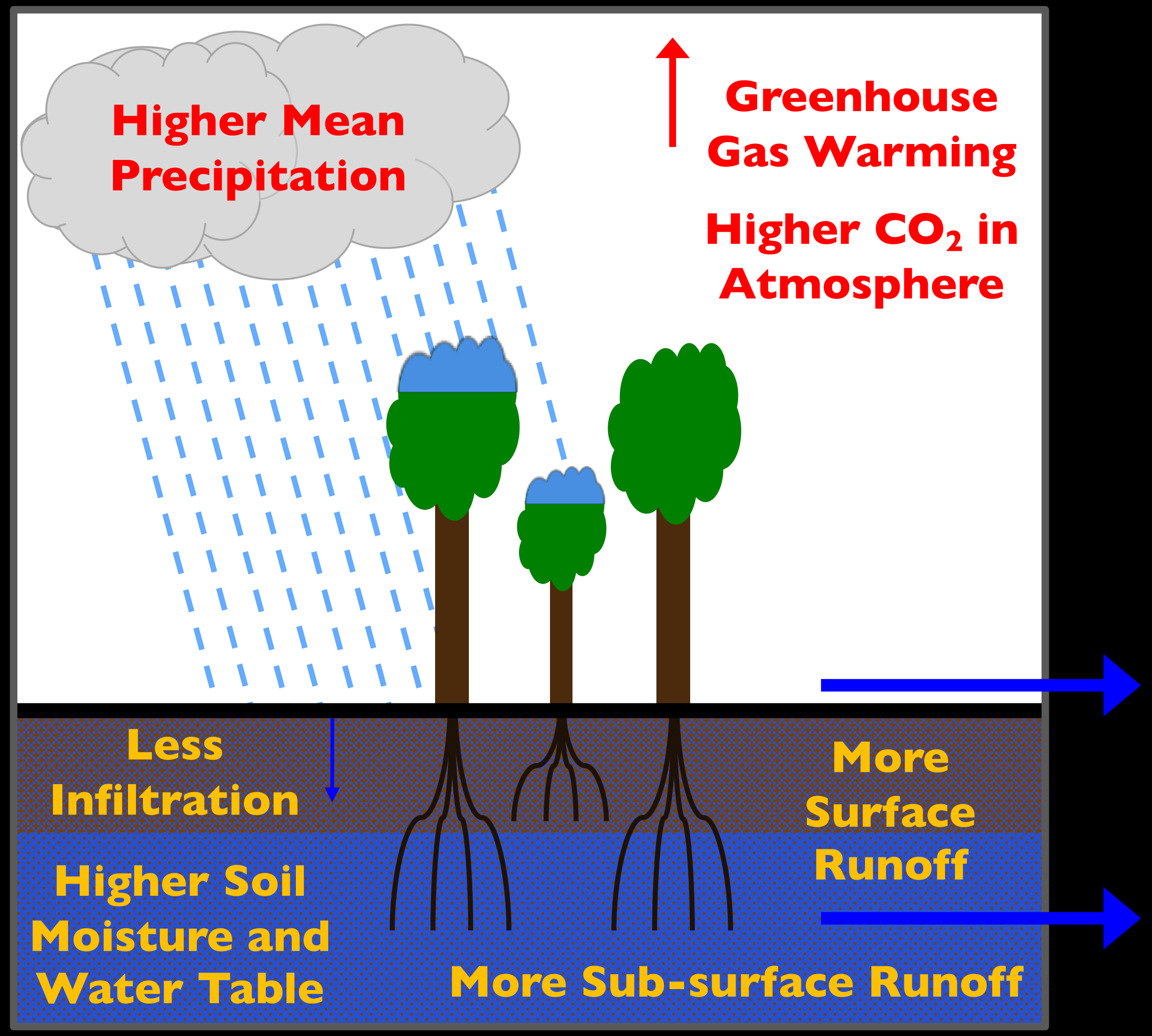
Both methods begin with global modeling results, but changes in runoff are driven by additional land-surface processes

Precipitation Intensity Change



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

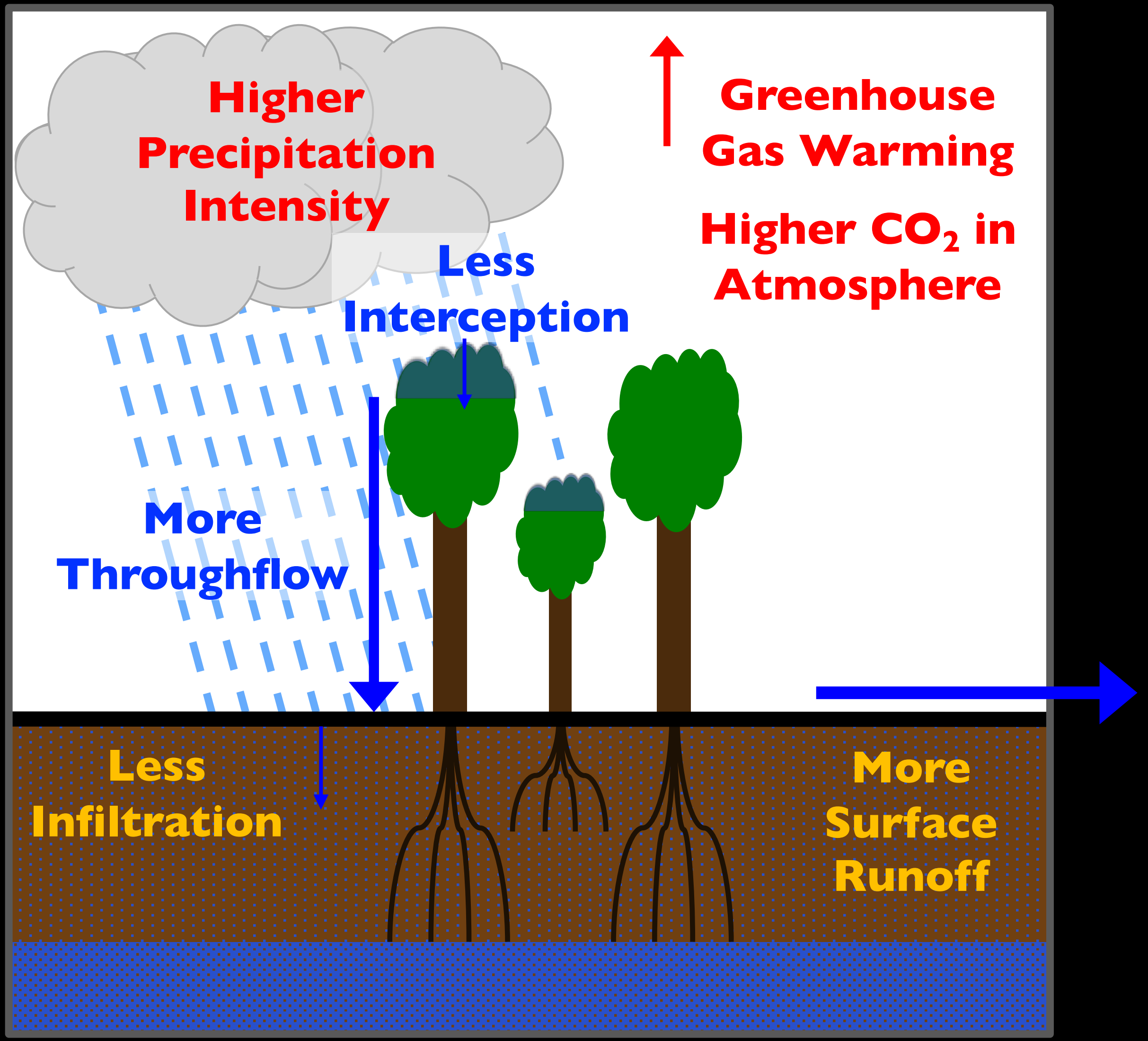
Mean Precipitation Change



- 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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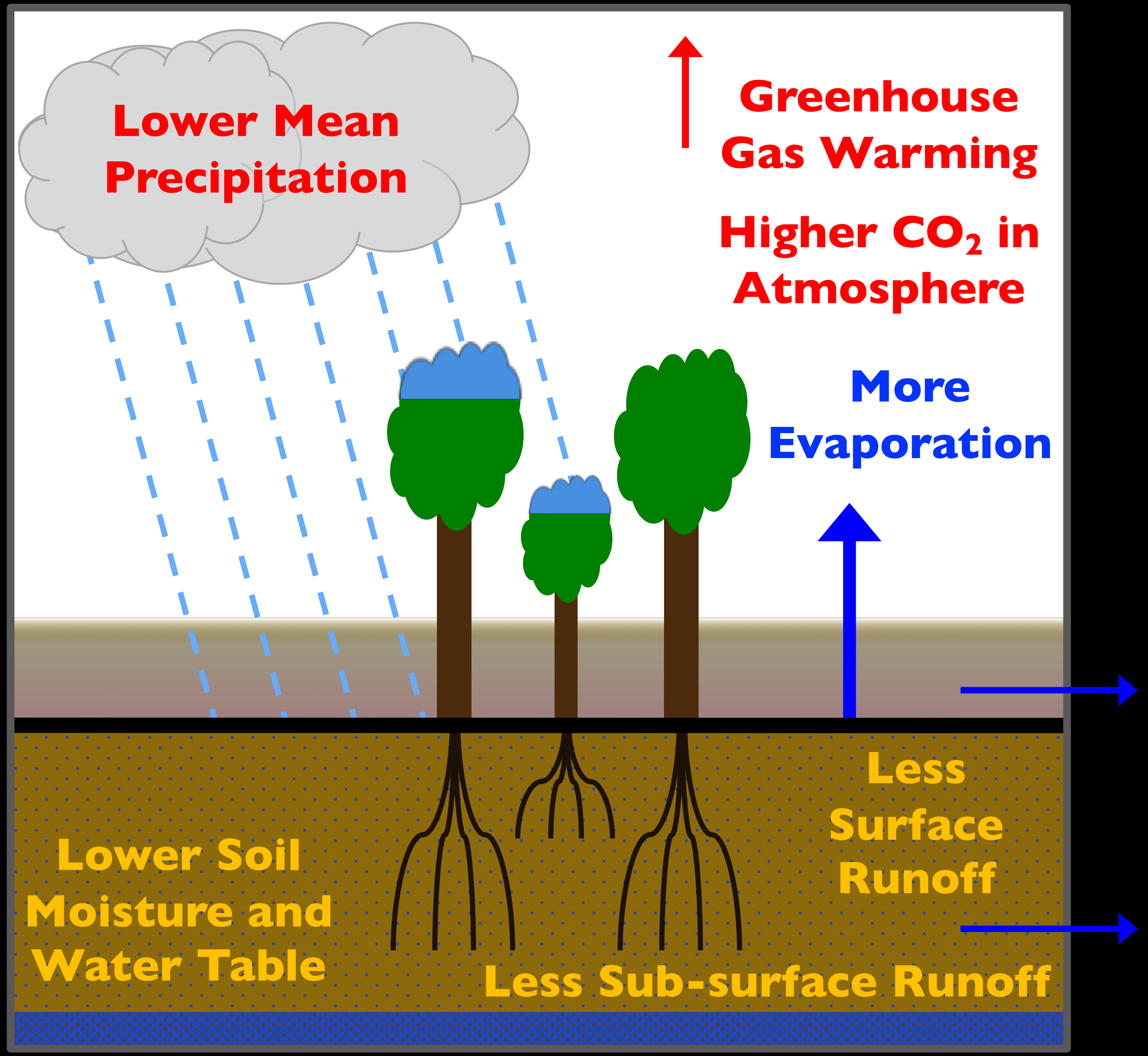
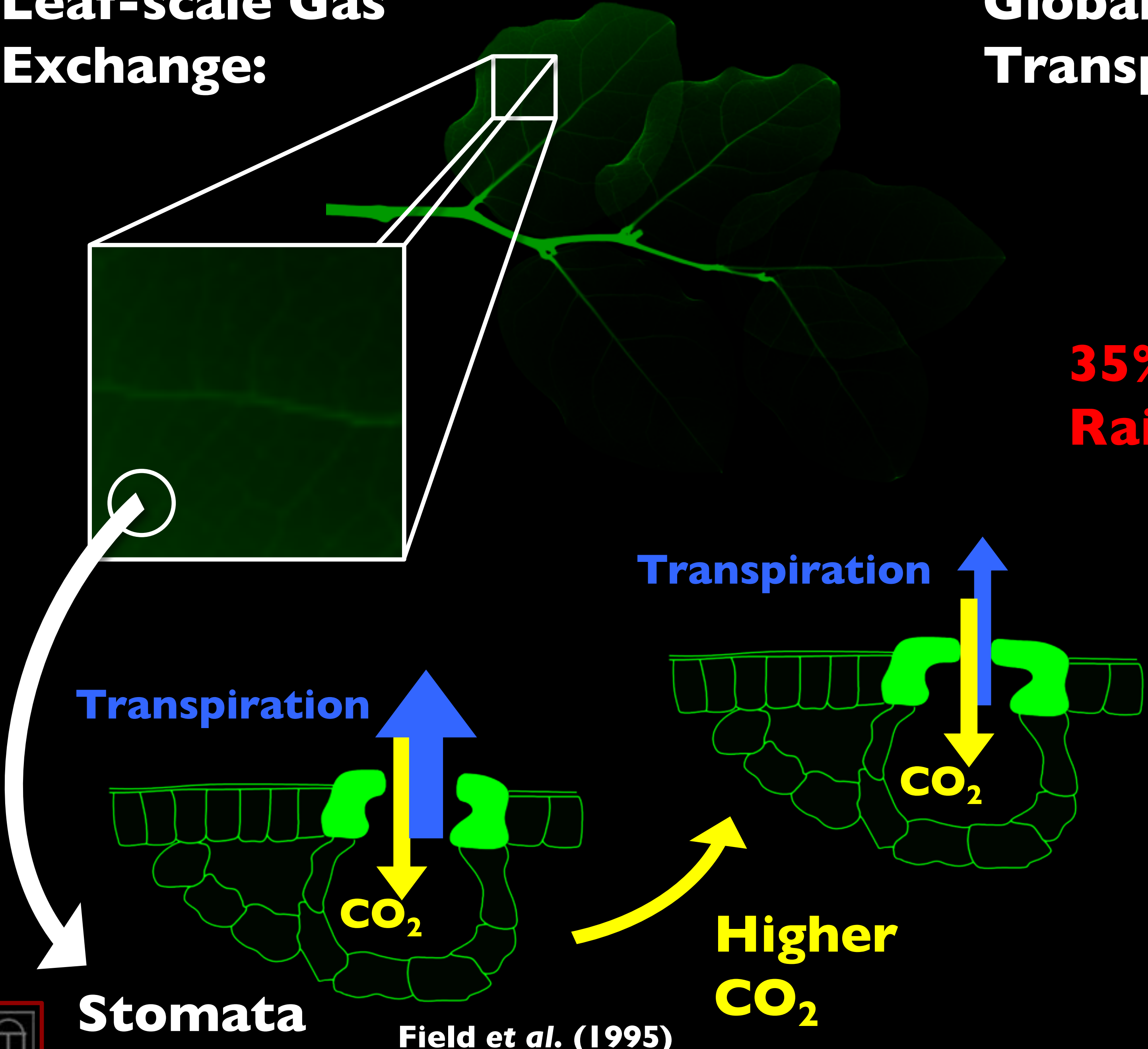
Mean Precipitation Change



- Regional mean precipitation decrease and higher evaporative demand

Rising CO_2 drives plant physiological response through reduced stomatal conductance and fertilization effects on transpiration

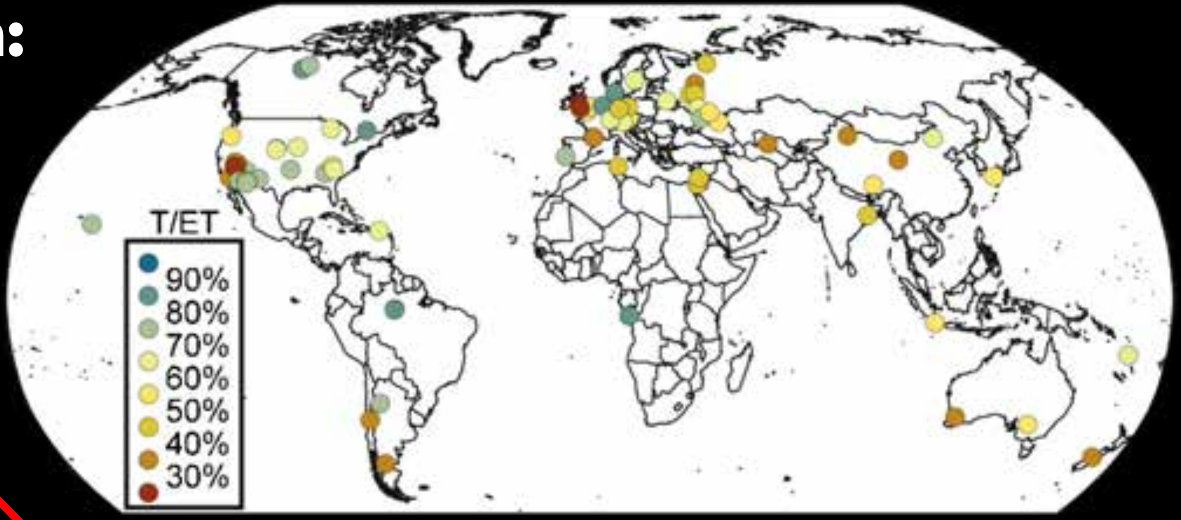
Leaf-scale Gas Exchange:



Field *et al.* (1995)

Global-scale Transpiration:

Percent Transpiration (%)

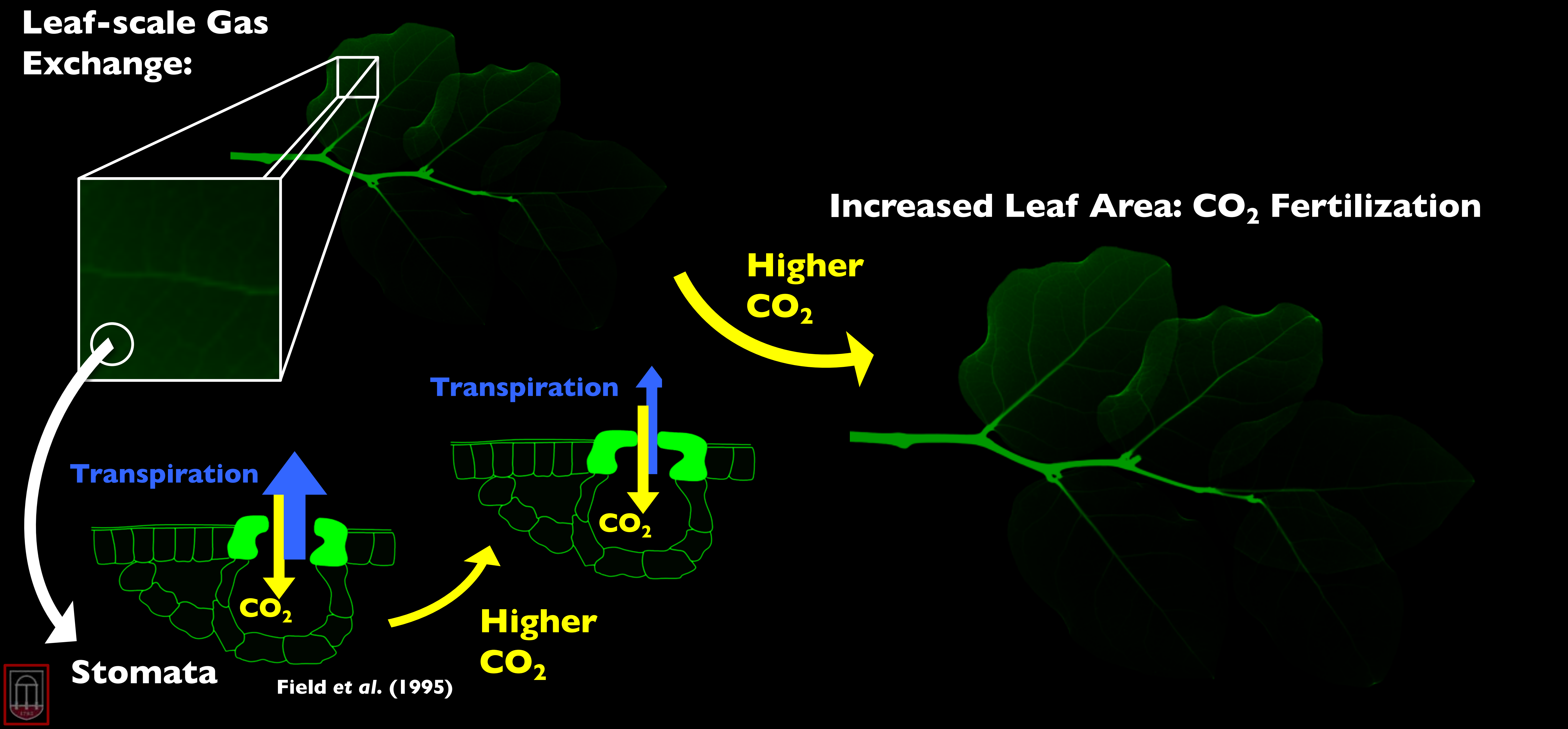


35% of Rainfall

Ecoregion	T/ET
Tropical rainforest	70 ± 14
Tropical grassland	62 ± 19
Temperate deciduous forests	67 ± 14
Boreal forest	65 ± 18
Temperate grassland	57 ± 19
Desert	54 ± 18
Temperate coniferous forest	55 ± 15
Steppe	48 ± 12
Mediterranean shrubland	47 ± 10

