The Aerial Hydrologic Cycle in a Warming World

Lessons from Numerical Water Tracers on Hydrologic Cycle Sensitivity

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Does Atmospheric Moisture Transport Change as the Climate Warms?

Fundamental Equation of Hydrology

$$P - E = -\nabla \cdot (vQ)$$

Thermodynamics & Dynamics Framework

Held & Soden (2006)

In a Warmer World…

Moisture Flux scales with Temperature

$$\frac{\delta(vQ)}{vQ} \approx \alpha\delta T$$

Clausius-Clapeyron Rate

$$\alpha = 0.07\ \mathrm{K}^{-1}$$

In Perturbed Form:

$$\delta(P - E) \approx \alpha\delta T(P - E)$$

- **Hydrological cycle sensitivity to warming is well-approximated by its thermodynamic component.** ***"Wet get wetter, dry get drier"***
- **The dynamic component is small and not robust.**

This is not the whole story!

How Atmospheric Moisture Transport Changes as the Climate Warms

Moisture Depletion Rate

$$\gamma = \frac{P}{Q}$$

2-3% K^{-1} 7% K^{-1}

$$\delta\gamma = \frac{P}{Q}\left(\frac{\delta P}{P} - \frac{\delta Q}{Q}\right)$$

Change in Moisture Depletion Rate

The moisture depletion rate decreases.

$$\delta\gamma < 0$$

$$\delta\tau > 0$$

The moisture residence time increases.

$$\tau = \frac{1}{\gamma}$$

Moisture Residence Time

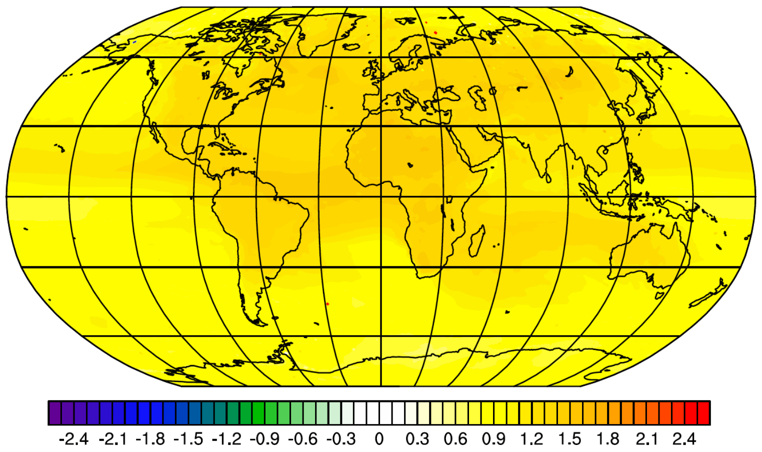
Moisture Transport Length Scale

$$\lambda = \frac{v}{\gamma}$$

$$\delta\lambda > 0$$

The moisture transport length scale increases.

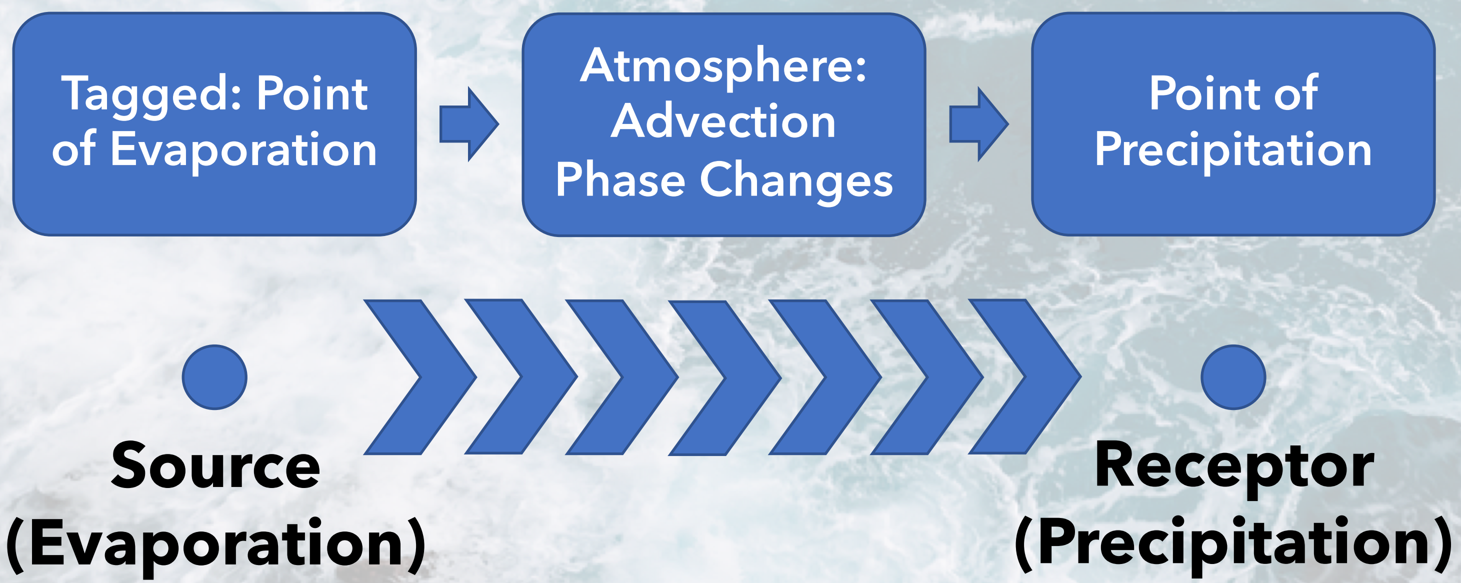
2XCO$_2$: Change in Moisture Residence Time (days)



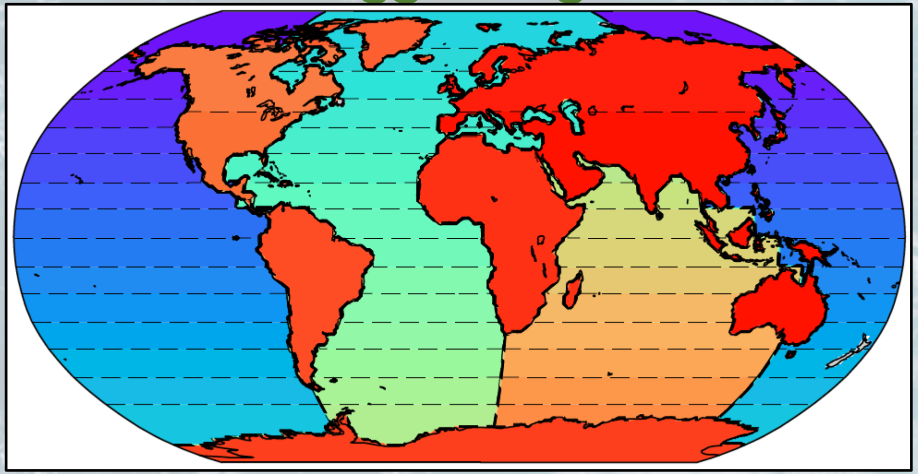
Singh et al (2016A, 2016B)

Evidence from Numerical Water Tracers

What are numerical water tracers?



