A Novel Mathematical Framework for Analysis of Numerical Water Tracers and the Aerial Moisture Source-Sink Relationship

**With Applications*

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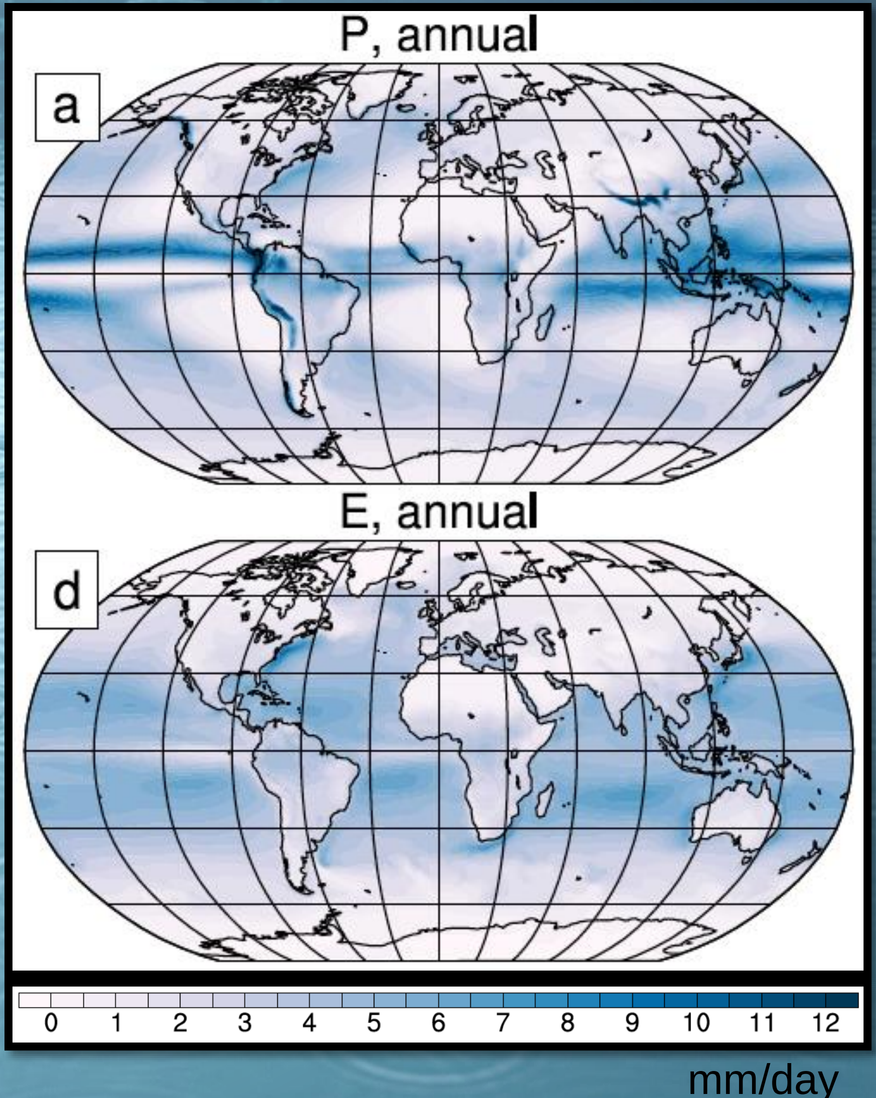
Motivation: P and E in CESM1.2-CAM5

Precipitation
(SINK)

Evaporation
(SOURCE)