Schlesinger and Jasechko (2014)

Rising CO_2 drives plant physiological response through reduced stomatal conductance and fertilization effects on transpiration



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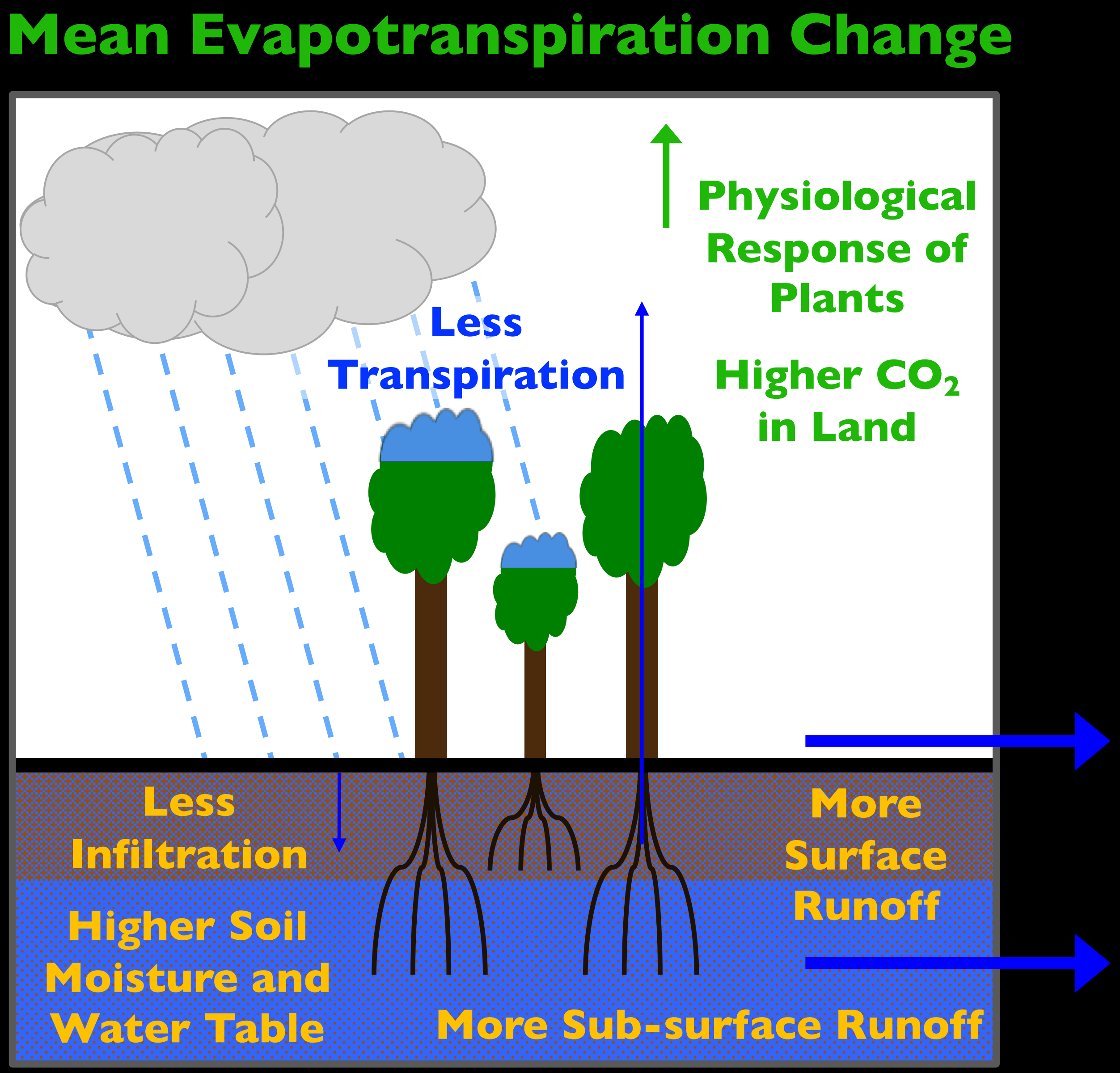
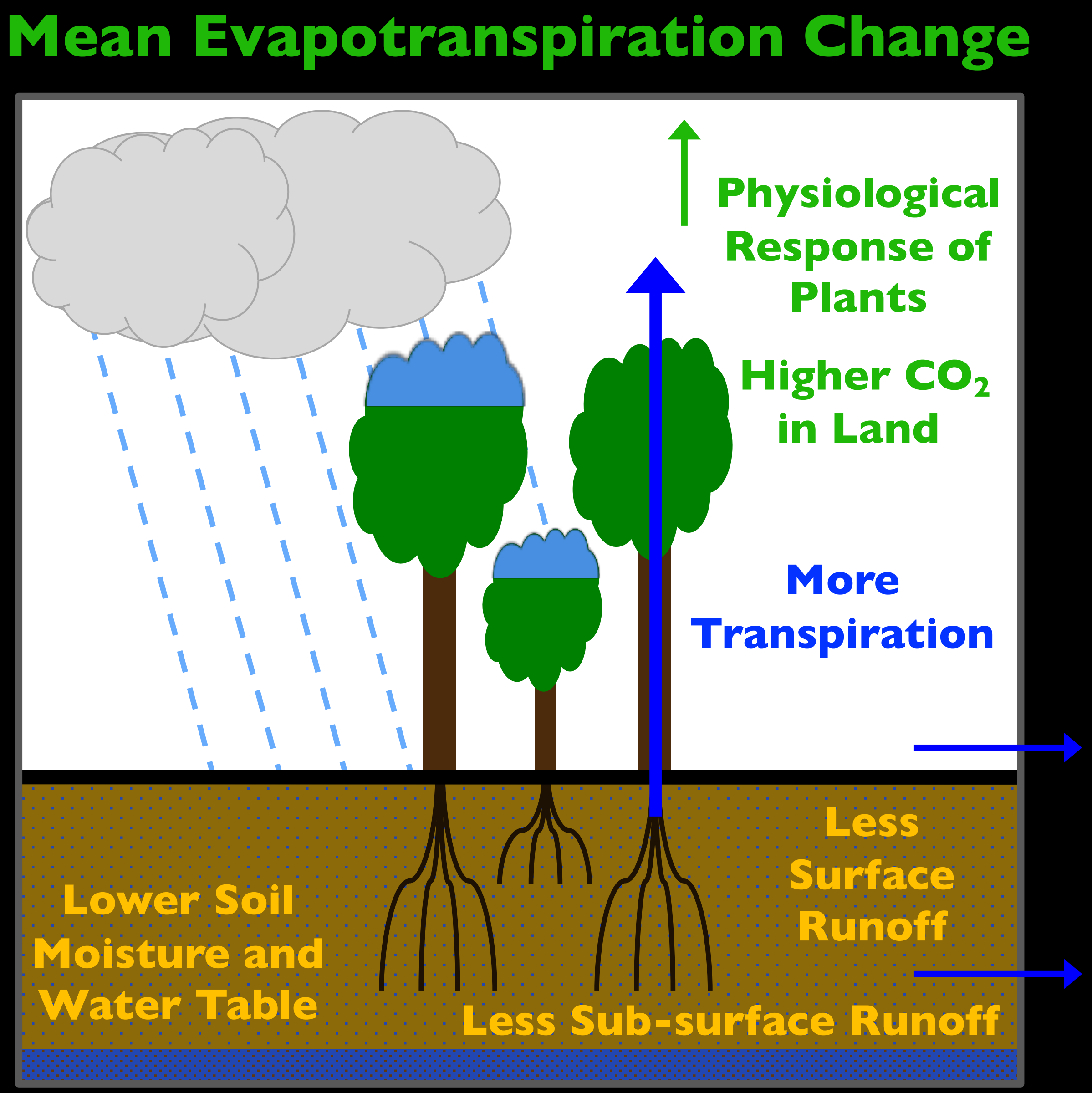


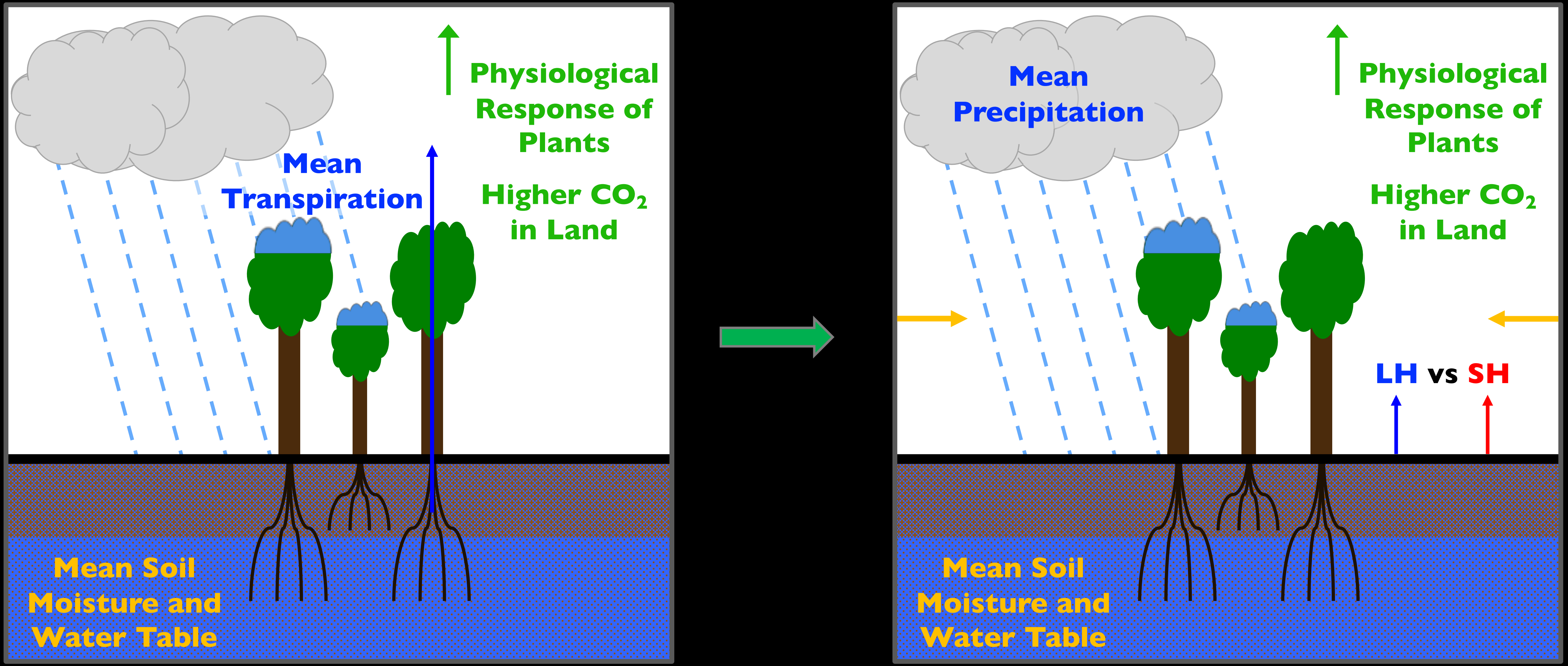


- Reduced stomatal conductance can lower transpiration and increase soil moisture
- CO_2 fertilization effect increases leaf area and can increase transpiration

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

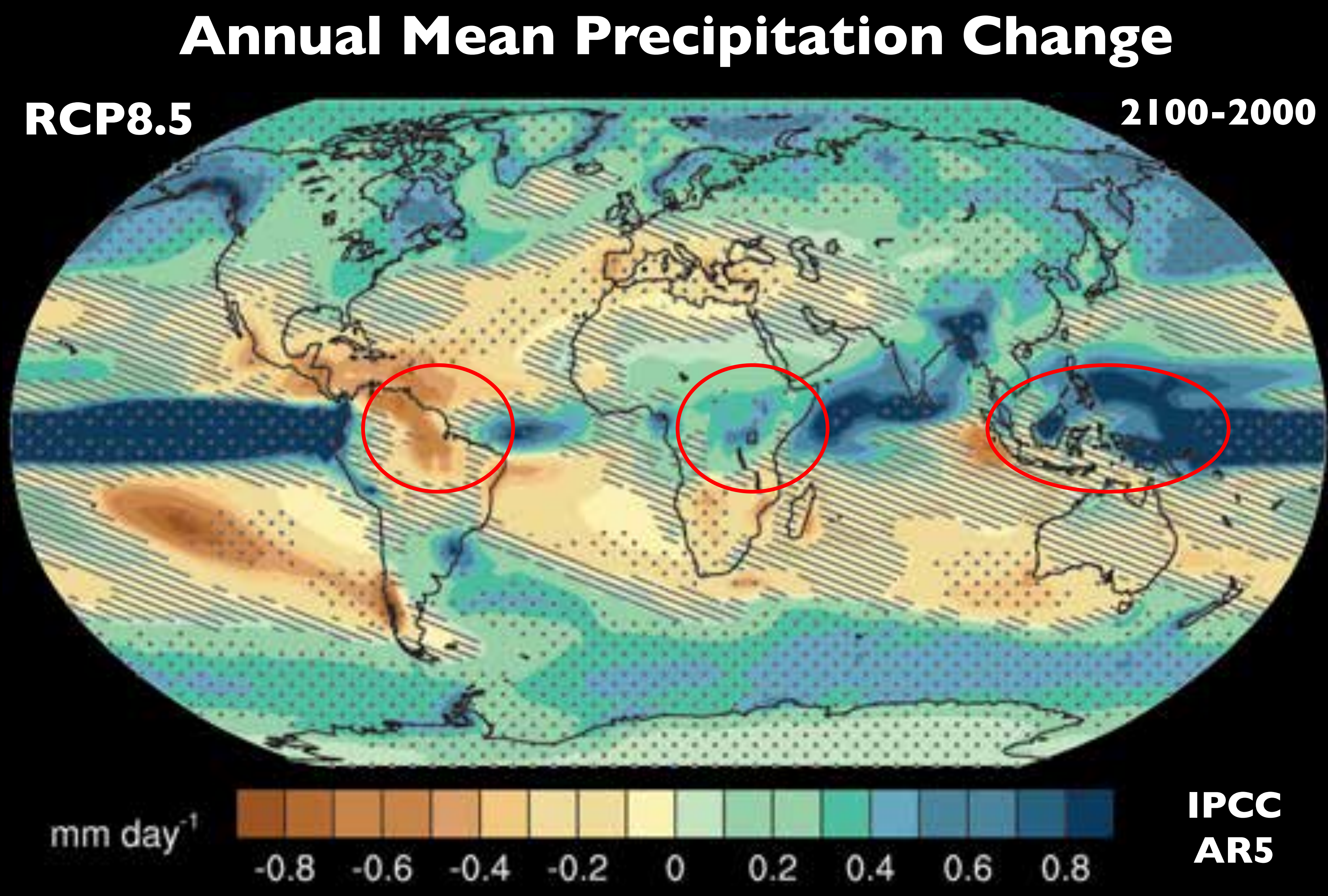
Mean Evapotranspiration Change

Mean Precipitation Change



- Stomatal conductance and CO_2 fertilization effects on transpiration and soil moisture
- Feedback on surface energy/moisture and circulation to influence mean precipitation

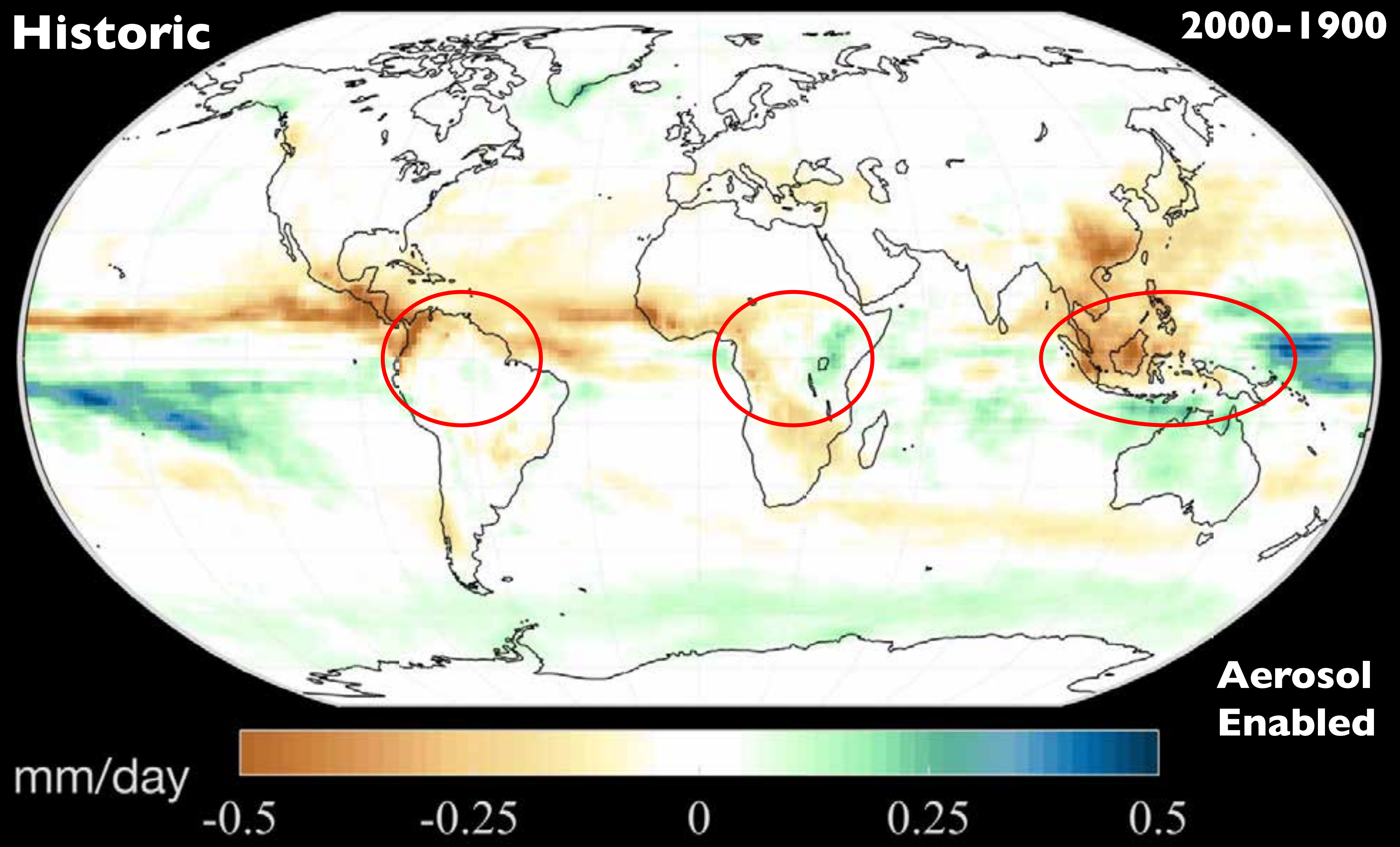
Tropical forests are critical for carbon cycling and biodiversity, but future rainfall changes over forests have seemed uncertain