48 Tagged Regions



2 Experiments with water tracers in the CESM1-CAM5:

- Pre-industrial Control
- $2XCO_2$ (yrs 300 to 330)

Moisture Transport Changes as the World Warms

Green's Function Approach to Precipitation

$$\vec{P} = \mathbf{M}\vec{E}$$

Change in Precipitation — Change in Evaporation

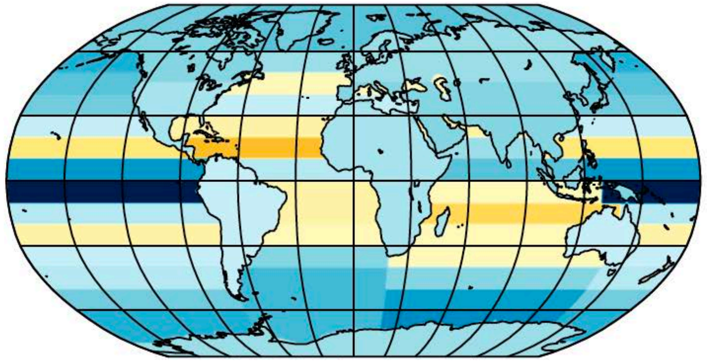
$$\Delta\vec{P} = \Delta\mathbf{M}\vec{E} + \mathbf{M}\Delta\vec{E}$$

Change in Transport

Since evaporation increases globally, changes in moisture transport are necessary to account for regions of declining precipitation.

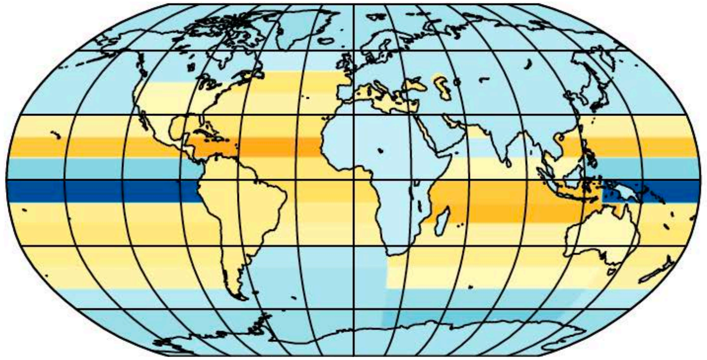
$\Delta\vec{P}$

Change in Precipitation with $2XCO_2$ (mm/day)



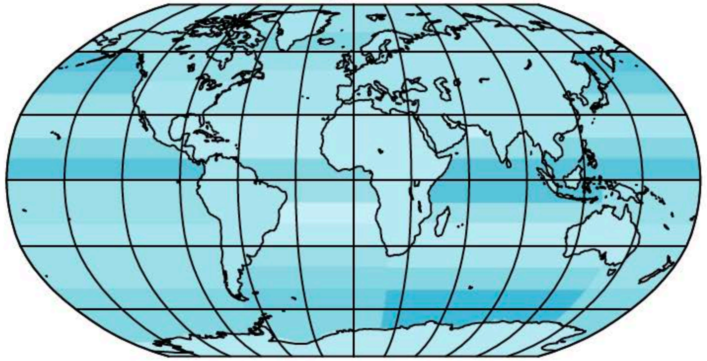
$\Delta\mathbf{M}\vec{E}$

...due to Changing Moisture Transport (mm/day)



$\mathbf{M}\Delta\vec{E}$

...due to Changing Evaporation (mm/day)



Singh et al (2016A)

The Local Declines and the Remote Increases

Remotely-sourced precipitation increases (nearly) globally.

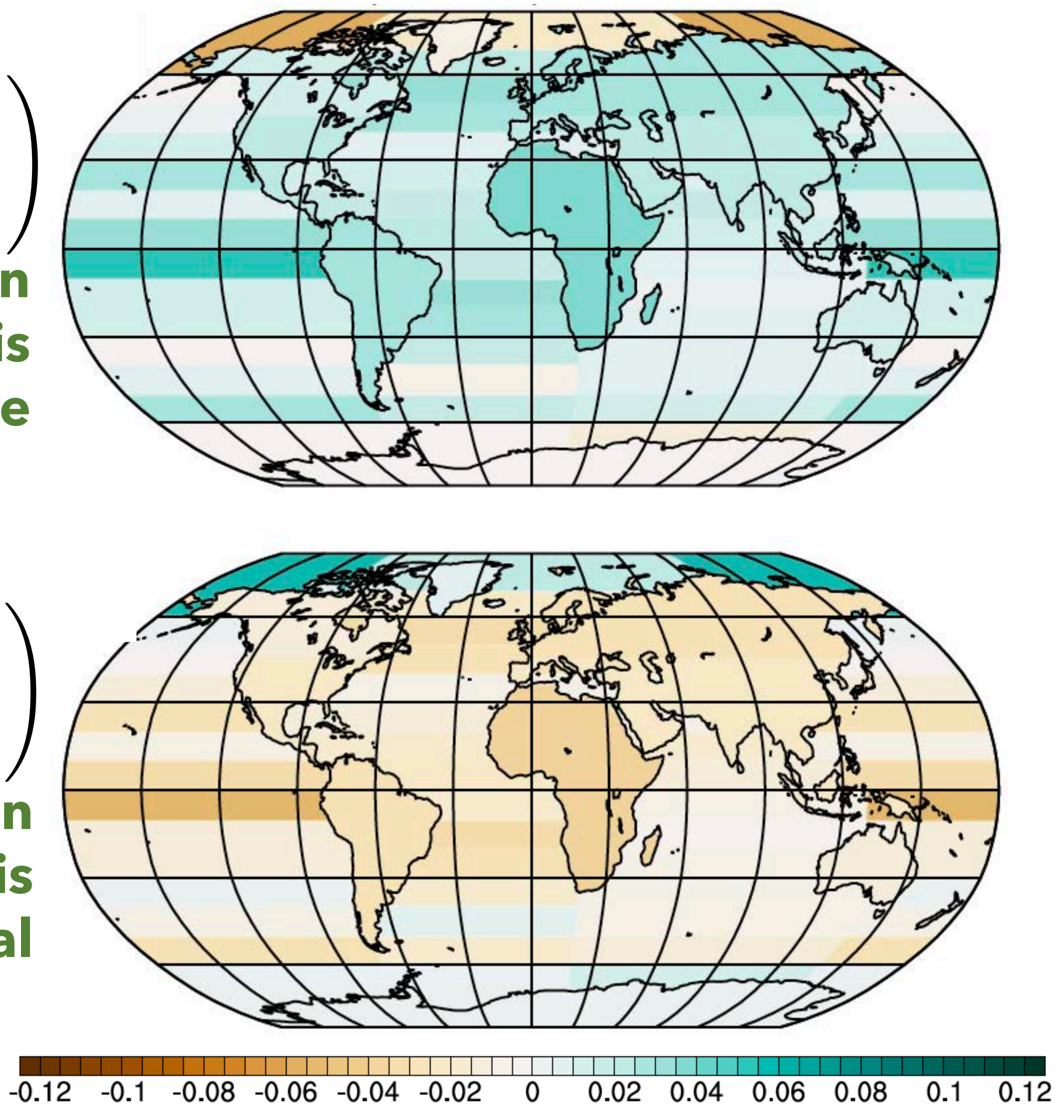
Locally-sourced precipitation decreases (nearly) globally.

$$\Delta\left(\frac{\vec{P}_{remote}}{\vec{P}_{total}}\right)$$

Change in the Fraction of Precipitation that is Remote

$$\Delta\left(\frac{\vec{P}_{local}}{\vec{P}_{total}}\right)$$

Change in the Fraction of Precipitation that is Local



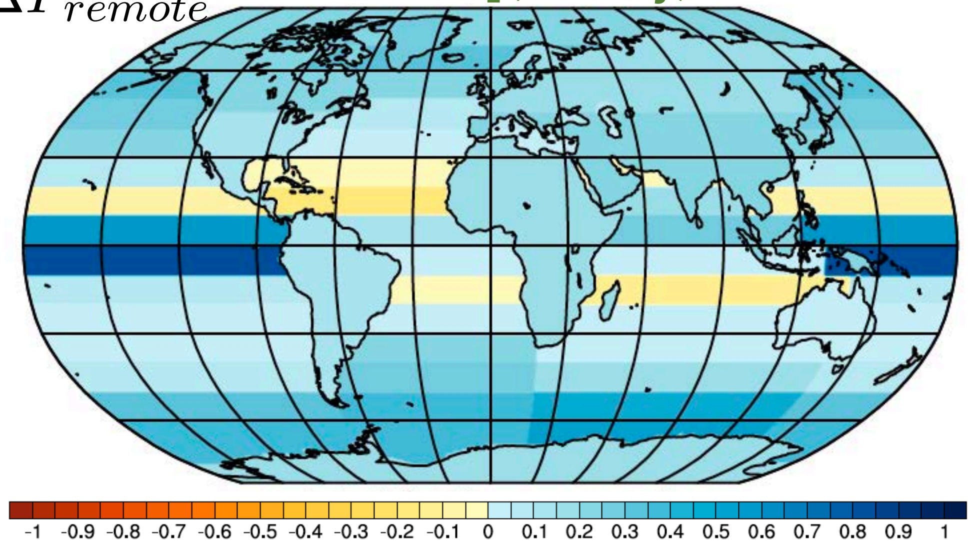
Singh et al (2016A)

Moisture Travels Further as the Planet Warms

Interbasin-sourced precipitation increases globally.

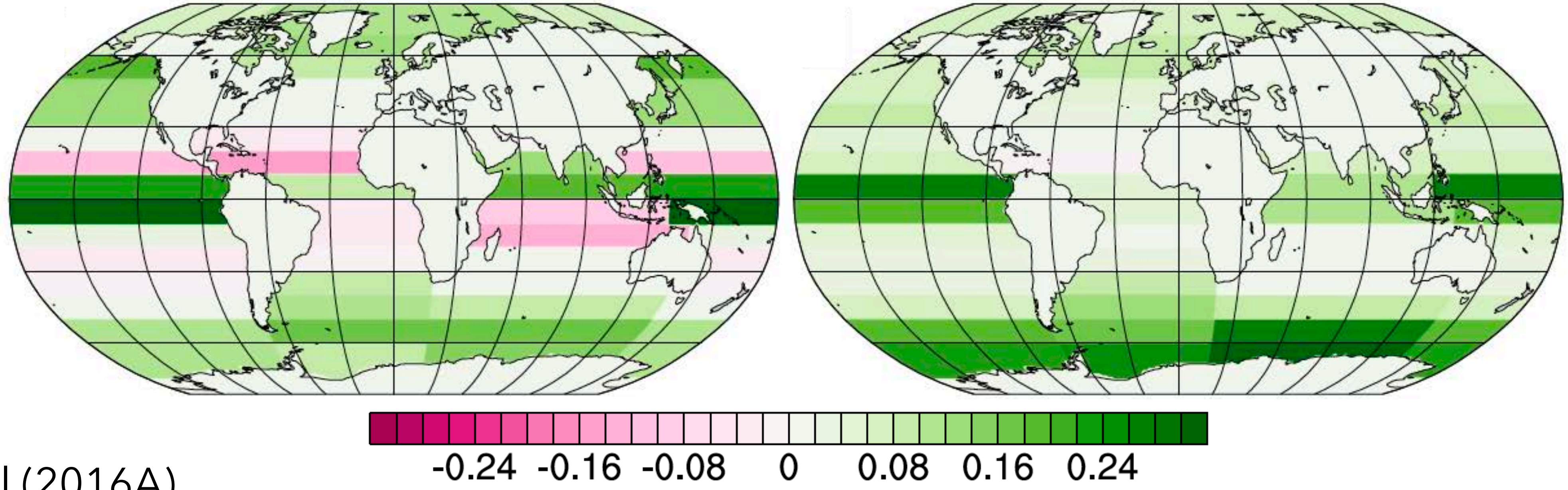
$\Delta\vec{P}_{remote}$

Change in Remotely-Sourced Precipitation with 2XCO_2 (mm/day)



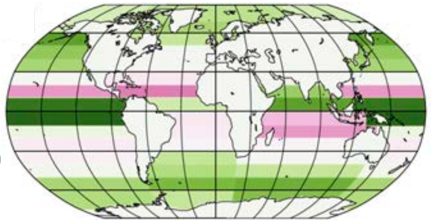
Change in Intrabasin-Sourced Precipitation with 2XCO_2 (mm/day)

Change in Interbasin-Sourced Precipitation with 2XCO_2 (mm/day)



Singh et al (2016A)

Change in Intrabasin-Sourced Precipitation with $2XCO_2$ (mm/day)

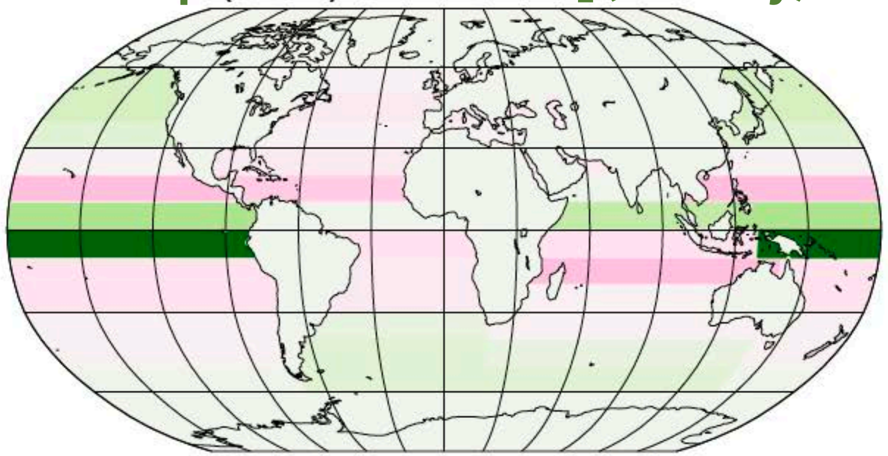


Moisture Travels Further as the Planet Warms

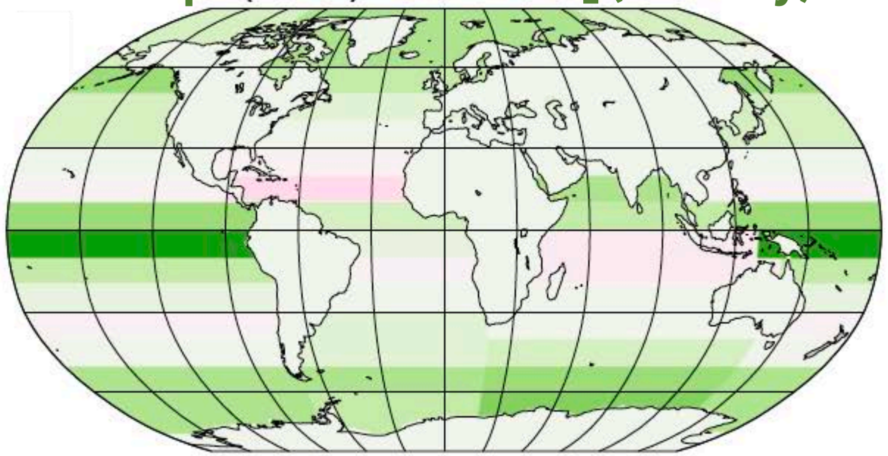
Intrabasin-sourced precipitation coming from nearby regions **declines** over many regions.