- CMIP5 models project large rainfall changes over tropical forests, but with uncertainty
- 21st century changes driven by greenhouse gas emissions…

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

Annual Mean Precipitation Change



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- but historical changes are driven by aerosol in models with online aerosol-cloud physics

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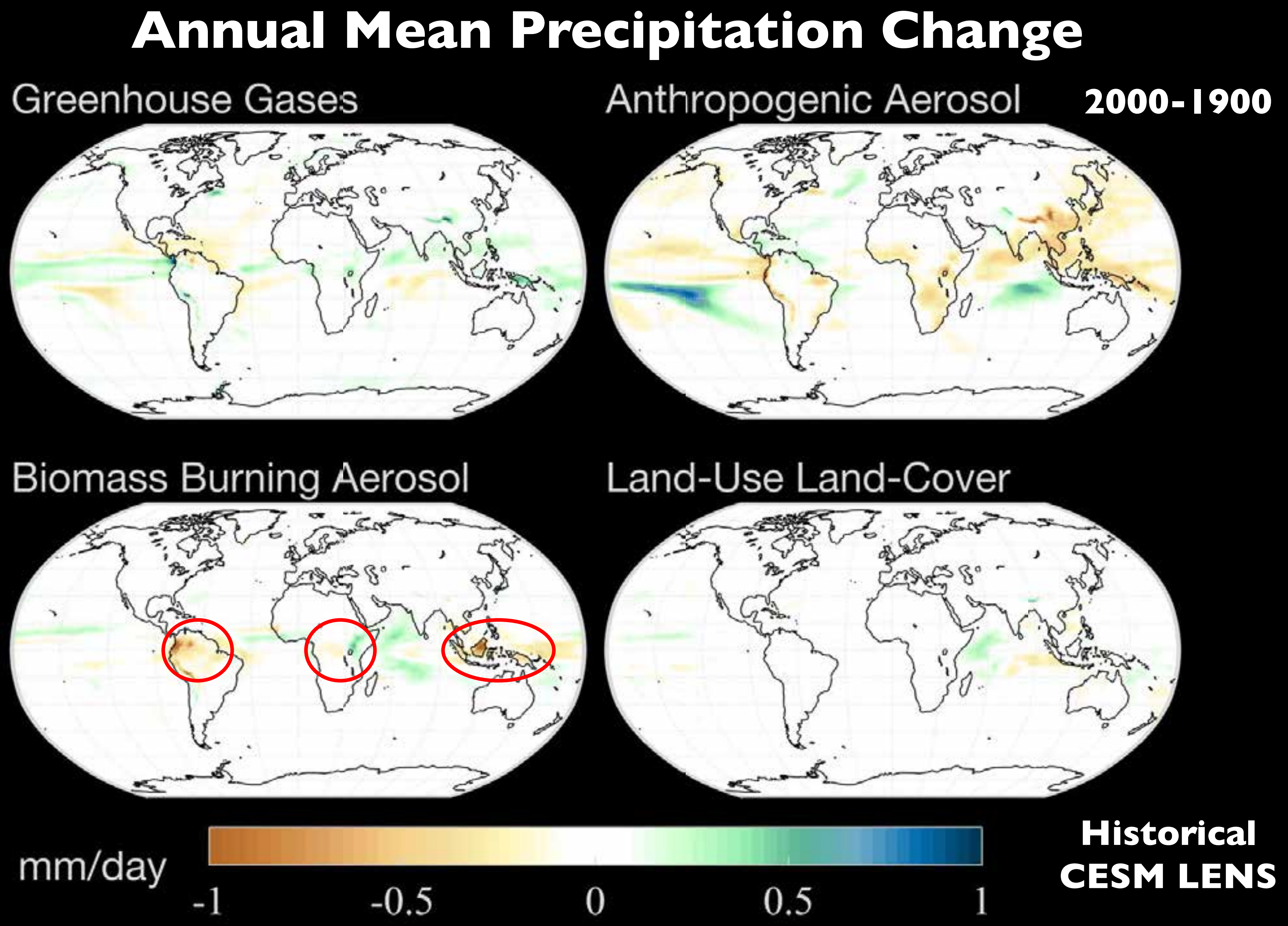
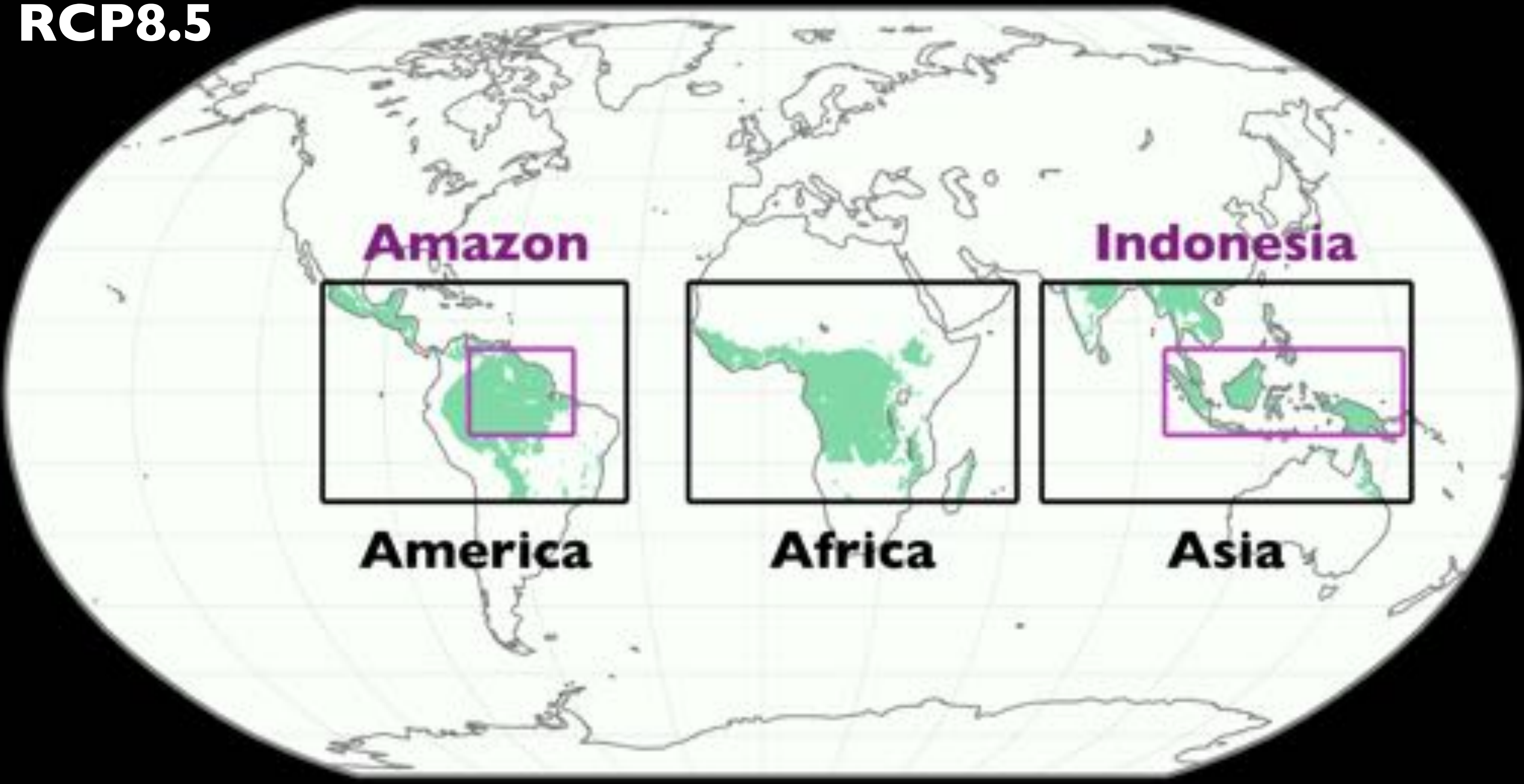


- **CMIP5 models project large rainfall changes over tropical forests, but with uncertainty**
- **21st century changes driven by greenhouse gas emissions…**
- **but historical changes are driven by aerosol in models with online aerosol-cloud physics**
- **Historical changes in tropical rainfall have have been influenced by forest fire aerosol**

Despite this uncertainty, all CMIP5 climate models project a growing zonally asymmetric rainfall pattern across the tropics

Tropical Forest Regions

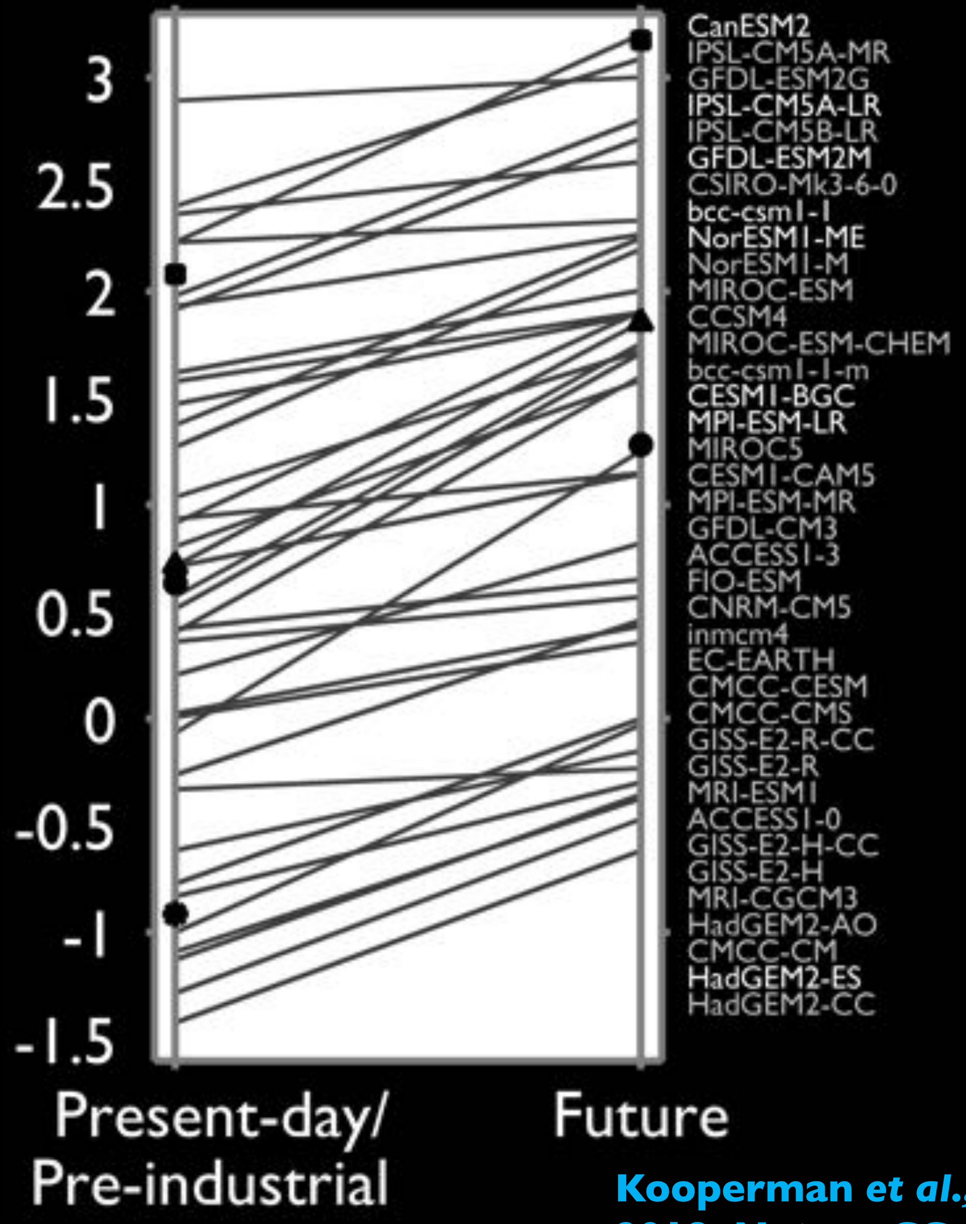
RCP8.5



Tropical Precipitation Asymmetry Index

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

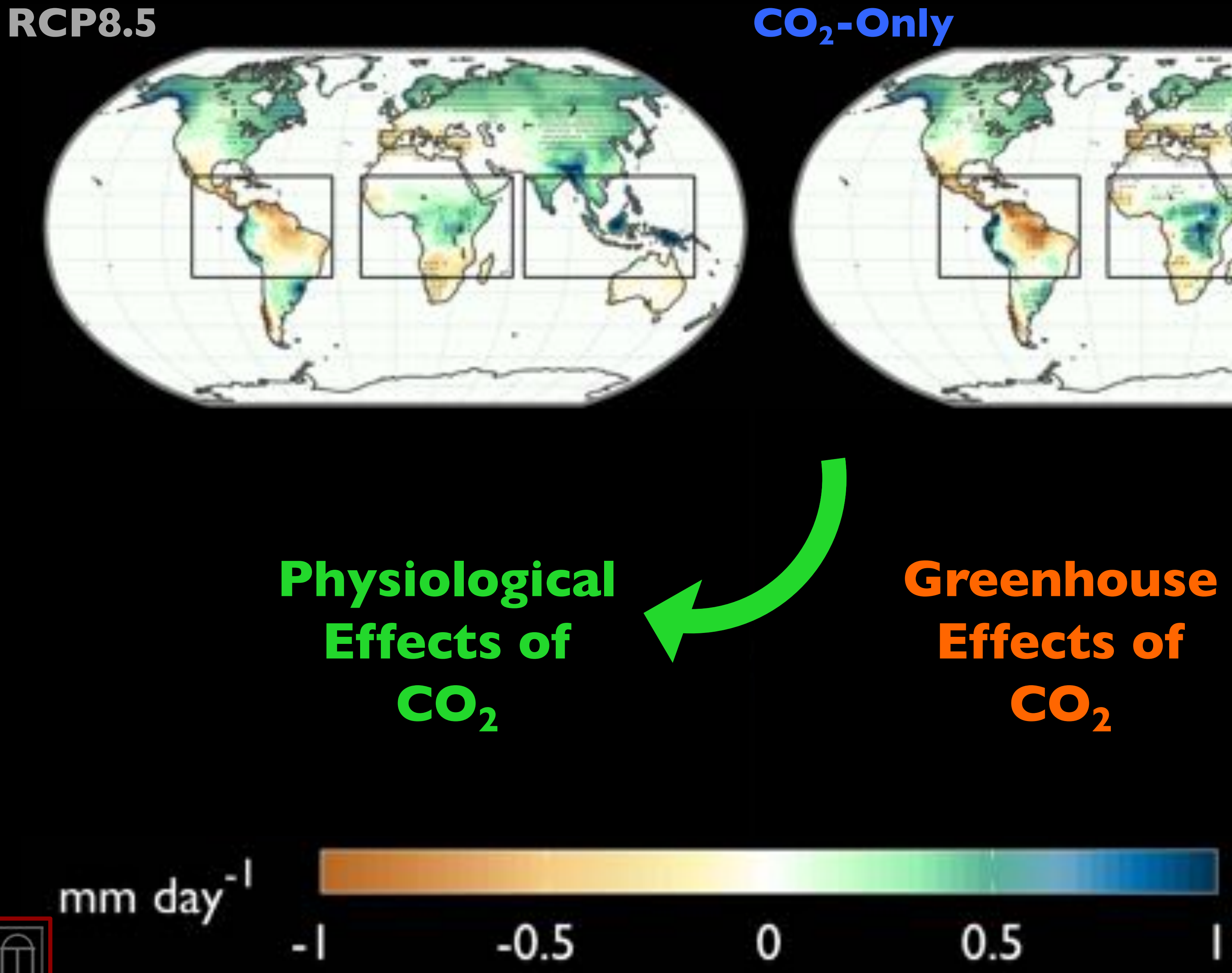
Precipitation Asymmetry



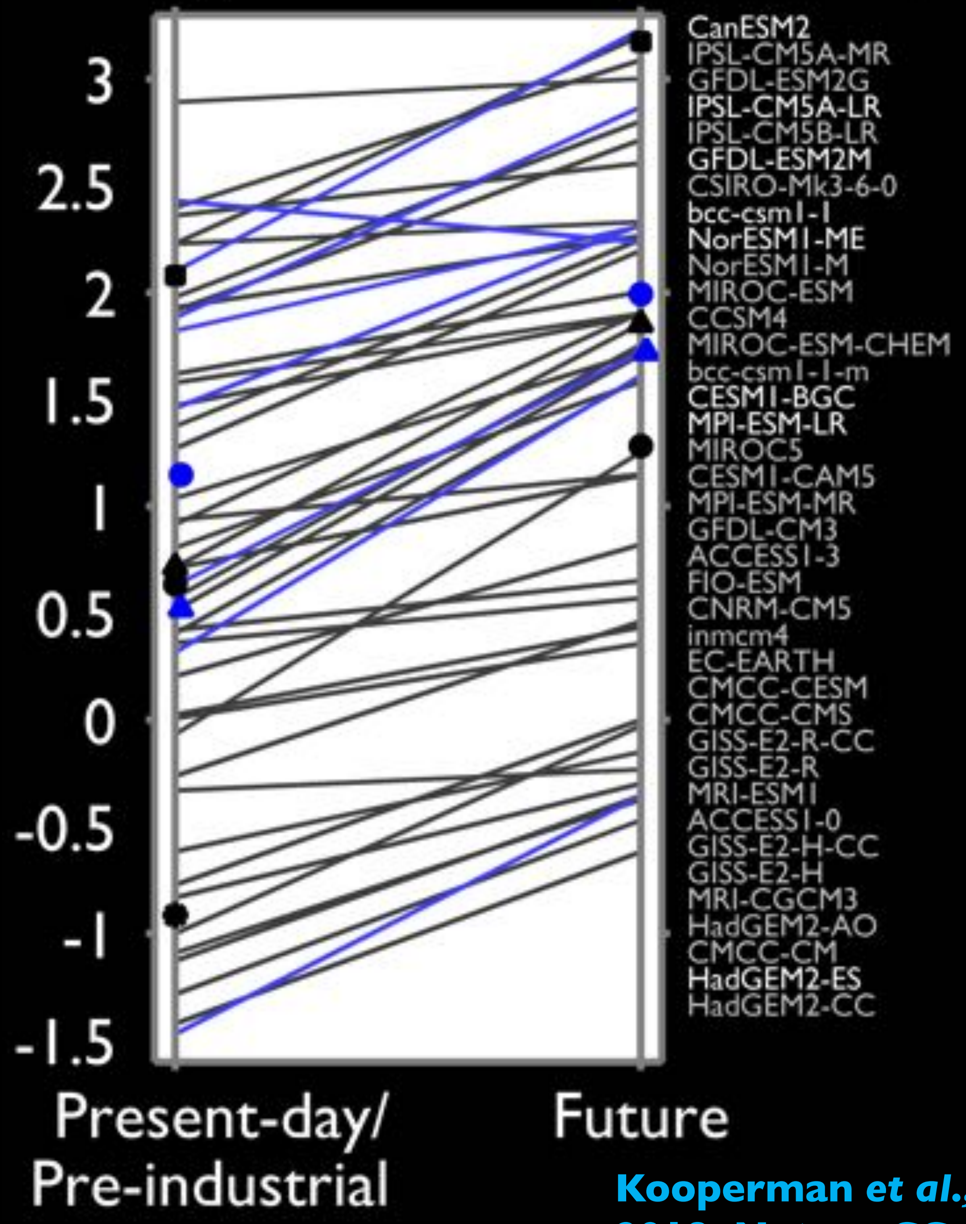
Kooperman *et al.*, 2018, Nature CC

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

Annual Mean Precipitation Change



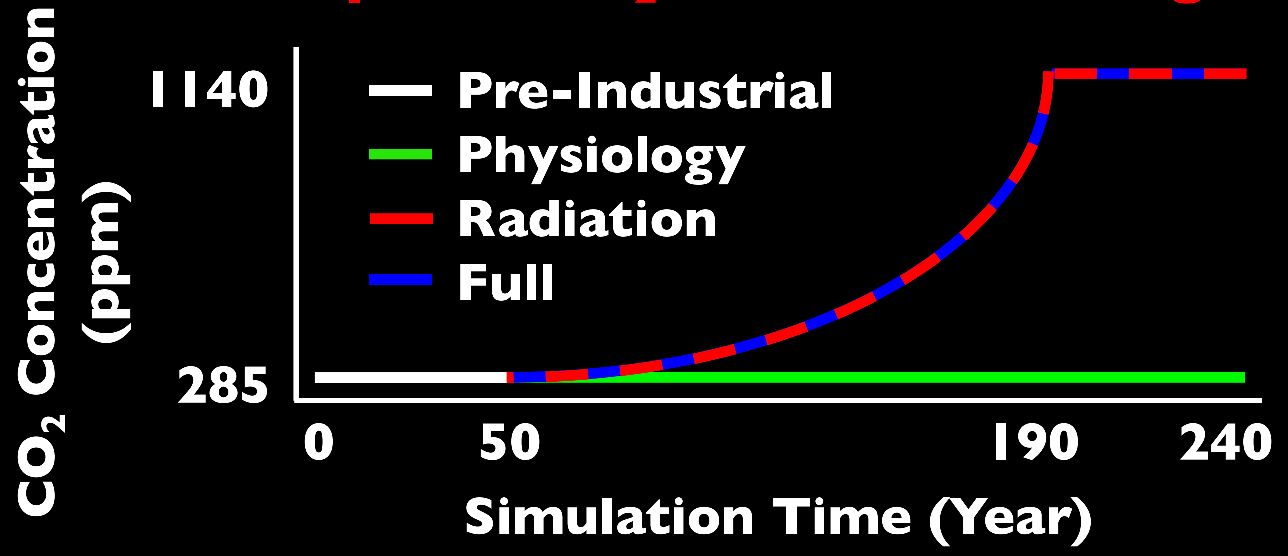
Precipitation Asymmetry



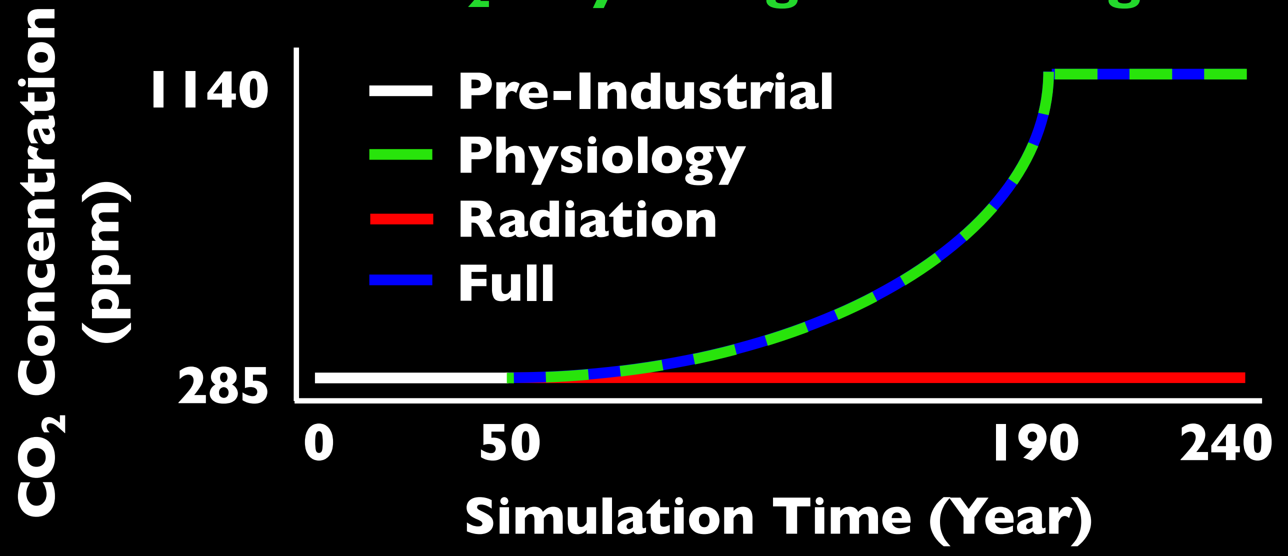
Kooperman *et al.*, 2018, Nature CC

Idealized CO_2-only forcing simulations (C4MIP) separate plant-physiology and radiative-greenhouse impacts of rising CO_2

Atmosphere CO_2 Radiative Forcing



Land CO_2 Physiological Forcing

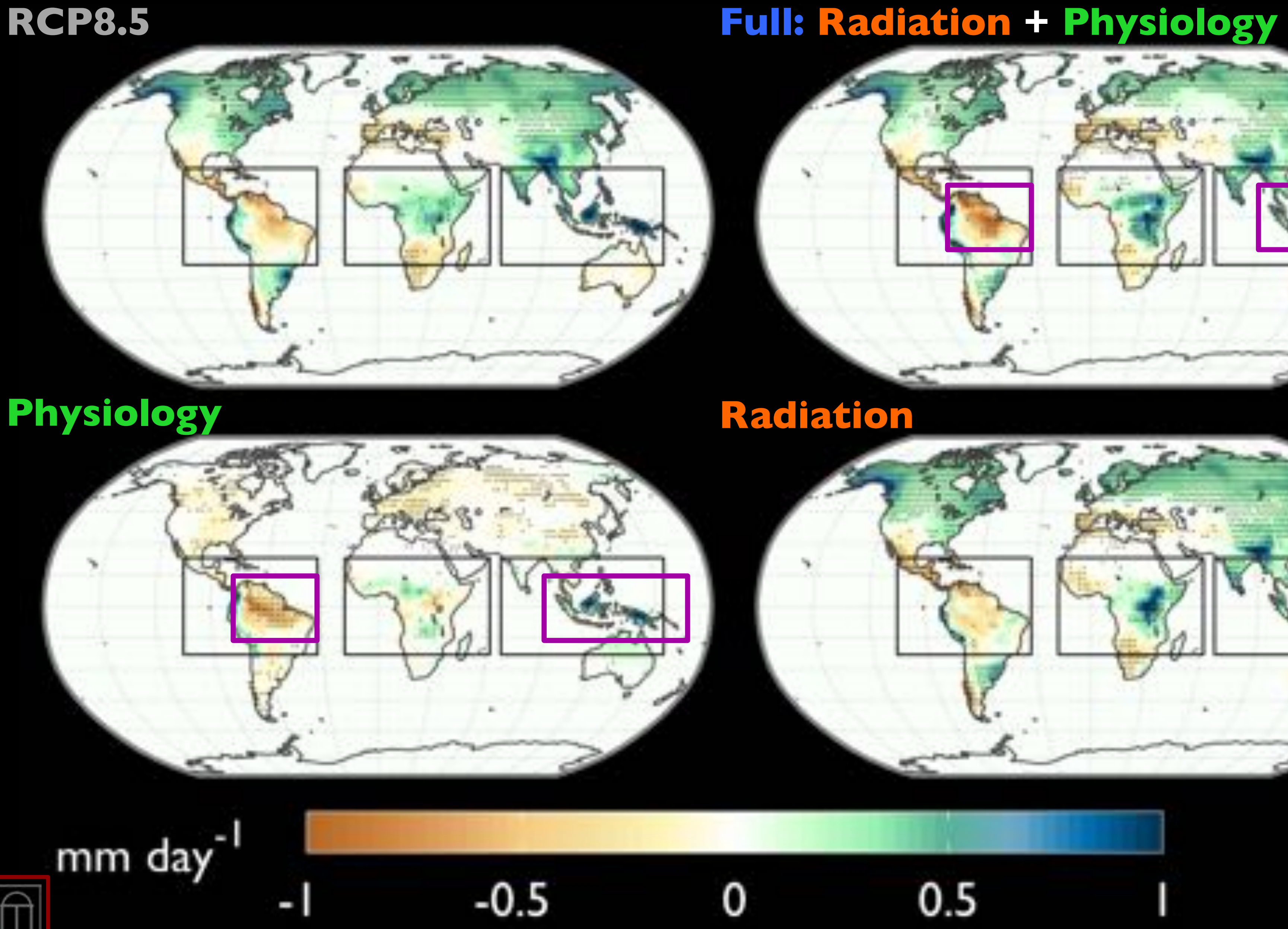


Community Earth System Model

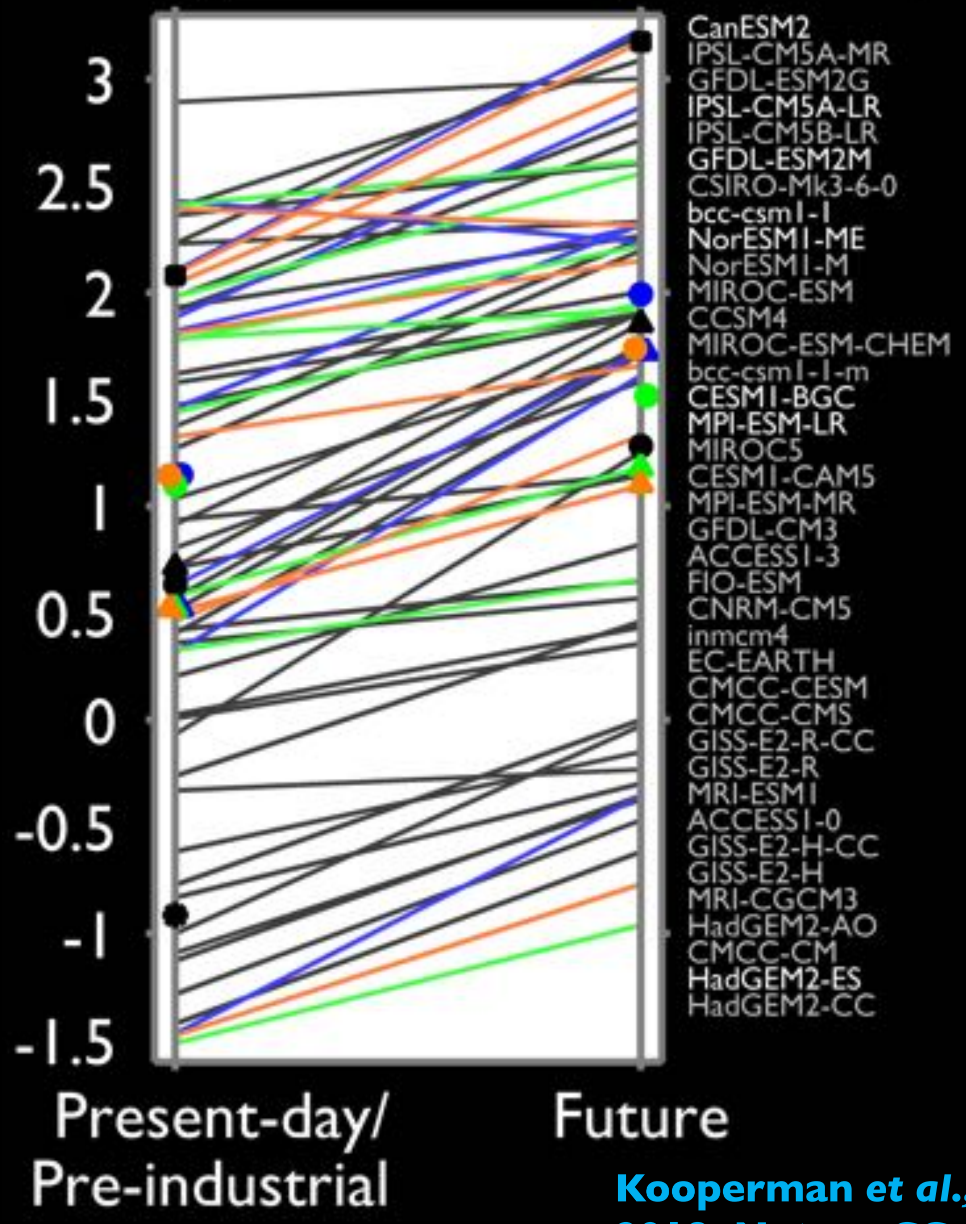
CAM	CLM
Pre-Industrial	Pre-Industrial
$4xCO_2$	$4xCO_2$
$4xCO_2$	Pre-Industrial
Pre-Industrial	$4xCO_2$

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

Annual Mean Precipitation Change



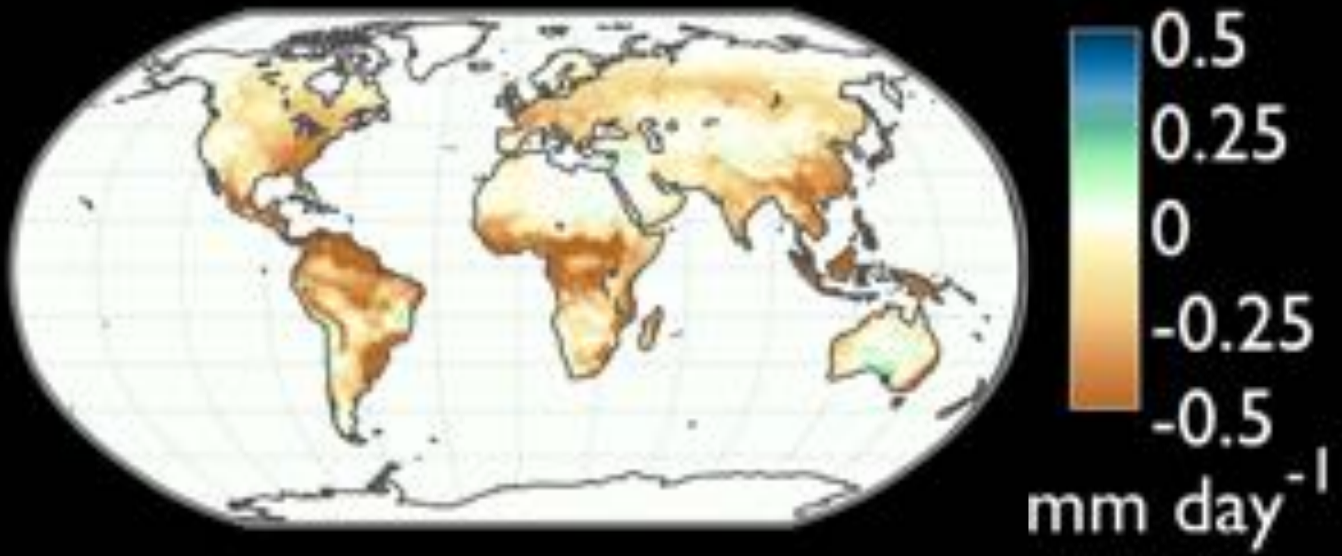
Precipitation Asymmetry



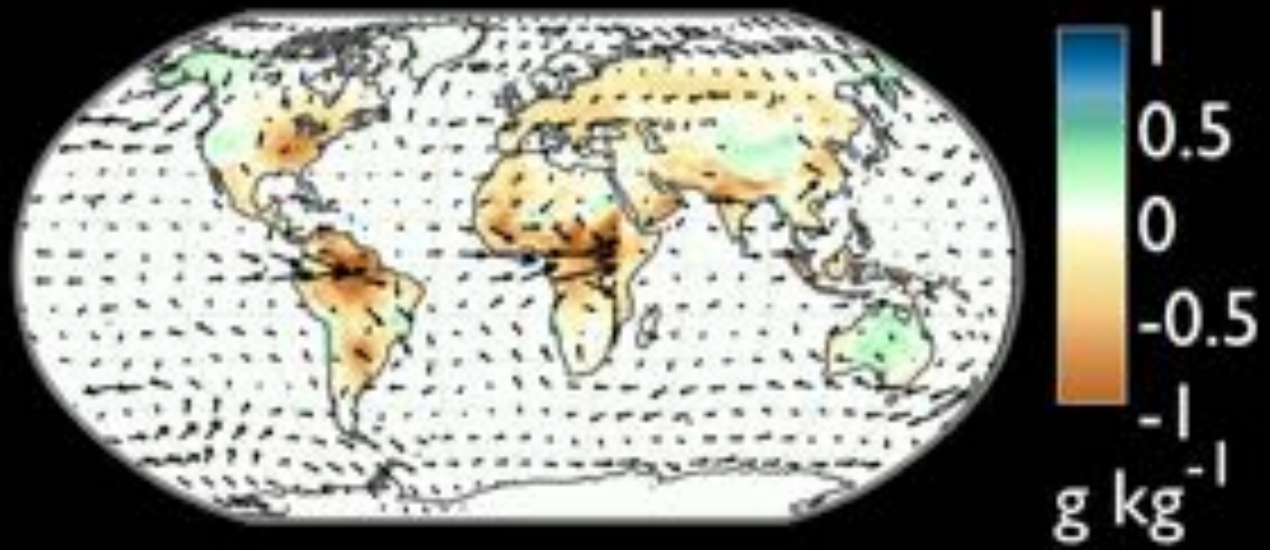
Kooperman *et al.*, 2018, Nature CC

Higher CO_2 reduces stomatal conductance and transpiration, modifying surface heat fluxes, humidity, and circulation