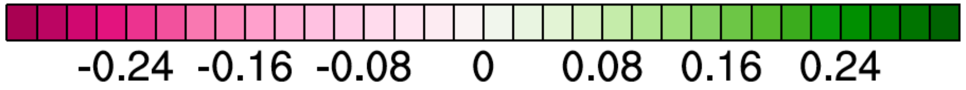
Intrabasin-sourced precipitation coming from more distant regions **increases** (nearly) globally.

Change in Intrabasin "Near" Sourced Precipitation with $2XCO_2$ (mm/day)



Change in Intrabasin "Far" Sourced Precipitation with $2XCO_2$ (mm/day)

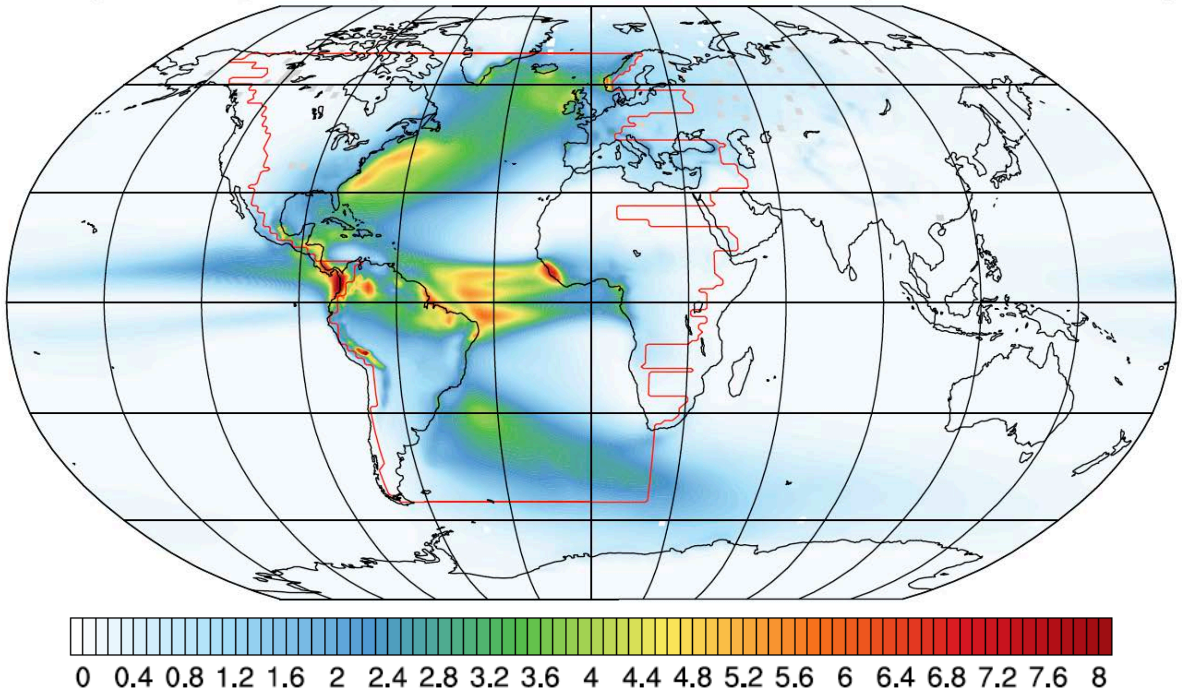




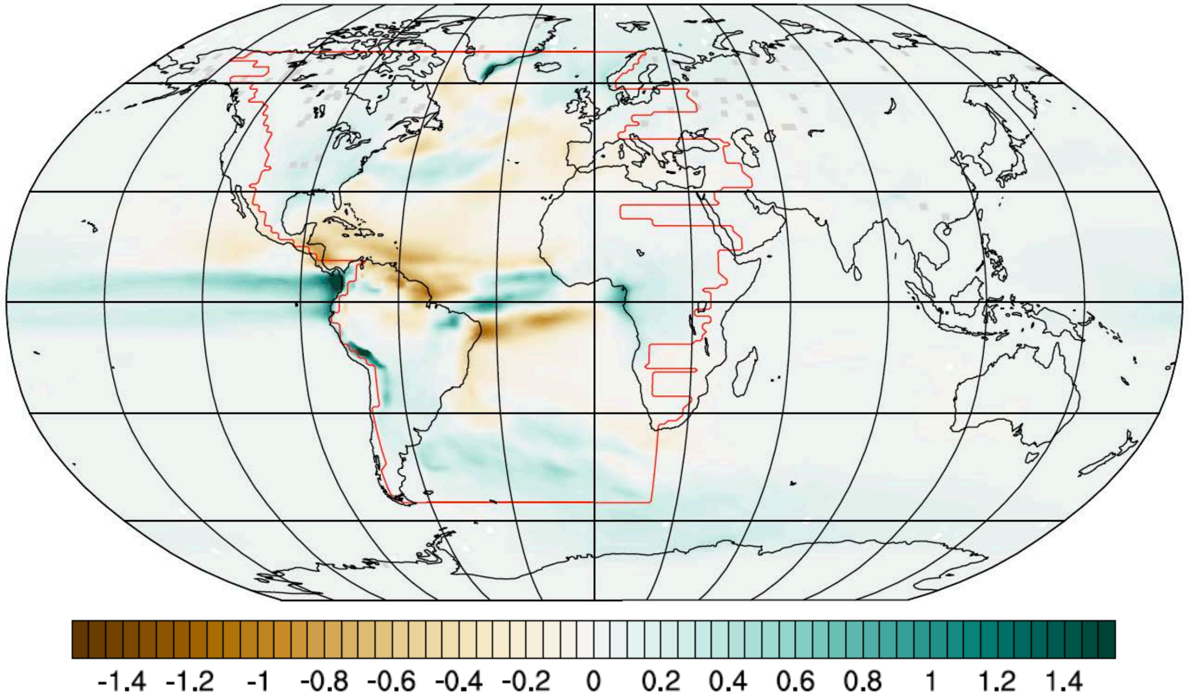
Singh et al (2016A)

The Atlantic gets Saltier and the Pacific gets Fresher as Moisture Transport Length Scales Increase

Pre-industrial Control: Precipitation Sourced from the Atlantic Basin (mm/day)



$2XCO_2$: Change in Precipitation Sourced from the Atlantic Basin (mm/day)