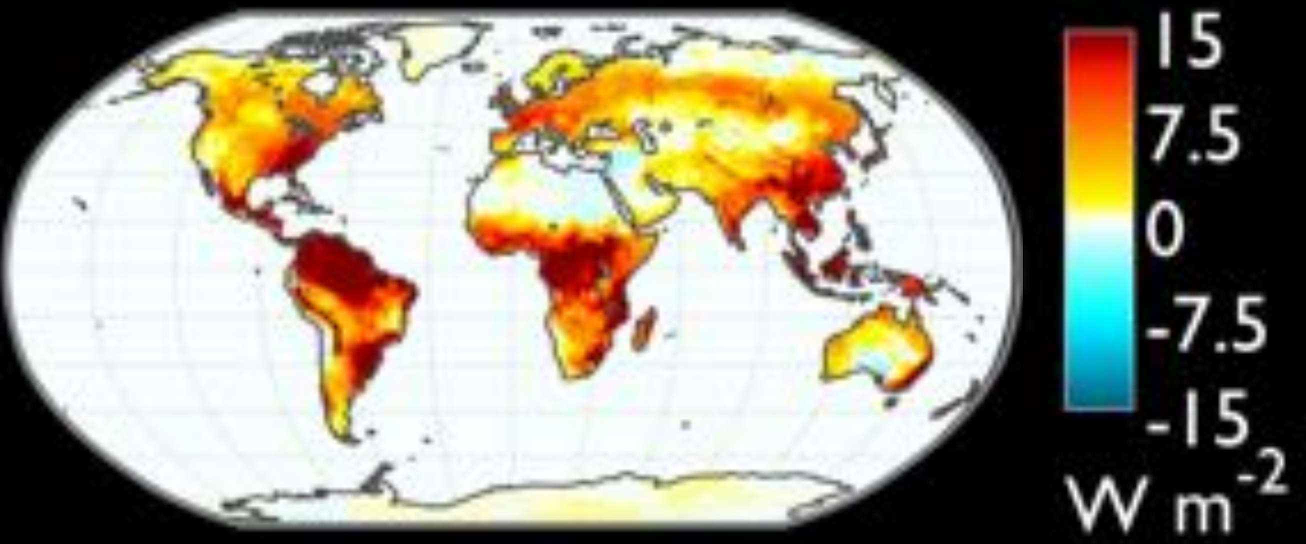
Evapotranspiration



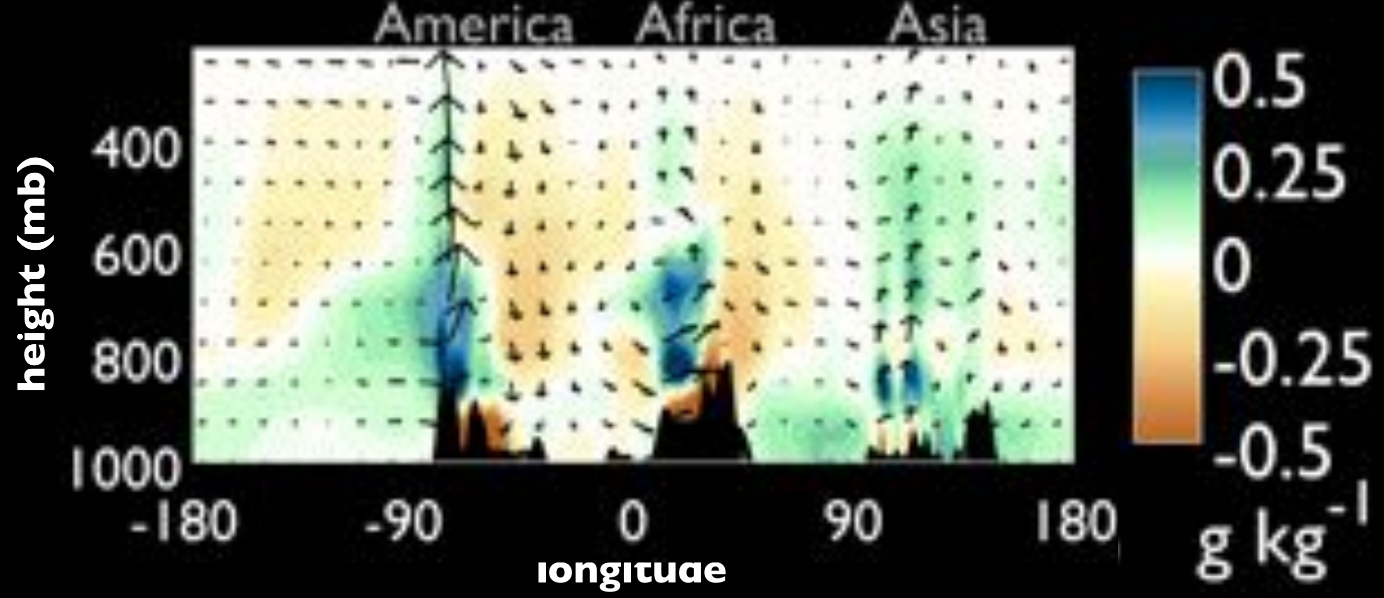
Near Surface Specific Humidity



Sensible Heat Flux

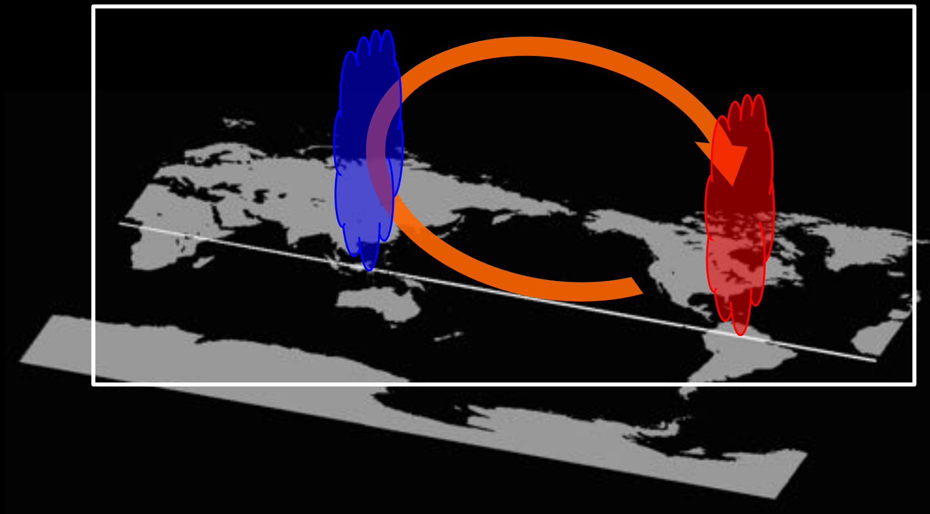


Tropical (5˚S–5˚N) Specific Humidity

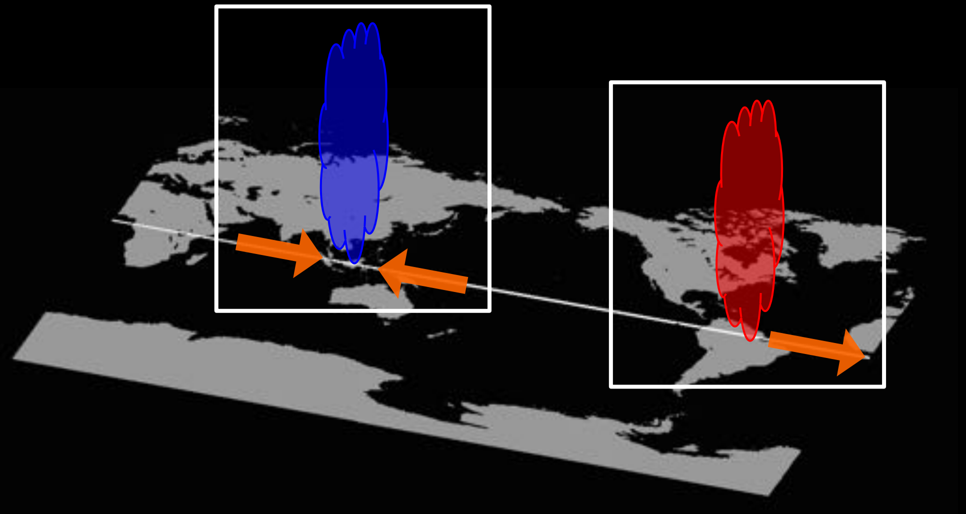


A controlled experiment with CESM tests if pattern is driven by tropics-wide (Walker Circulation) or regional mechanisms

Tropics Wide Mechanism



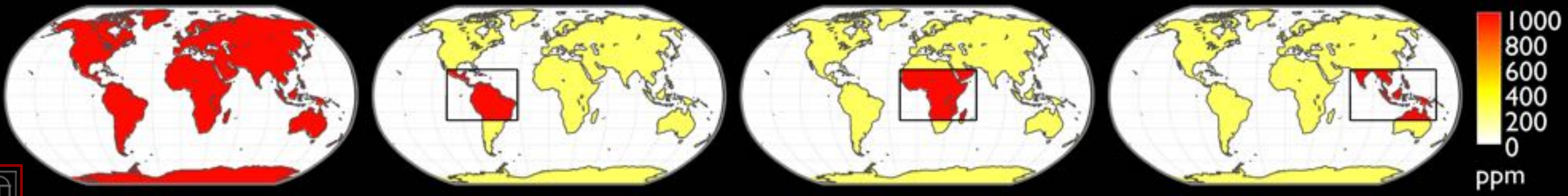
Regional Mechanisms



Community Earth System Model

Land-Surface CO_2 Concentration

Global America Africa Asia



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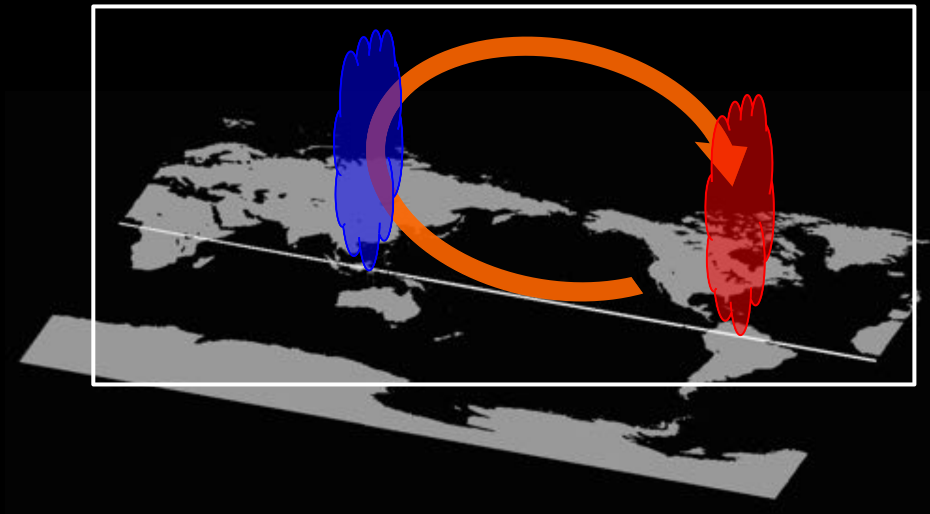
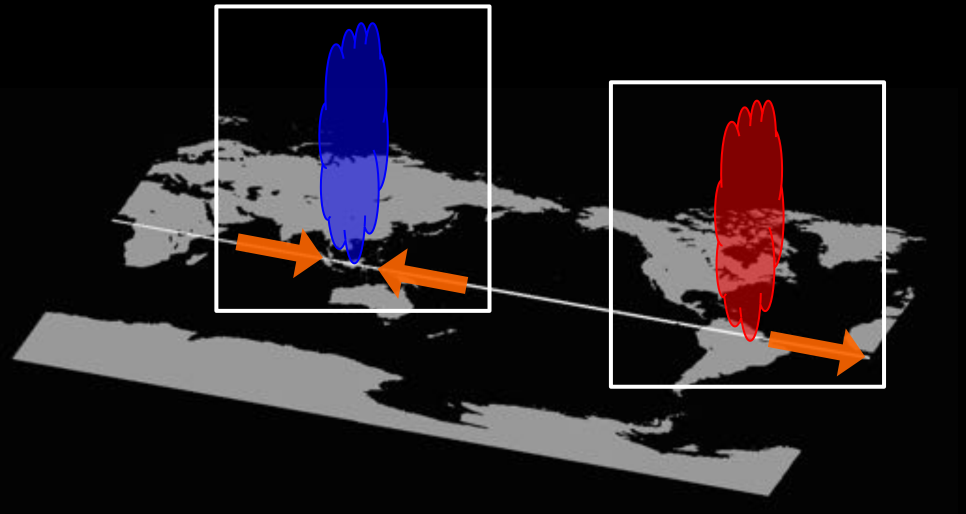


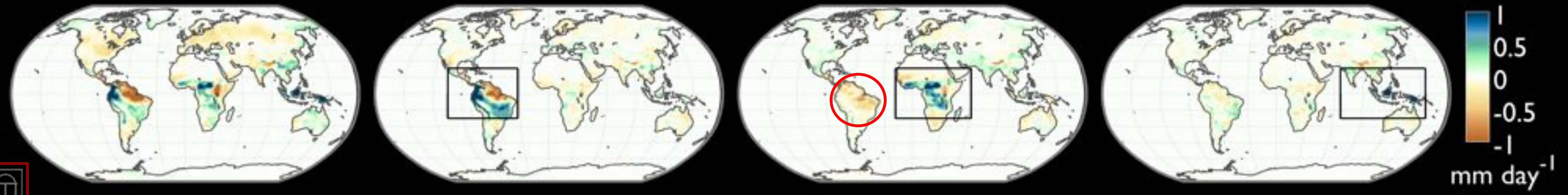
Regional Mechanisms



Community Earth System Model

Annual Mean Precipitation Change

Global America Africa Asia



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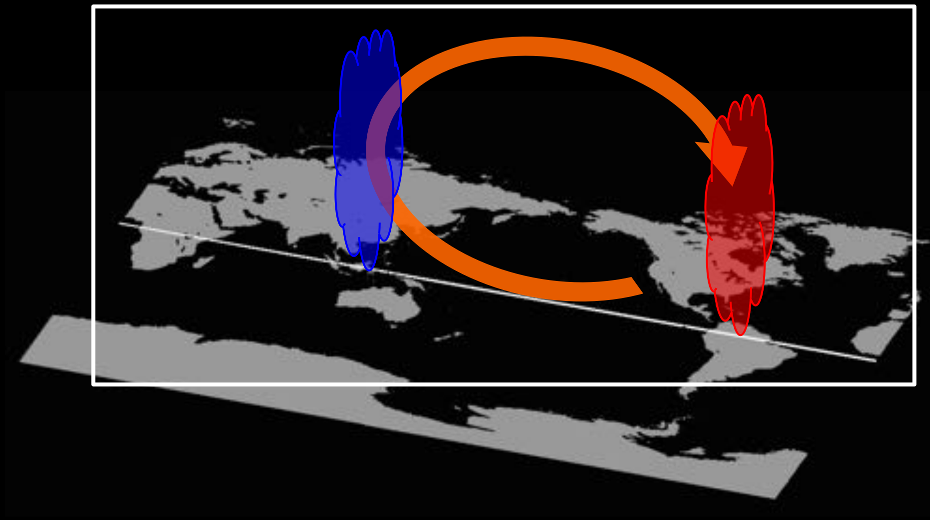
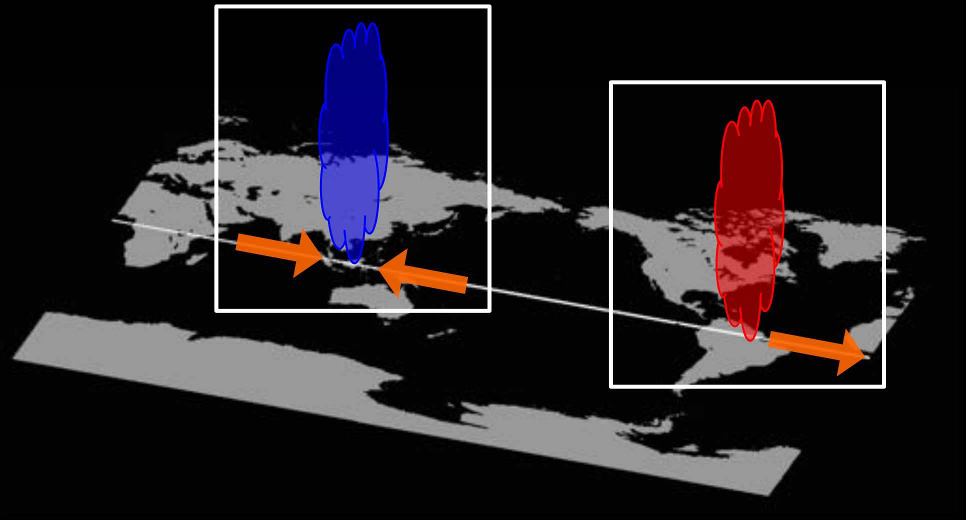
Tropics Wide Mechanism



Regional Mechanisms

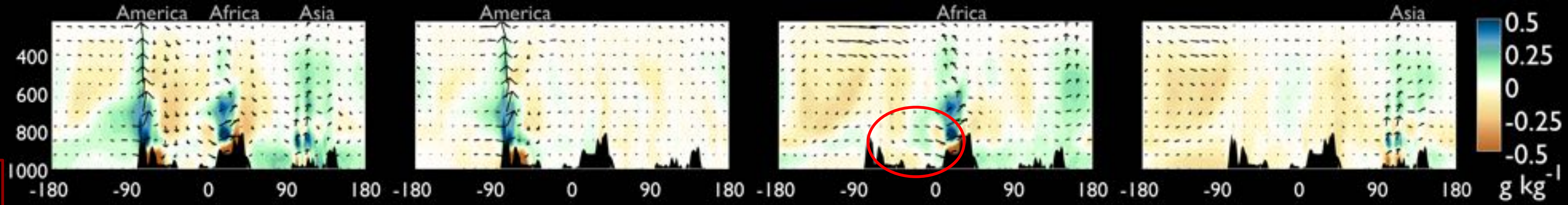


Community Earth System Model

Pre-Industrial **4xCO_2**

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

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

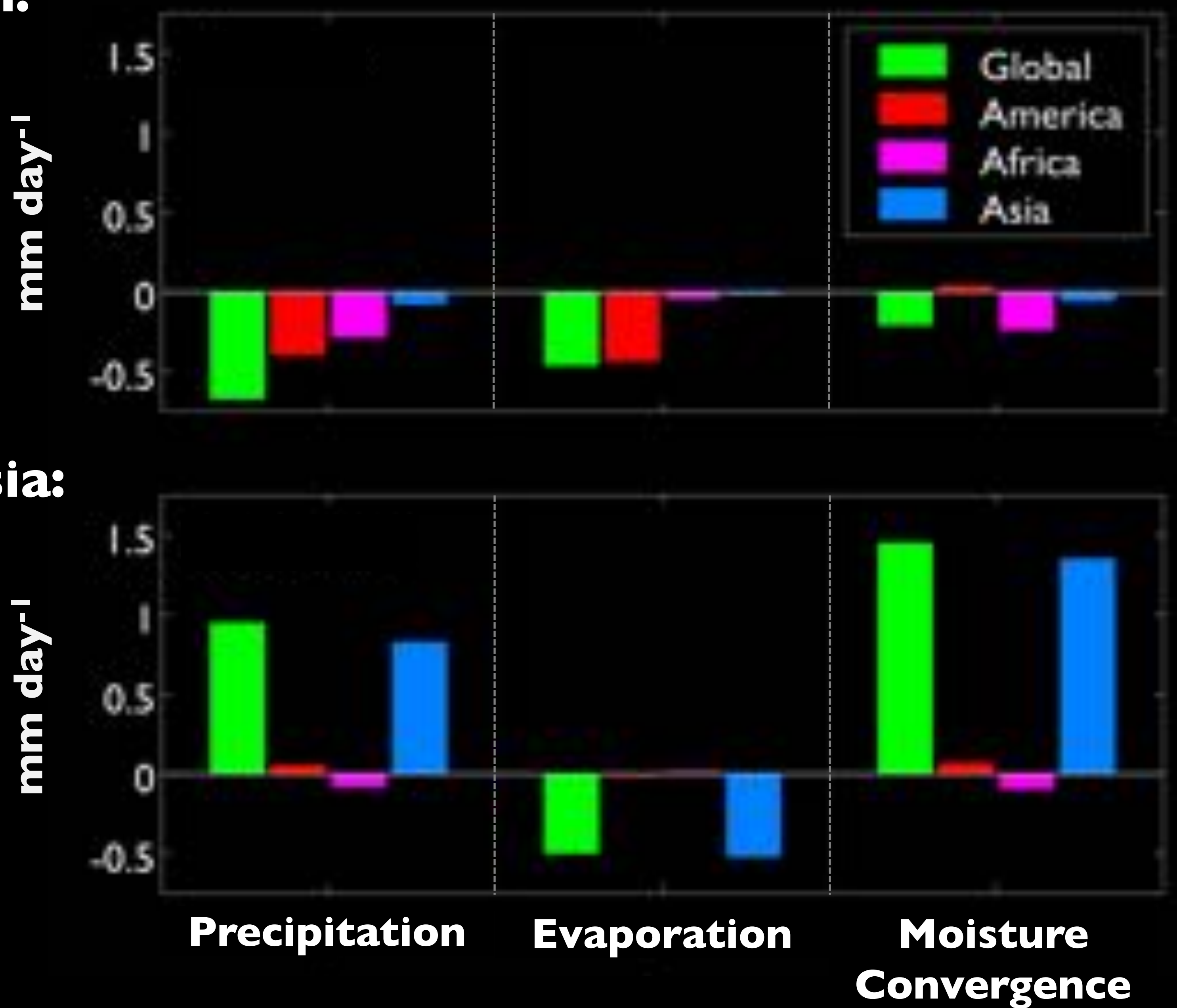


Locally and non-locally driven moisture convergences changes lead to less rainfall over the Amazon and more over Indonesia