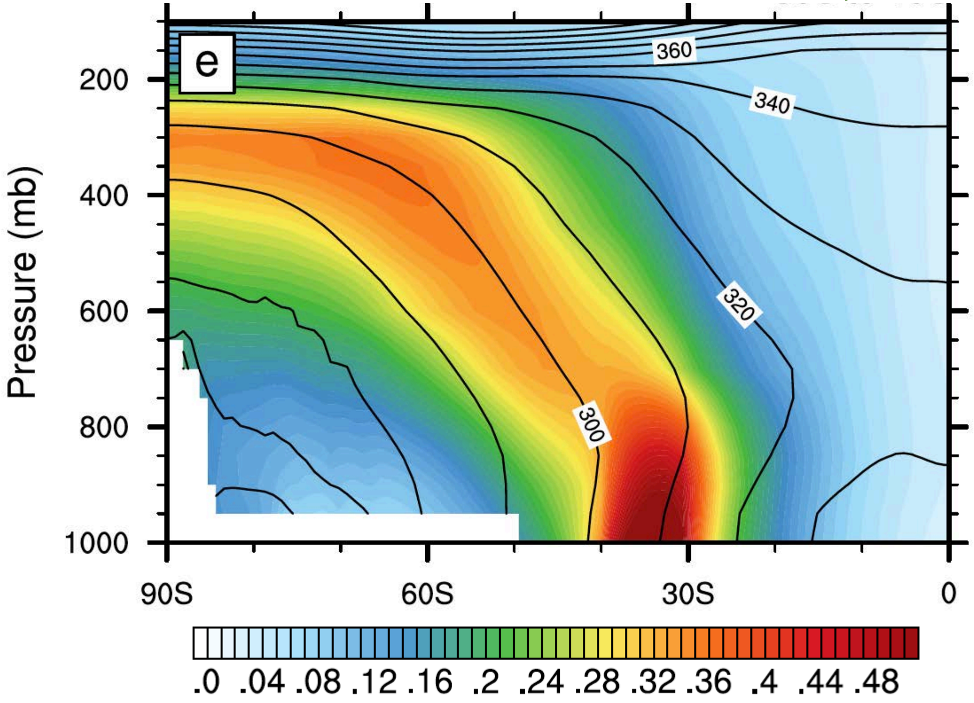
With CO_2-doubling, Atlantic-sourced precipitation…

- declines over the Atlantic Basin.
- increases over the tropical East Pacific

Singh et al (2016B)

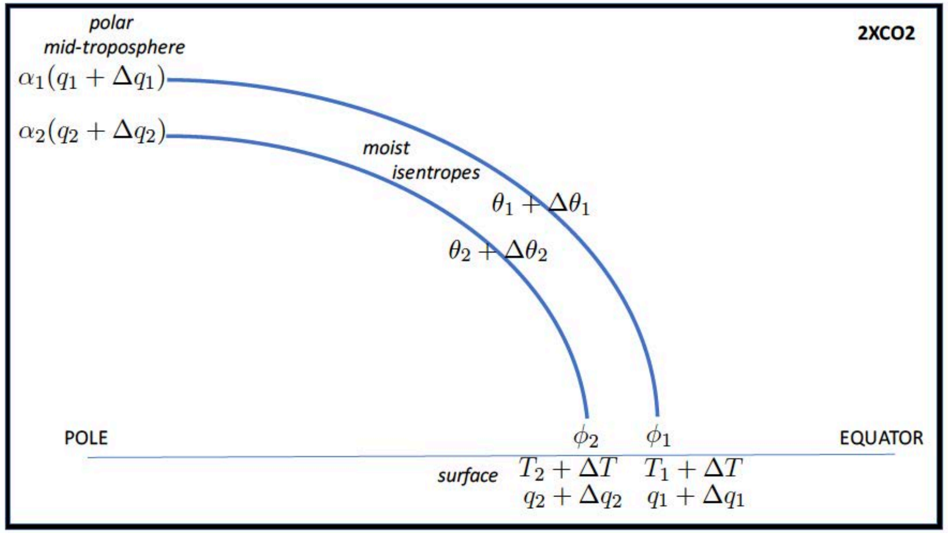
Moist Isentropic Arguments: Extratropical Moisture will come from more Equatorward Sources

Pre-industrial Control: Moist Isentropes (contours; K)
Fraction of moisture from 30S-40S (colors)



Poleward moisture transport (roughly) follows contours of moist entropy.

$2XCO_2$: Moist Isentropes shift Uniformly

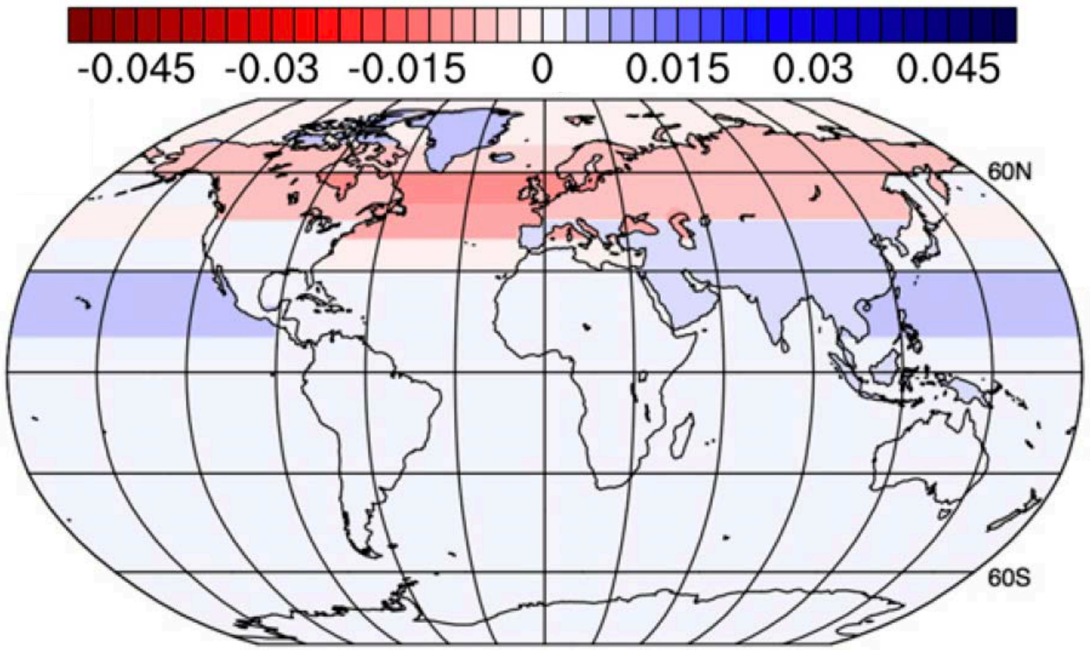


$2XCO_2$: Atmospheric moisture increases at the Clausius-Clapeyron rate of 7% K^{-1}

Extratropical precipitation will originate from more equatorward sources.