Δ Moisture Budget

Amazon:

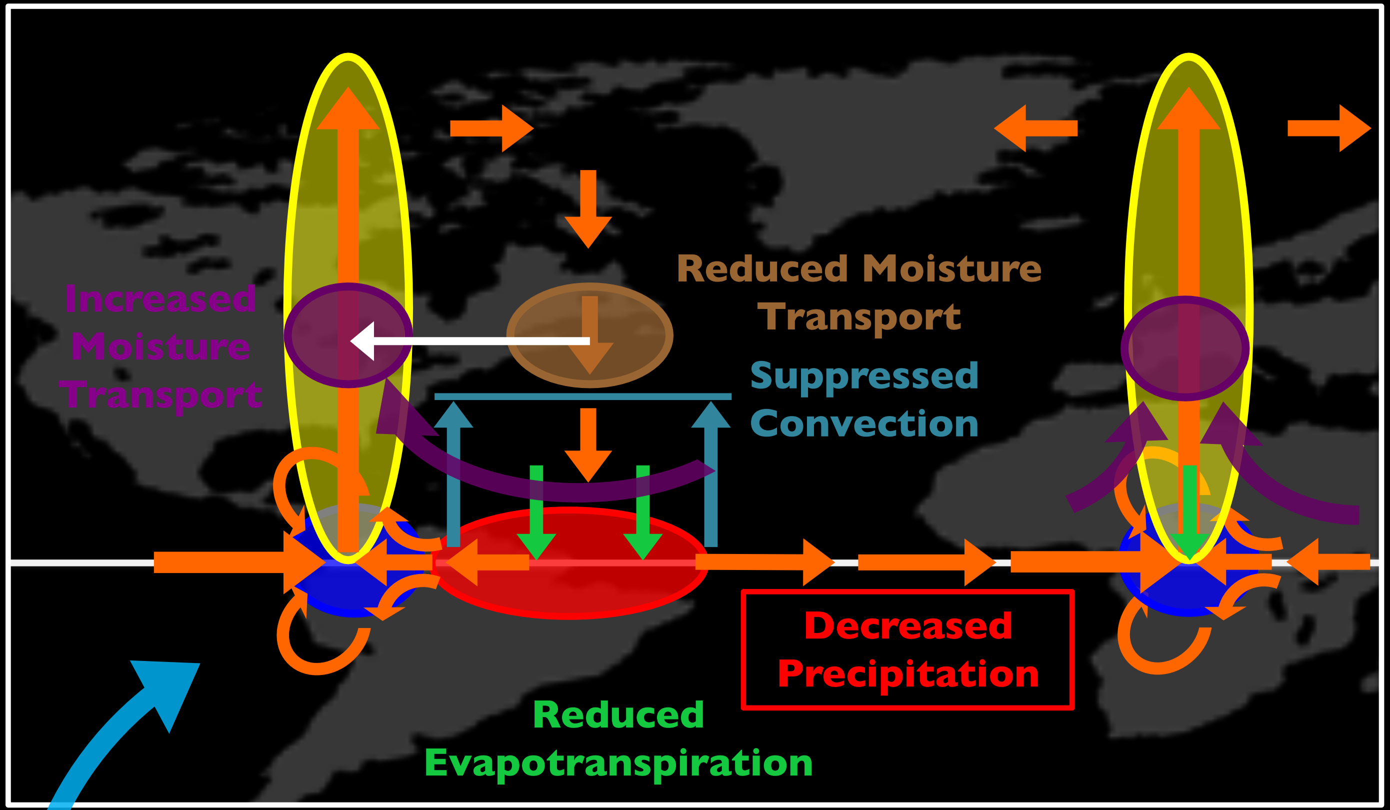
Indonesia:



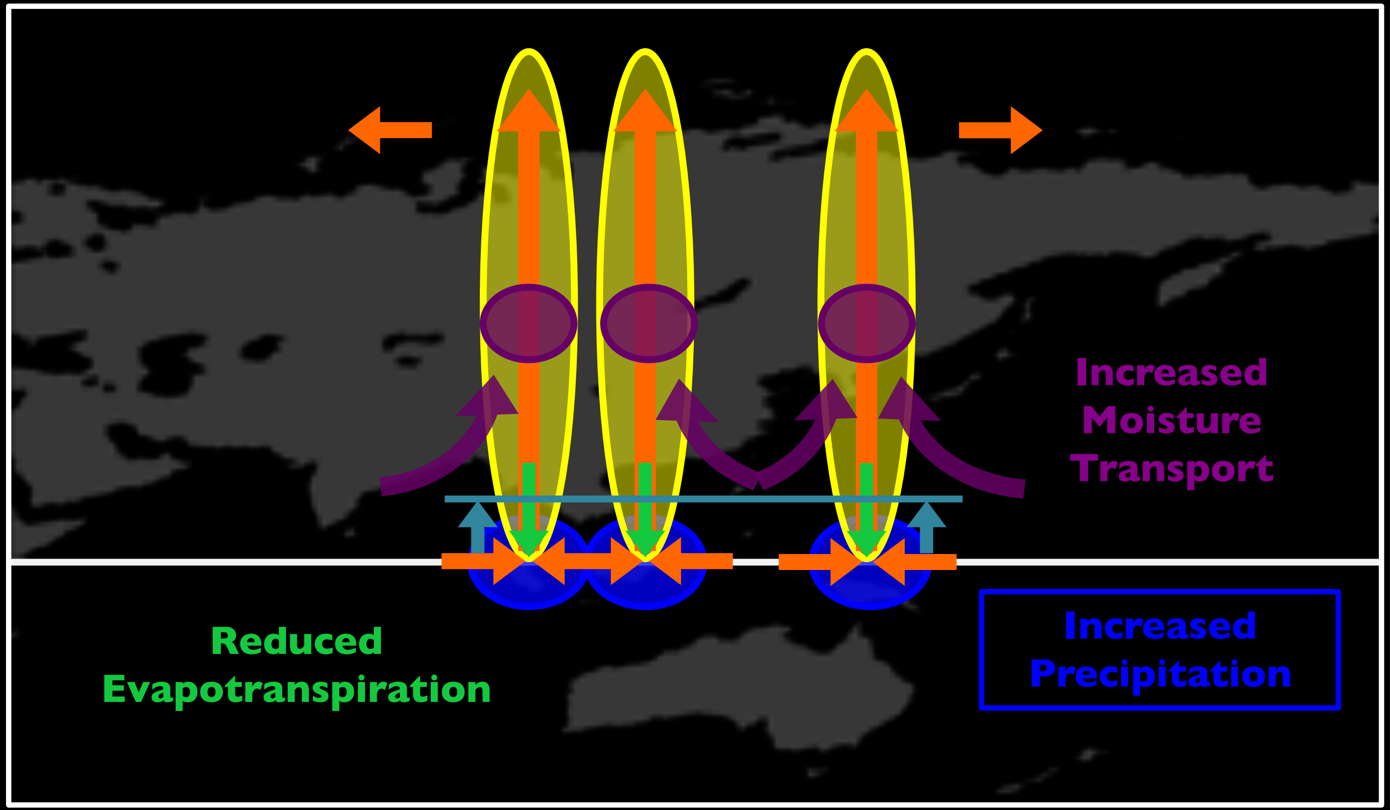
- **Precipitation reduction over the Amazon has local and non-local (Africa) influences**
- **Evapotranspiration reduction from local forcing over the Amazon and Indonesia have similar magnitudes**
- **Indonesia has a larger rise in moisture convergence than evapotranspiration reduction**
- **Circulation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

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

Amazon



Indonesia



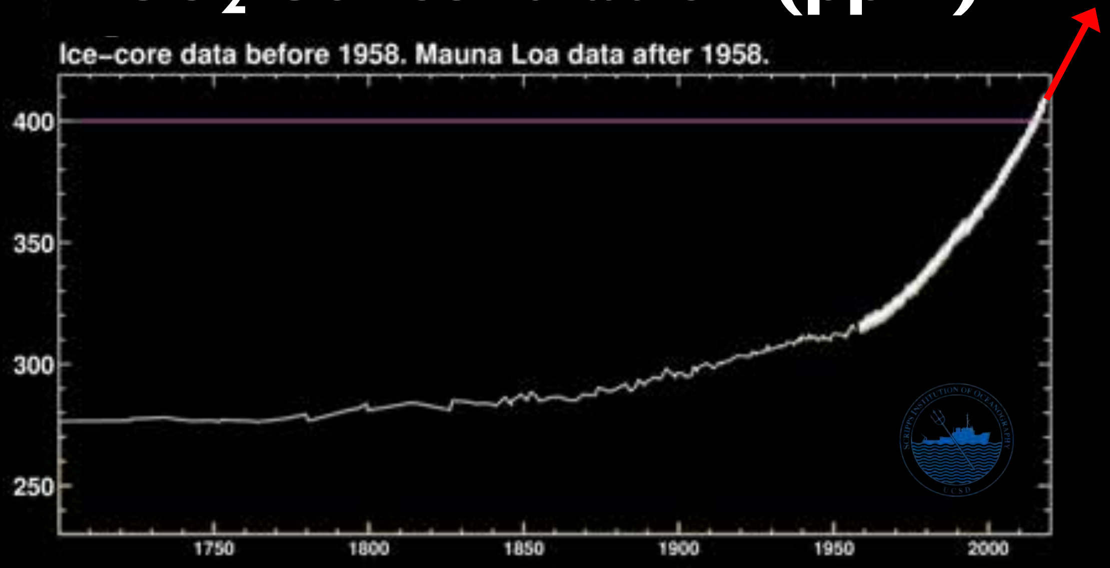
Precipitation ↑
Precipitation ↓
Evapotranspiration ↓
Condensation Level ↑
Convective Heating ↑
Circulation Anomaly ←
Moisture Convergence ↑
Moisture Convergence ↓

Export of Moist Static Energy ←

Langenbrunner *et al.*, Earth's Future 2019

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

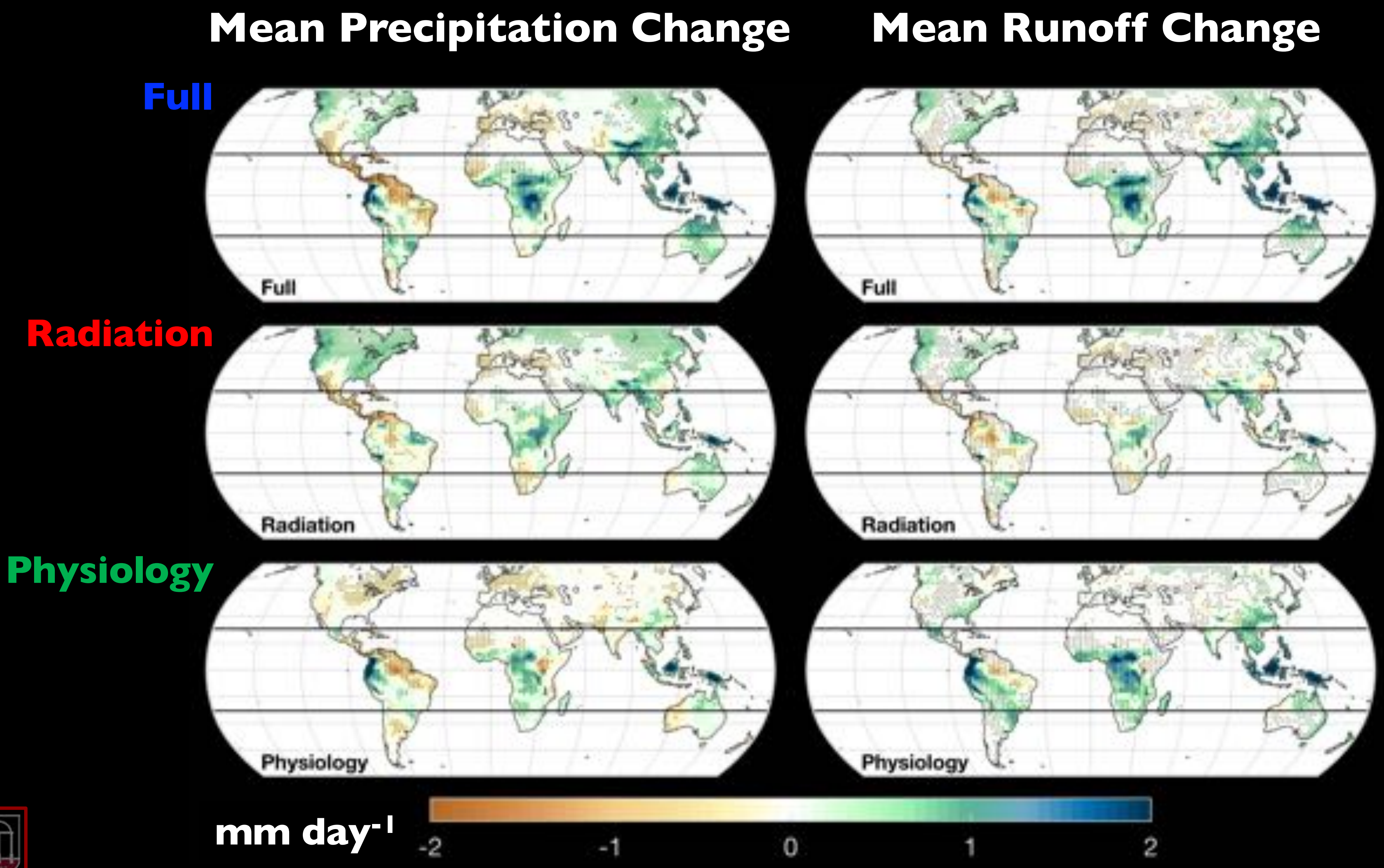
CO_2 Concentration (ppm)



Precipitation

Flooding

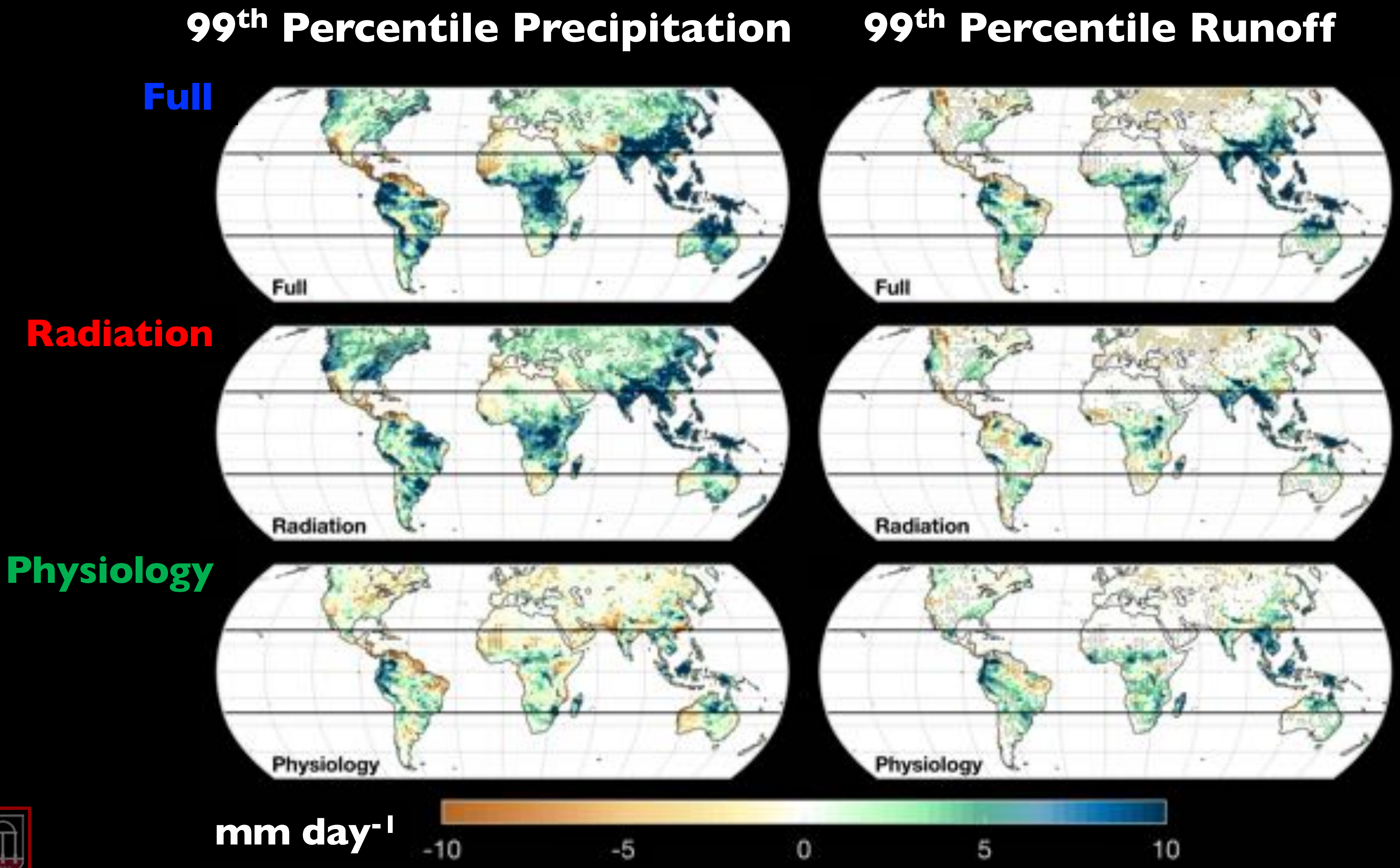
Plant-physiological and radiative effects both contribute to mean rainfall changes, but runoff is dominated by physiology