Bailey, Singh, & Nusbaumer (2019)

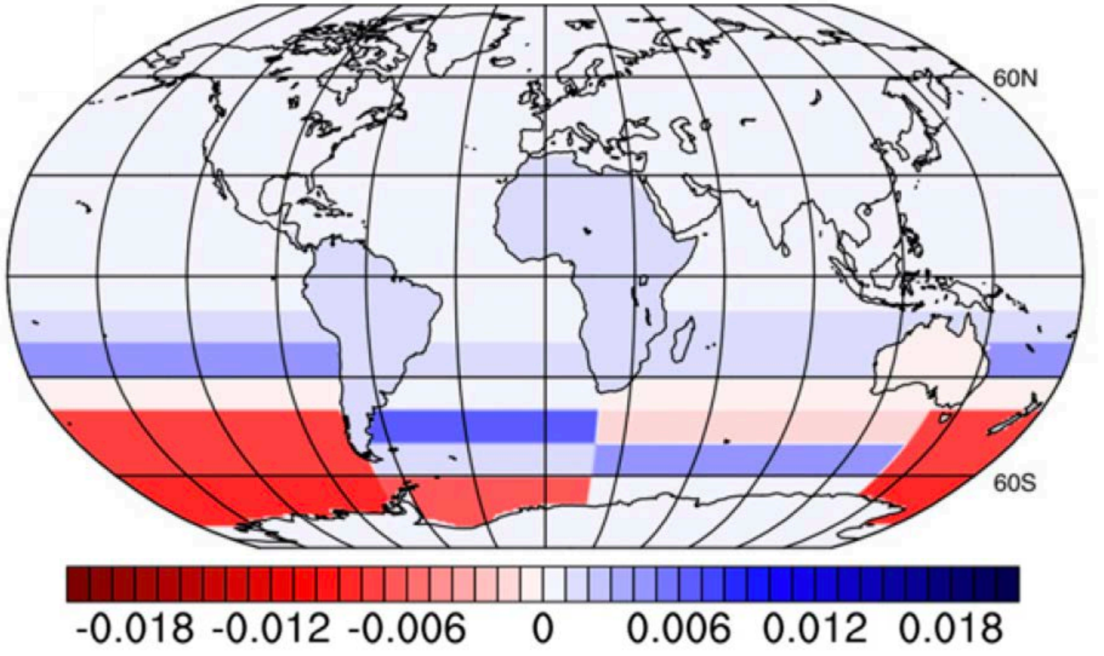
In **Summer**, Polar Precipitation Comes from more Equatorward Moisture Sources in a Warmer World



Change in Fraction of Precipitation coming from each tagged source region <u>to the Arctic</u>

The fraction of precipitation coming from <u>**proximal**</u> sources declines.

The fraction of precipitation coming from <u>**distant**</u> sources increases.



Change in Fraction of Precipitation coming from each tagged source region <u>to the Antarctic</u>

Consistent with an increase in the moisture transport length scale.

Singh et al (2017)

In **Winter**, Polar Precipitation Comes from more POLEWARD Moisture Sources in a Warmer World

The fraction of precipitation coming from **proximal** sources increases.

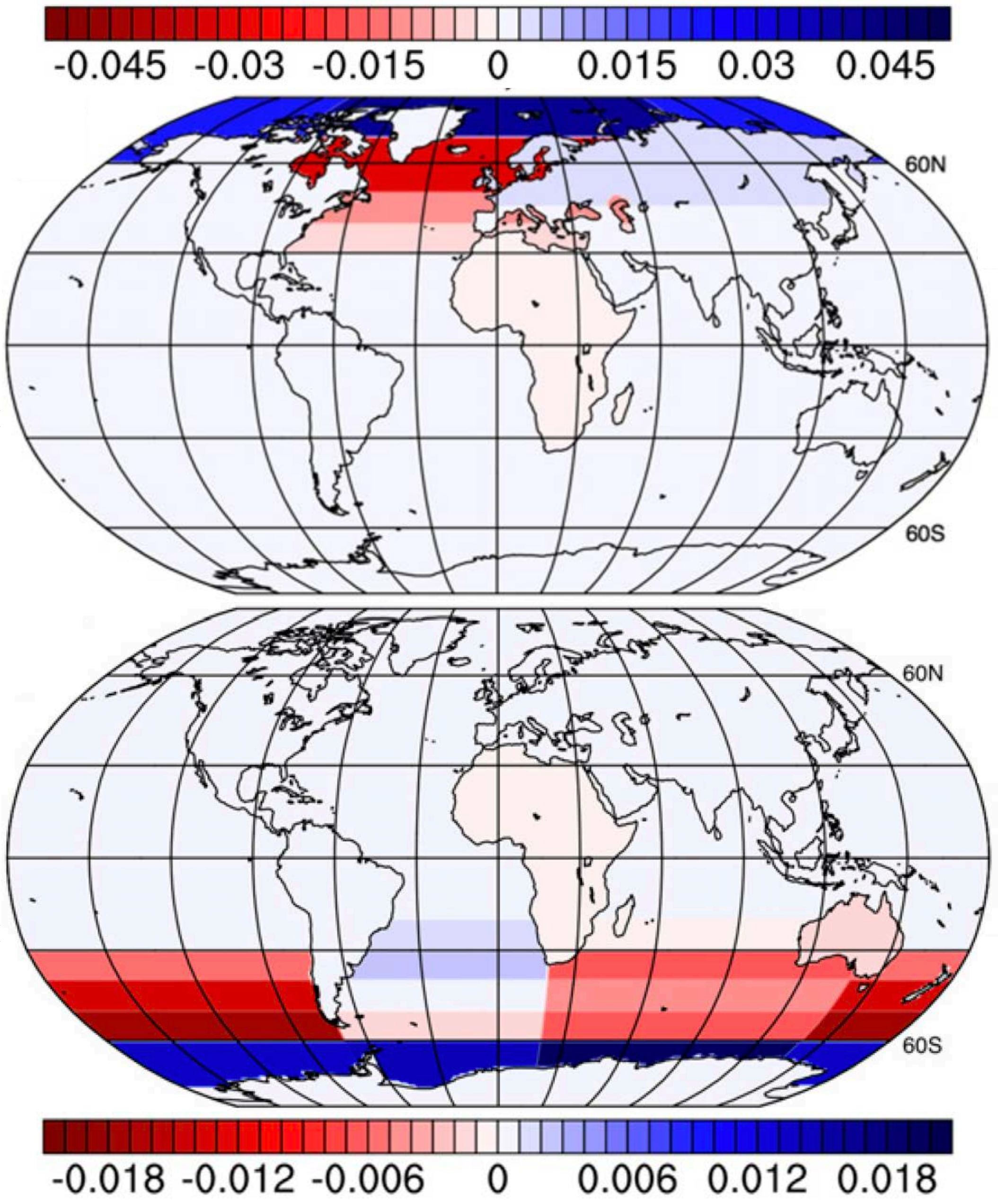
The fraction of precipitation coming from **distant** sources declines.