- 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

Kooperman et *al.*, 2018, GRL

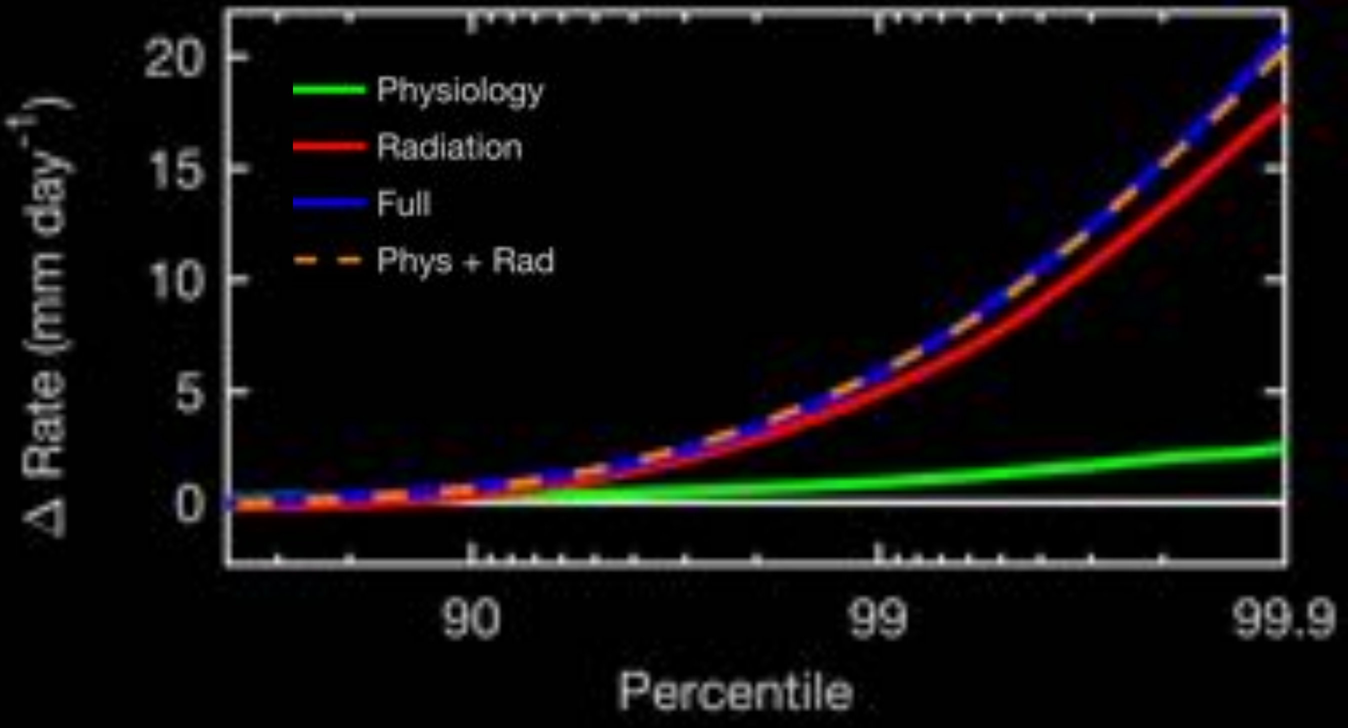
Rainfall intensification is primarily driven by radiative effects, but runoff intensity changes are also influenced by physiology



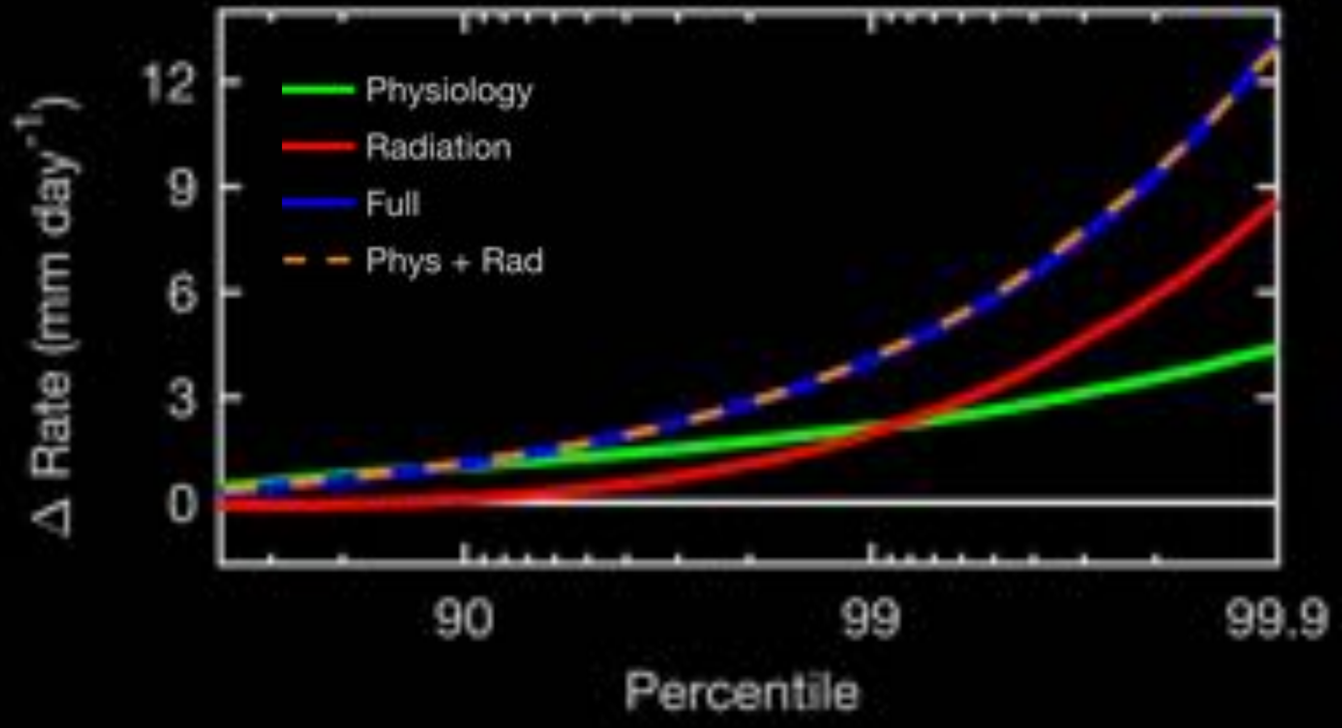
- Daily rain intensity increases across the tropics in response to increasing CO_2
- Daily runoff also increases intensity significantly due to increasing CO_2
- Rainfall intensity is primarily driven by radiative effects
- Runoff change has contributions from both radiation and physiology effects

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

Precipitation Percentile Change



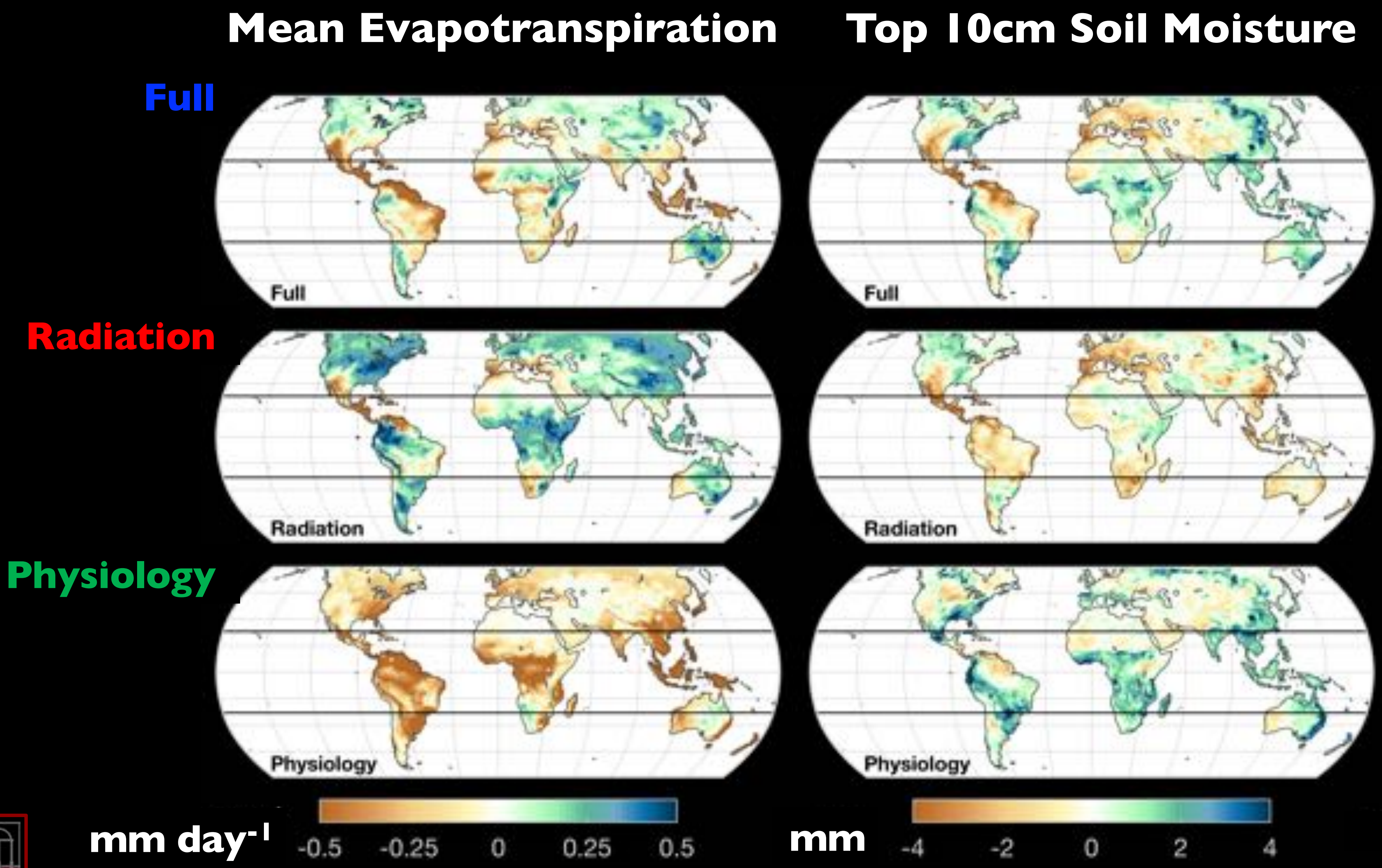
Runoff Percentile Change



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

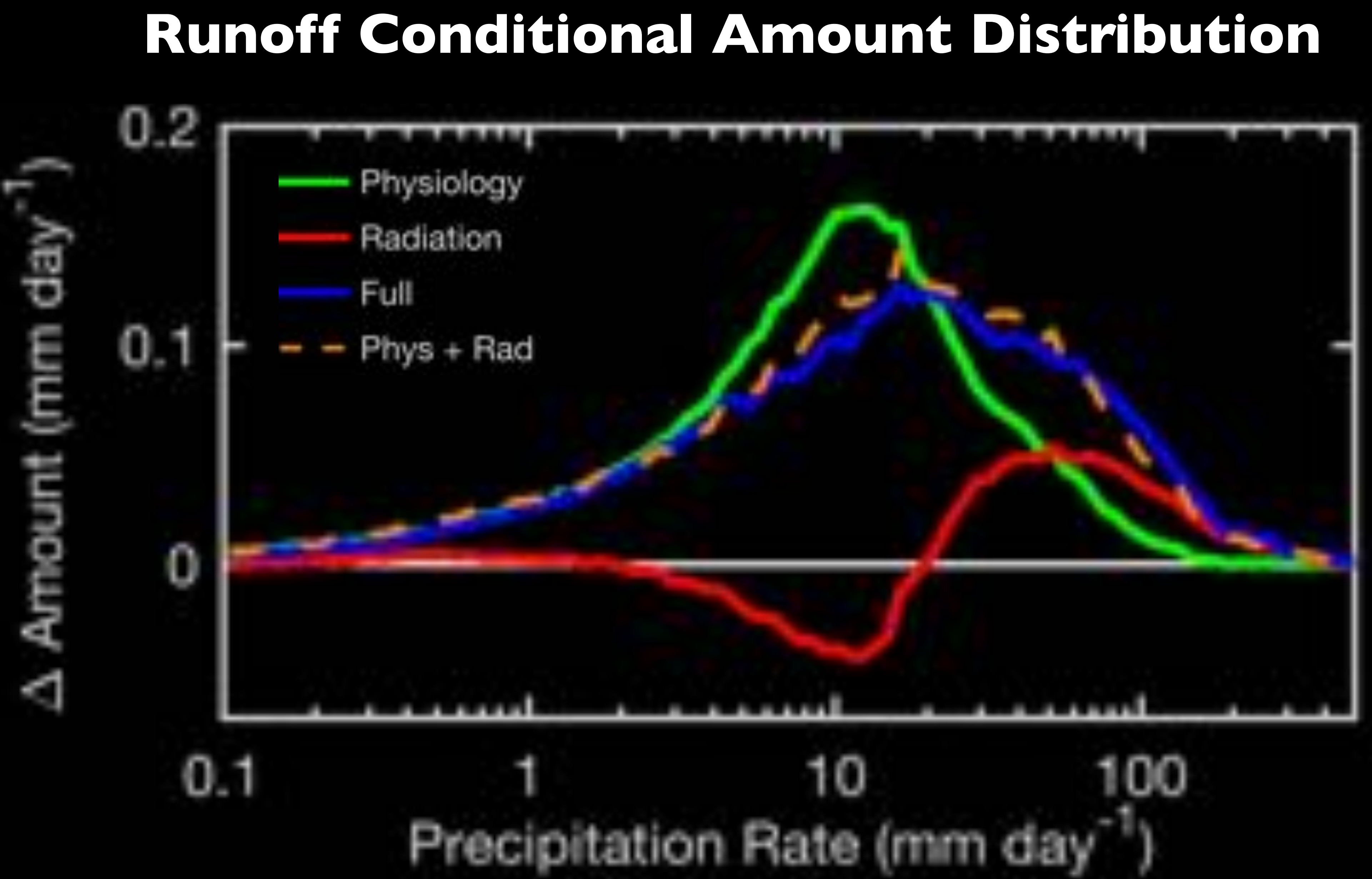
- **Daily runoff intensity changes are largest from physiology up to 99th percentile**
- **Physiology adds ⅓ to 99.9th percentile**
- **Full simulation is a linear combination of physiology and radiation simulations**

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

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



- The radiative effects drive increases in precipitation from the highest rates and decreases from the lowest rates, which lead to similar shifts for runoff amount…
- but the influence of physiology increases the amount of runoff from all precipitation rates (i.e., same rain rates produce more extreme runoff)

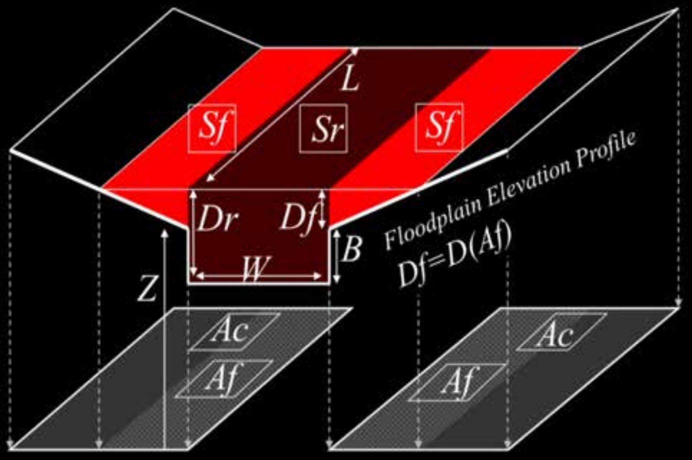
Downscaling CESM daily runoff using the CaMa-Flood model captures streamflow and inundation in major river systems

Fowler *et al.*, in review 2019:

- Thirty years of daily runoff data from fully-coupled 1° CESM 4xCO_2 simulations

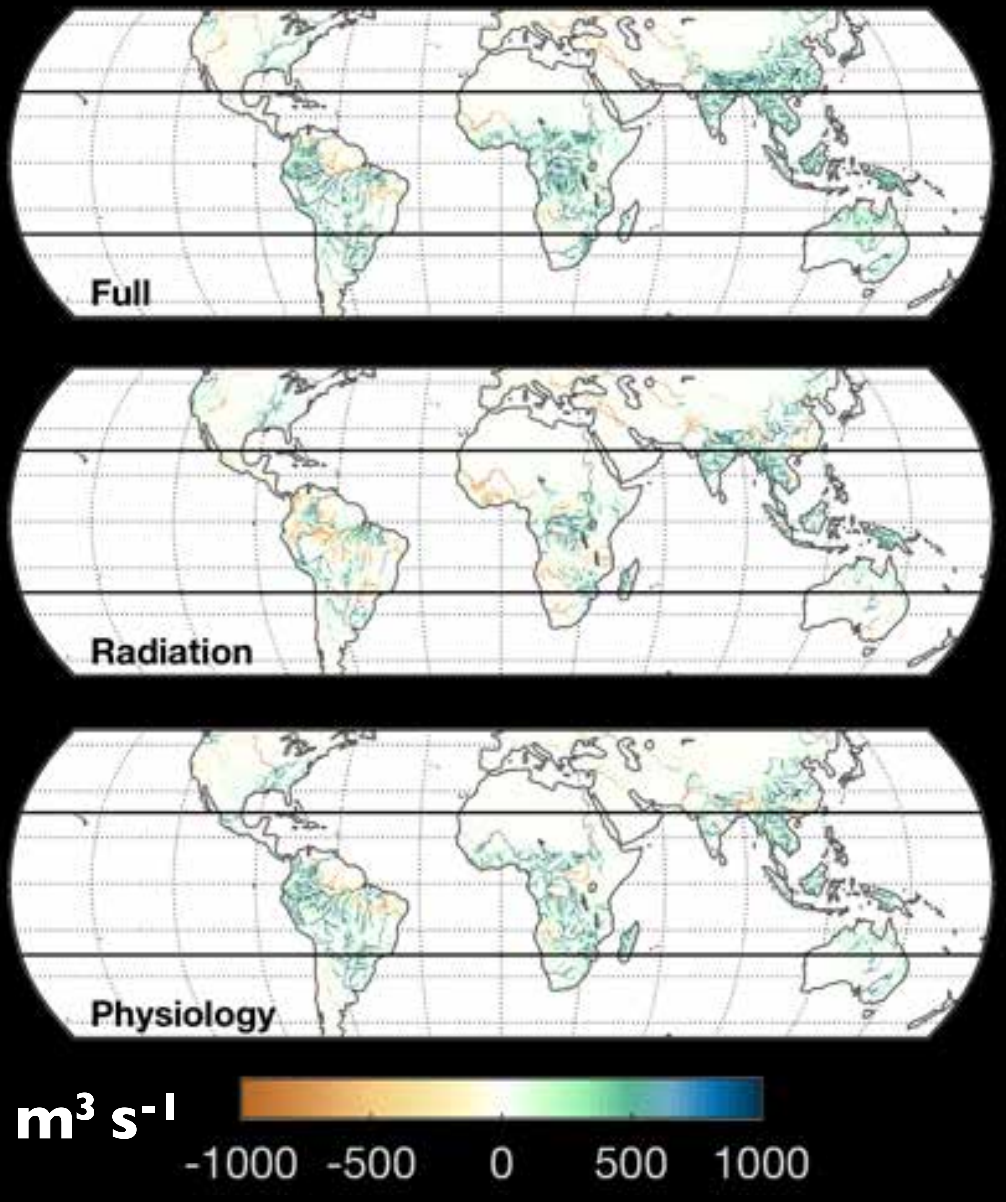
River Channel and Floodplain Reservoirs

- Downscaling with the Catchment-based Macroscale Floodplain Model yields daily river discharge at 0.25°
- Fit max to GEV to get return period