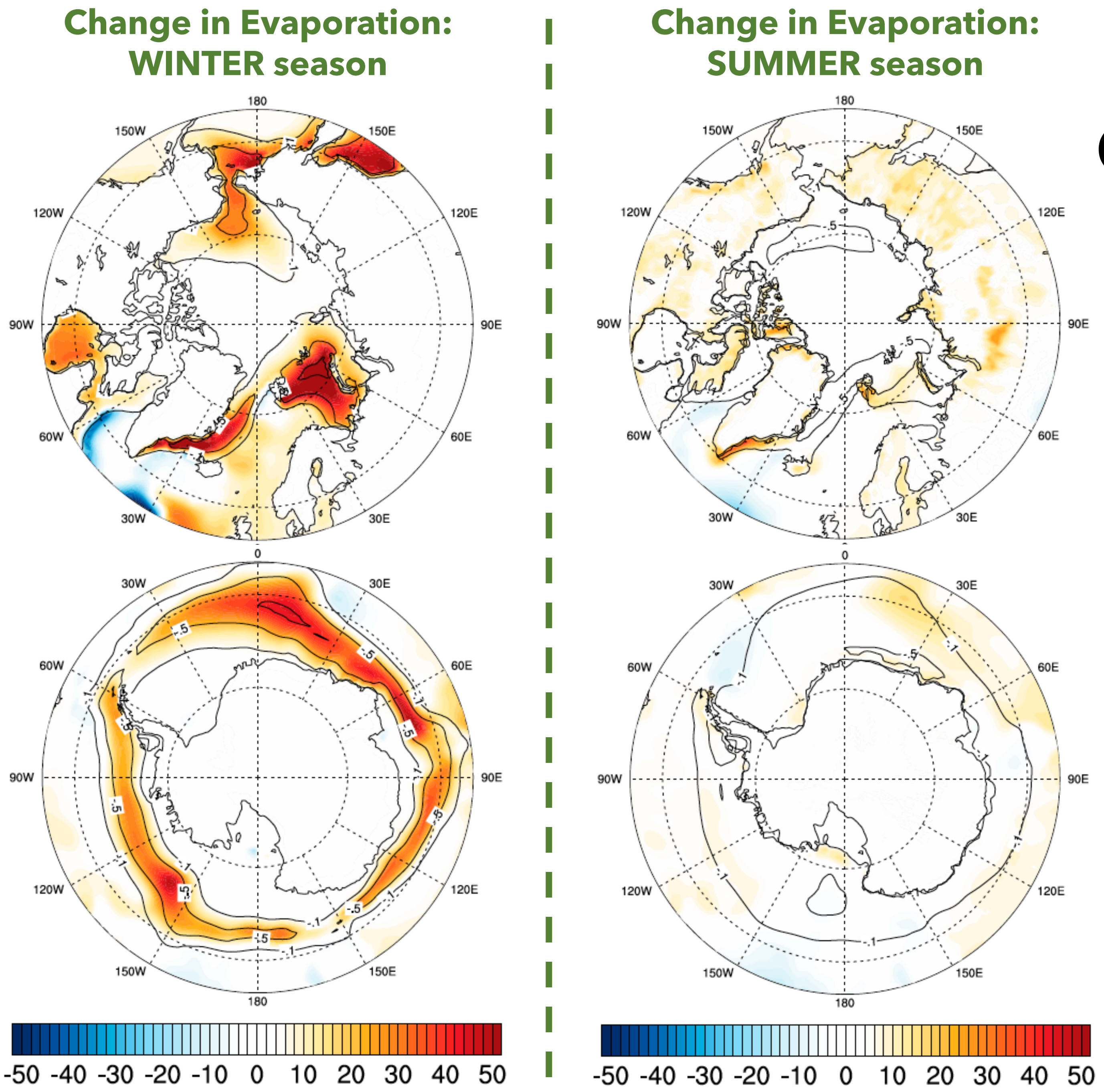
NOT consistent with an increase in the moisture transport length scale.

Singh et al (2017)

Change in Fraction of Precipitation coming from each tagged region to the Arctic

Change in Fraction of Precipitation coming from each tagged region to the Antarctic





Sea Ice Retreat Plays a Central Role in High-Latitude Hydrologic Cycle Sensitivity

Evaporation increases over areas of sea ice retreat in **winter**.

⇩

Local (polar) moisture sources contribute a GREATER fraction of the total precipitation.

Singh et al (2017)

What We Know
About Hydrologic Cycle Sensitivity

Source-Receptor Framework

- Moisture residence times increase globally
- Advective length scale of moisture transport increases (nearly) globally
- Because of sea ice retreat, the polar regions in winter are an exception

What We DON'T Know
About Hydrologic Cycle Sensitivity

- How do these results apply to hydrologic cycle sensitivity in the past, when climates were cooler?
- How do these results apply to interpretation of water isotopes in polar ice cores from different climate states?
- How does atmospheric moist entropy (mean and variance) change in different climate states?

Thank you! Questions?

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Eulerian Framework

Held & Soden (2006)

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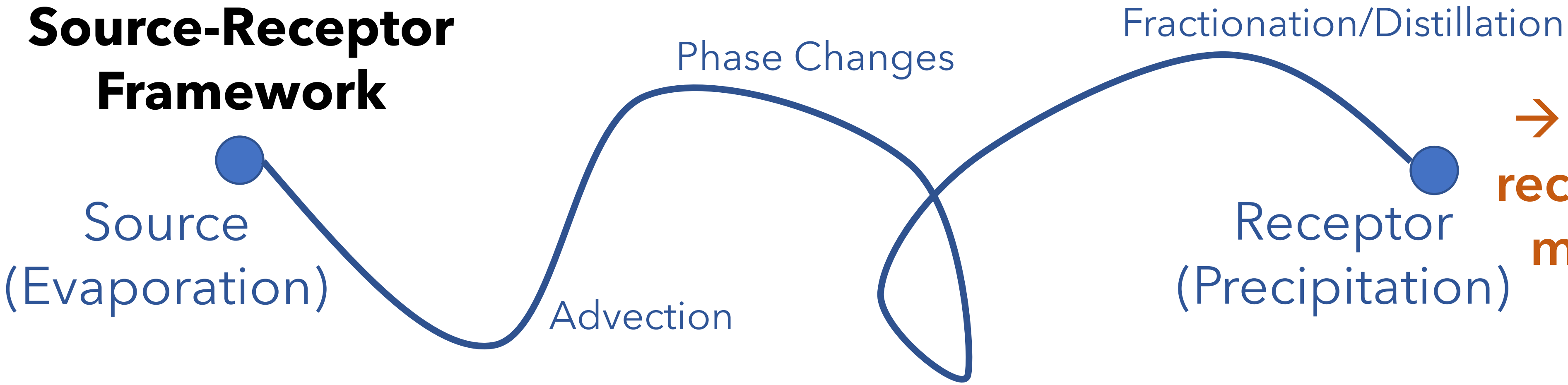
→ The dynamic component is small and not robust.

Source-Receptor Framework



→ **From a source-receptor perspective, moisture transport does change.**

Changing Moisture Transport Freshens the Pacific and Salinizes the Atlantic

Only changes in moisture transport account for…

- the decline in Atlantic-sourced precipitation over the Atlantic basin
- the increase in Atlantic-sourced precipitation over the tropical East Pacific