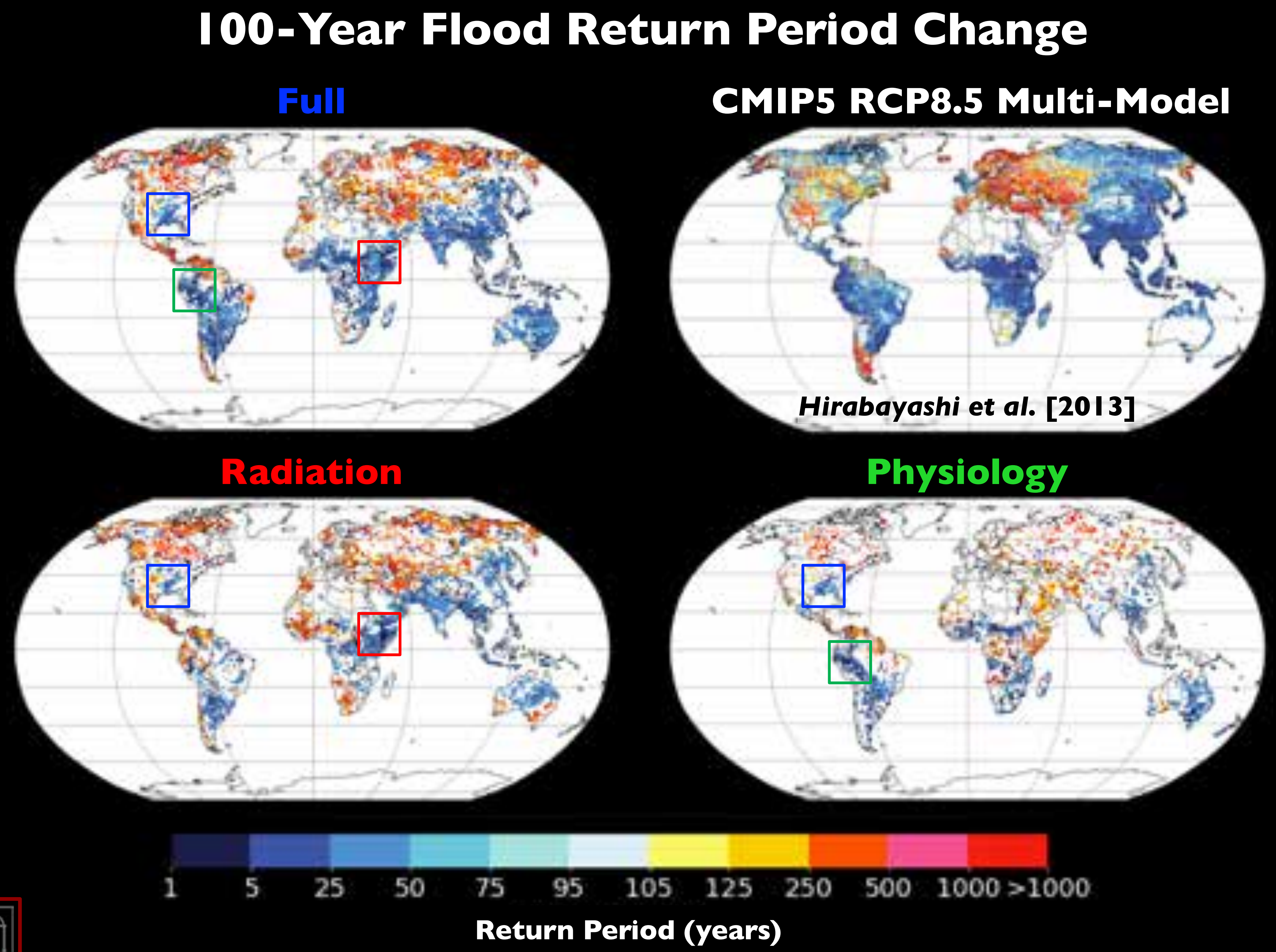


Yamazaki et al. [2011]

99th Percentile Discharge Change

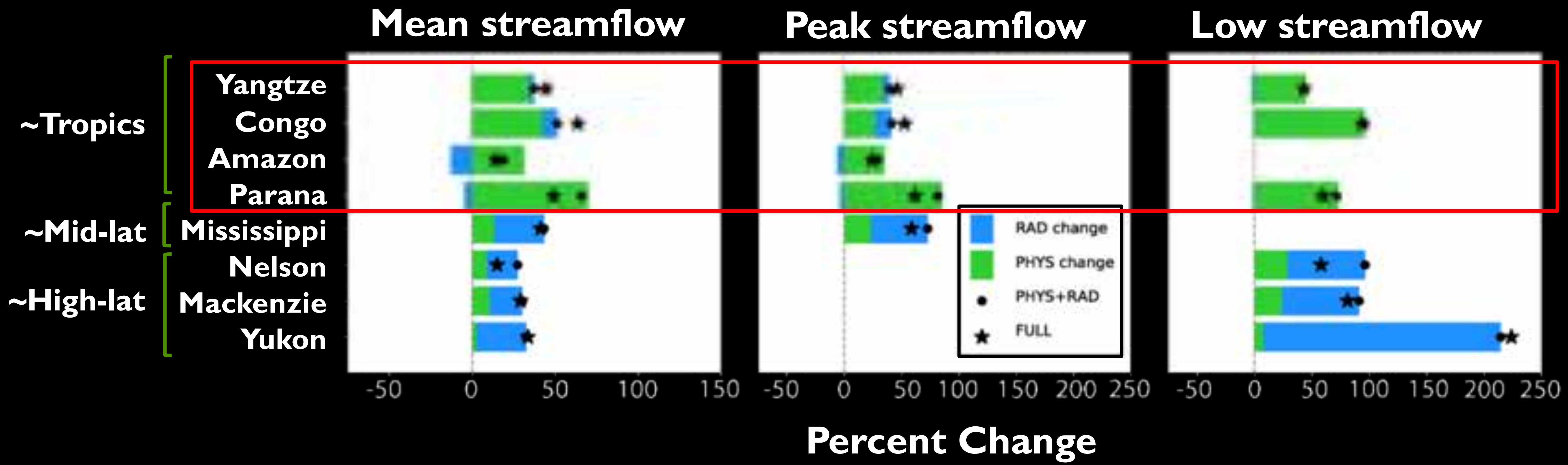


Idealized CO_2-only forcing captures RCP8.5 multi-model mean pattern of change, with significant increases in the topics



- Downscaling CESM runoff from Full 4xCO_2 simulation captures the same flood pattern as 78.3% of land areas in CMIP5 RCP8.5
- Statistical significant flood increase across most of the topics at 95% confidence
- Comparing Full, Radiation, and Physiology simulations identifies which mechanism controls flood frequency changes in different regions

The role of plants in tropics is also evident in more observable metrics (e.g. streamflow) that do not require extreme value fit



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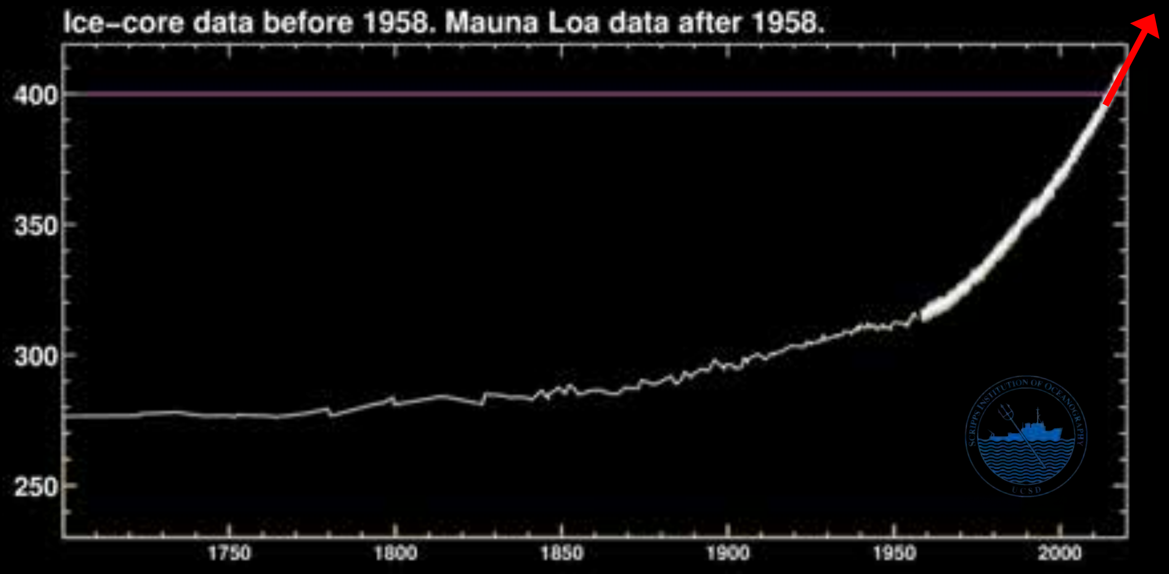
CO_2 Concentration (ppm)



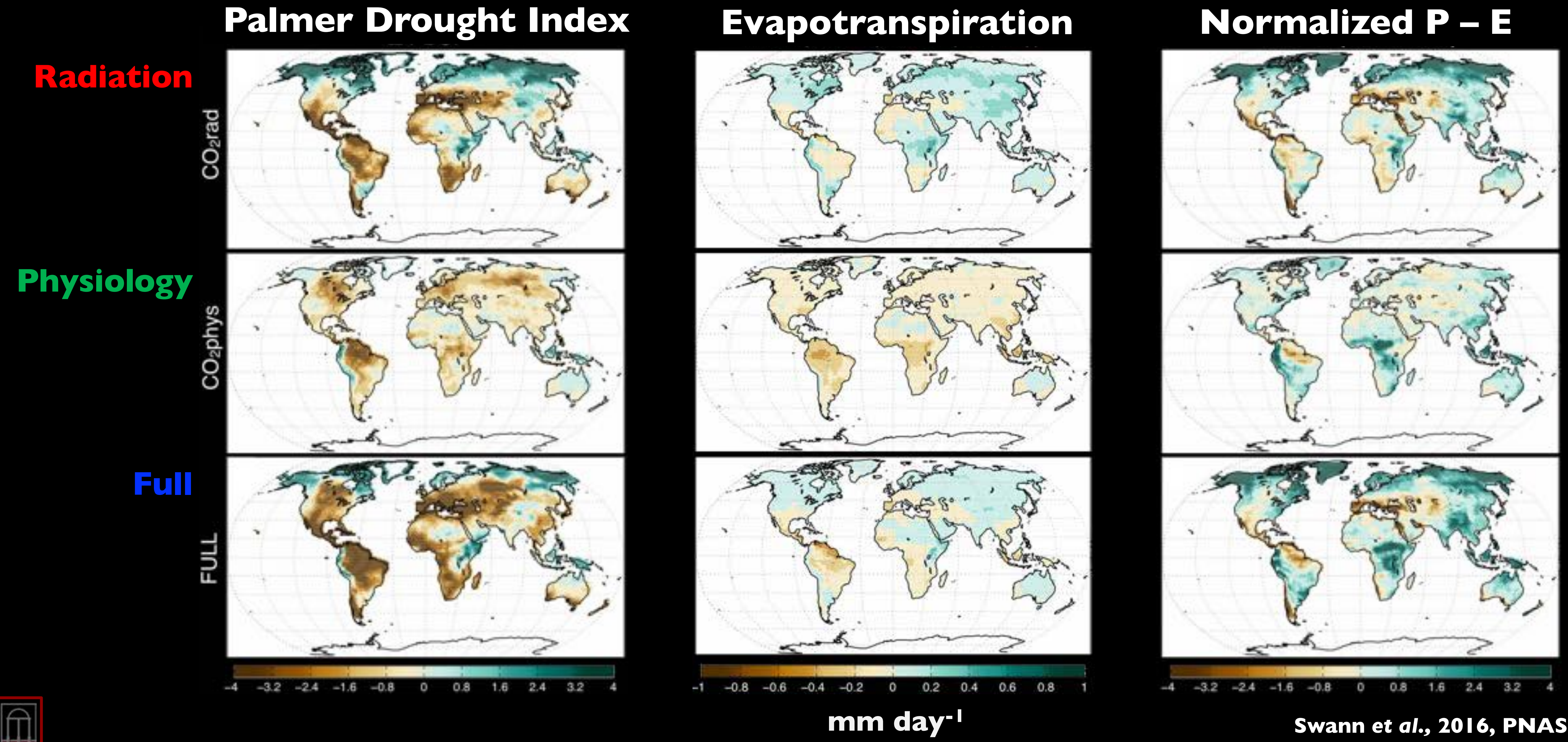
Precipitation

Flooding

Drought

Heat/Fire

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

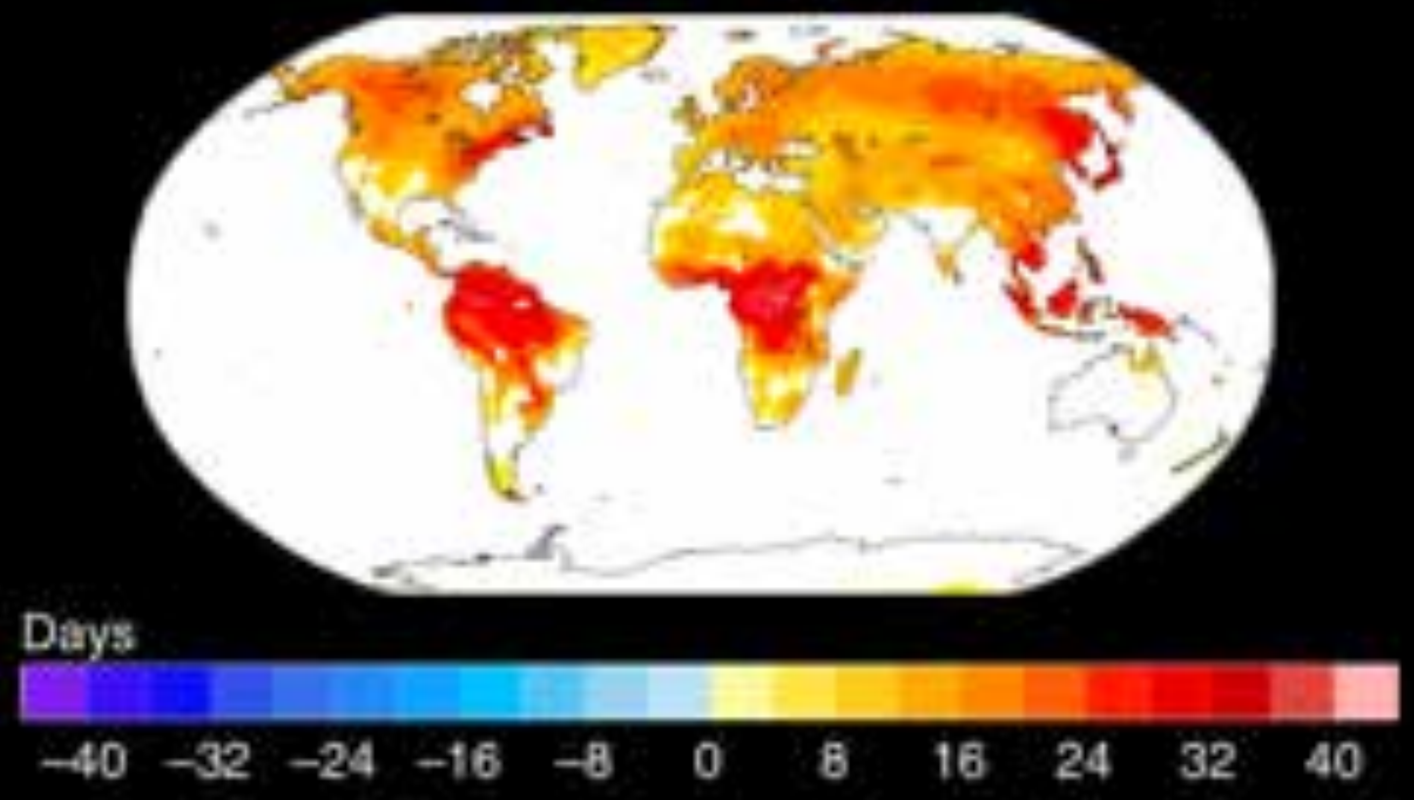


Swann *et al.*, 2016, PNAS

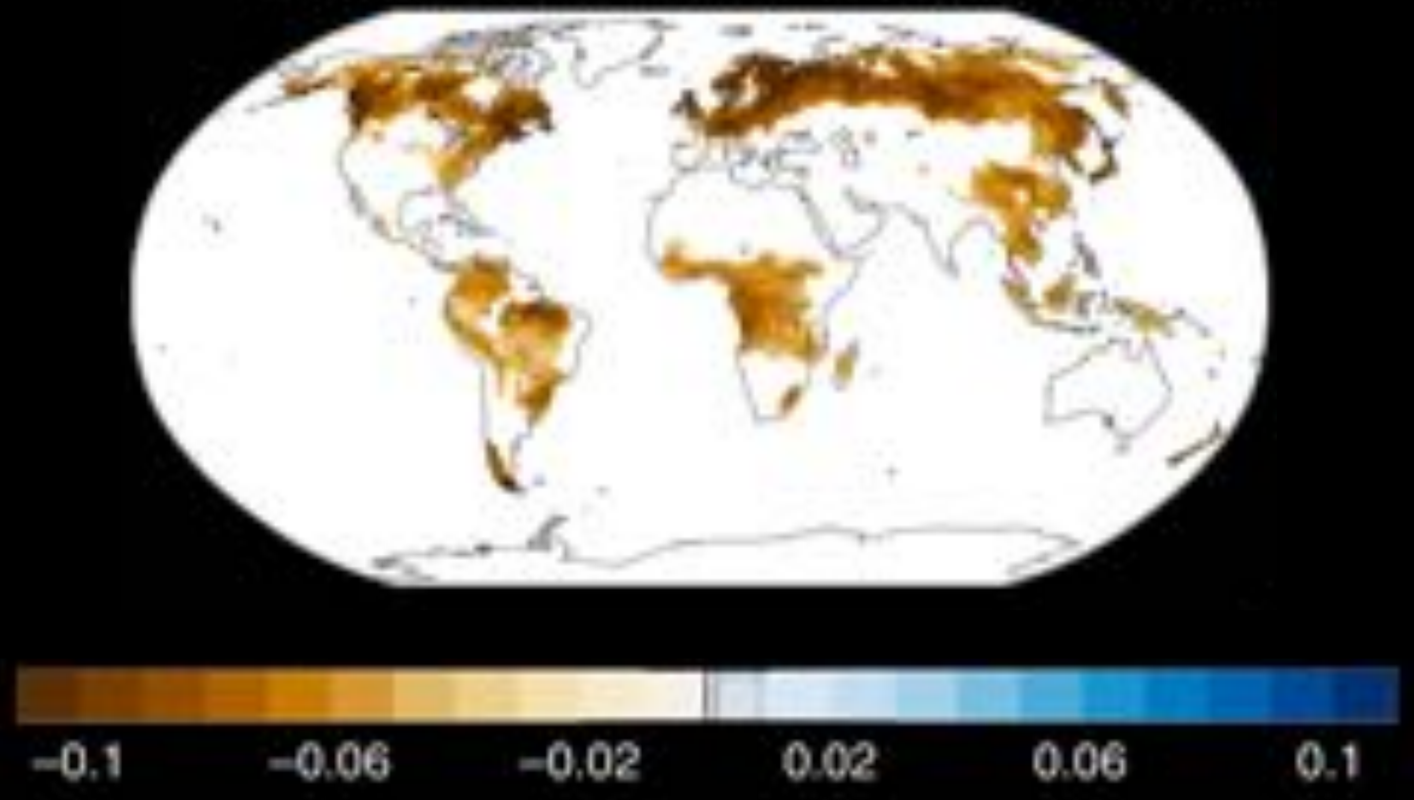
Physiological response has competing effects on the heat index by increasing temperature but decreasing relative humidity

CMIP5 Multi-Model Mean Change due to CO_2 Vegetation Forcing

Total Heat Wave Days



Evaporative Fraction



- By modifying the surface energy budget, plants contribute to changes in heat wave statistics…
- but reductions in humidity may offset the impact

Skinner *et al.*, 2018, *Nature Communication*

Conclusions

- 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, due to regional dynamic responses
- Results suggest that the Amazon will be more prone to drought while Asian forests will receive more rain
- Plants impact runoff through both feedbacks on precipitation changes and direct effects on soil moisture
- Regions where an intensification of rainfall and plant-physiology both contribute to runoff changes are at most risk for future flooding

Questions

- How realistically are these processes and plant physiological behavior represented in CMIP5 vs CMIP6 Earth system models?
- Do updates in land-surface models used in CMIP6, e.g., Ball-Berry vs. Medlyn leaf stomatal resistance models, significantly influence the strength of plant responses?
- How do plant physiological influences on climate extremes change in models with:
  - online river routing and inundation?
  - more intense and realistic precipitation?
  - aerosol effects on cloud microphysics?
  - nutrient limitation?
  - in context of simulations that include all other realistic forcings as well as CO_2 effects alone (exclusion experiments)?