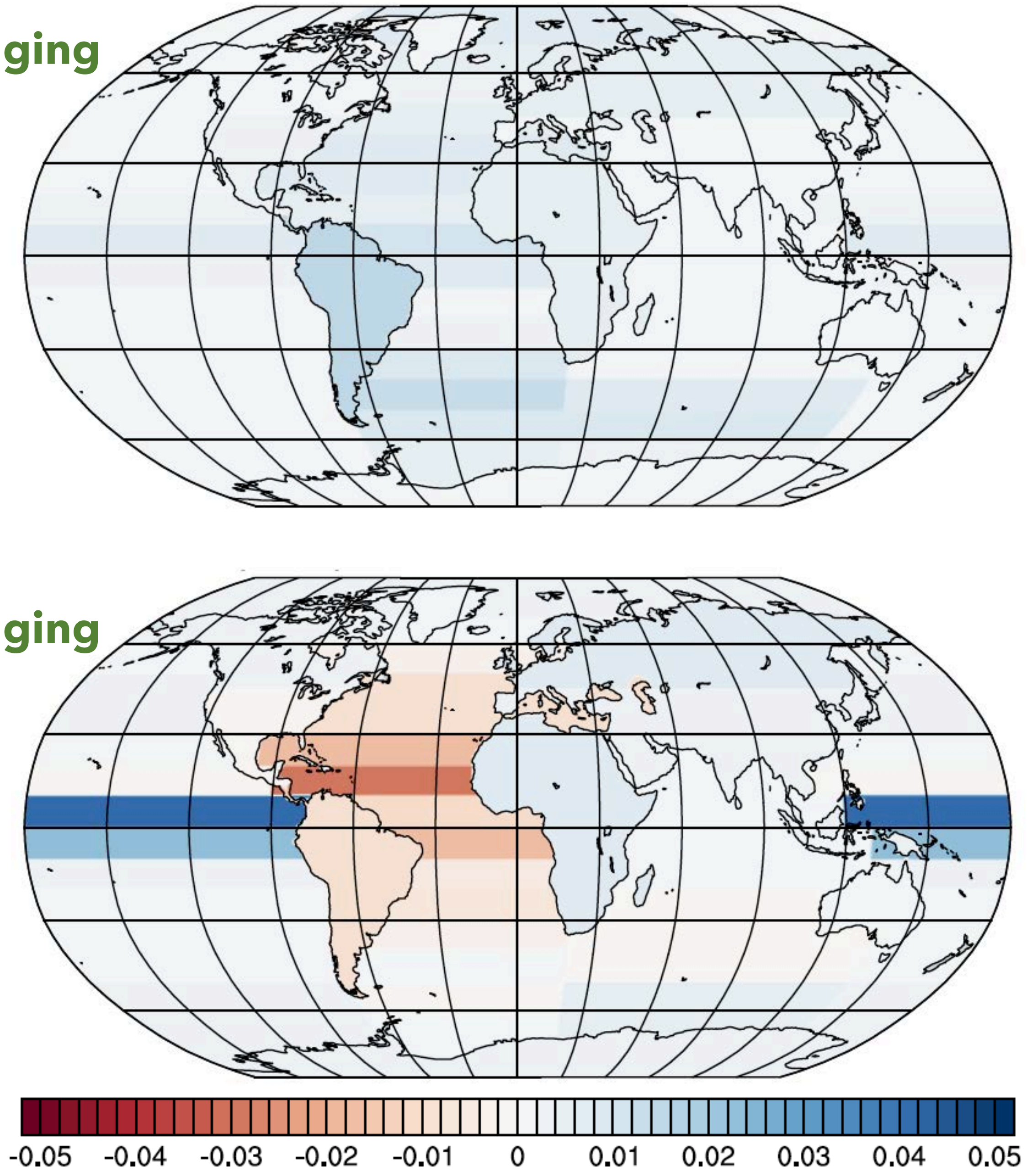
Change in Atlantic-Sourced Precipitation (in Sv)…

Due to Changing Evaporation

$$\mathbf{M}\Delta\vec{E}$$

Due to Changing Moisture Transport

$$\Delta\mathbf{M}\vec{E}$$

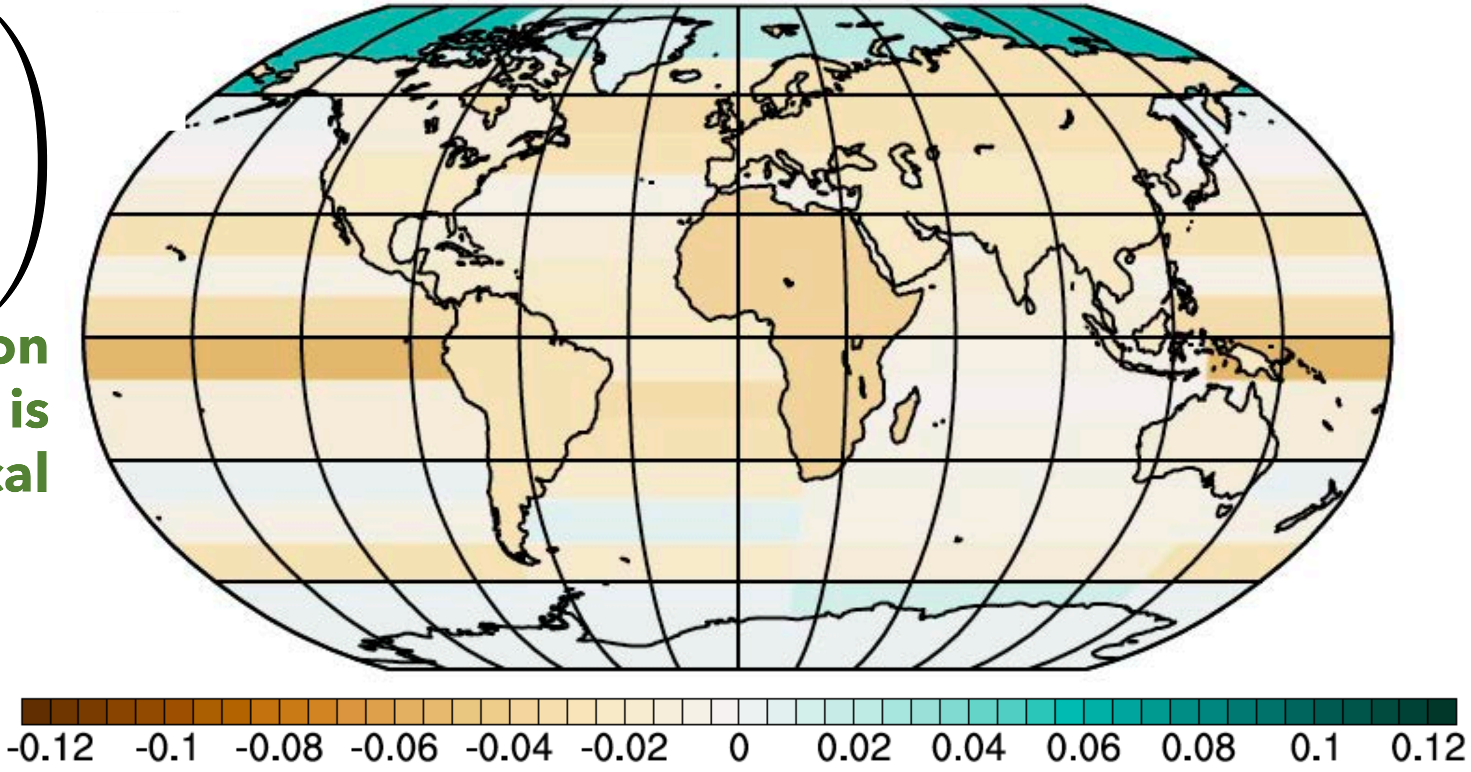


Singh et al (2016B)

Local Recycling Decreases as the Planet Warms

$$\Delta\left(\frac{\vec{P}_{local}}{\vec{P}_{total}}\right)$$

Change in the Fraction of Precipitation that is Local



Locally-sourced precipitation declines (nearly) globally, which is consistent with an increase in the moisture transport length scale.

Singh et al (2016A)