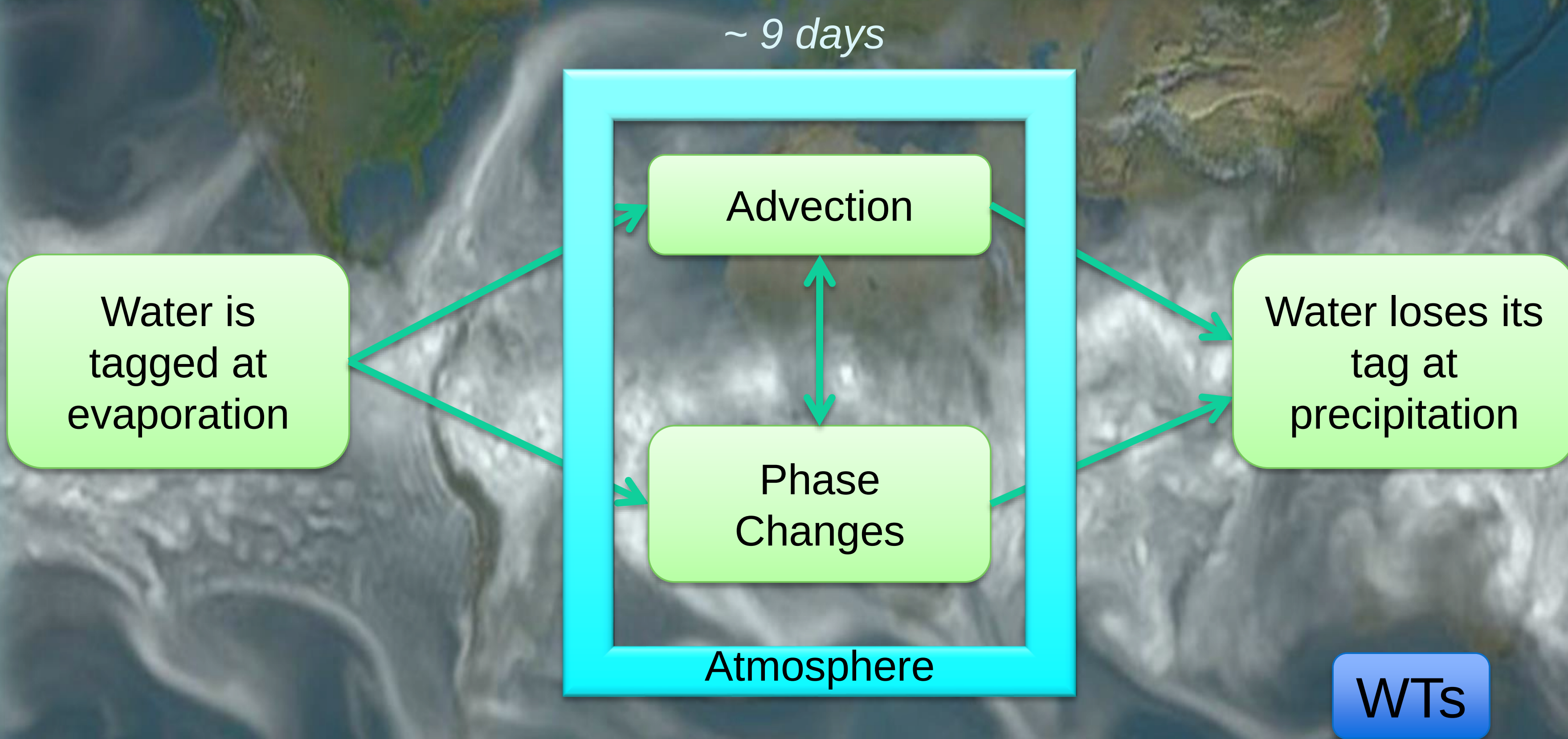


Moisture has heterogeneous source and sink regions.

The aerial hydrologic cycle is fundamentally about TRANSPORT.

A Great Tool for Understanding the Lagrangian Hydrologic Cycle:

Numerical Water Tracers



Bulk Formulation

Introducing…

- ★ A Novel Matrix Operator Framework

  Systematic analysis of WT results

- ★ Application to Perturbations of the Hydrological Cycle
  - ★ 2 X CO_2 Problem

From a Lagrangian perspective, moisture transport does change in a warmer world.

  - ★ Atlantic-Pacific Interbasin Salinity Contrast
  - ★ Seasonal Polar Hydroclimate Changes

A Lagrangian Matrix Operator Framework

$$P - E = -\nabla \cdot Q$$

Fundamental Equation of Hydrology

$$\vec{P} - \vec{E} = \mathbf{F}\mathbf{T}\vec{E} - \mathbf{T}\vec{E}$$

- $\mathbf{F}\mathbf{T}\vec{E}$: Convergence of Remotely-Evaporated Moisture
- $\mathbf{T}\vec{E}$: Divergence of Locally-Evaporated Moisture

- $\mathbf{I}$ Identity matrix
- $\mathbf{T}$ Diagonal matrix. Entries are e_i
- $\mathbf{F}$ Hollow matrix. Entries are f_{ji}

Green's Function Formulation

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

$$\mathbf{M} = \mathbf{I} - \mathbf{T} + \mathbf{F}\mathbf{T}$$

$$\vec{E} - \mathbf{T}\vec{E} + \mathbf{F}\mathbf{T}\vec{E} = \vec{P}$$

- $\vec{E}$: Local Evaporation
- $\mathbf{T}\vec{E}$: Local Evaporation that Diverges
- $\vec{E} - \mathbf{T}\vec{E}$: Local Evaporation that Precipitates Locally
- $\mathbf{F}\mathbf{T}\vec{E}$: Remote Evaporation that Precipitates Locally

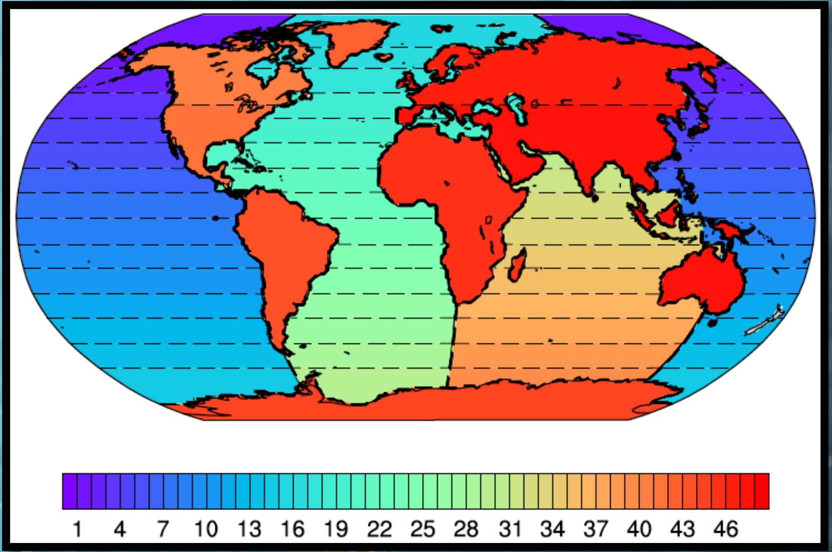
Singh et al (2016A)

The Control Experiment

- ★ CESM1 / CAM5
- ★ Fully-coupled
- ★ Preindustrial settings
- ★ 1° spatial resolution
- ★ 30+ years with WTs

The 2XCO_2 Experiment

- ★ CO_2 doubled
- ★ Run for 270 years
- ★ Run for further 30 years with WTs
- ★ Compared to Control



PERTURBATION STUDIES:

HIGHLIGHTS

Attributing the Change in Precipitation

Green's Function Formulation

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

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

Increased E can only increase precipitation.

Changes in transport are necessary to create the spatial pattern of precipitation change.

$\Delta\vec{P}$

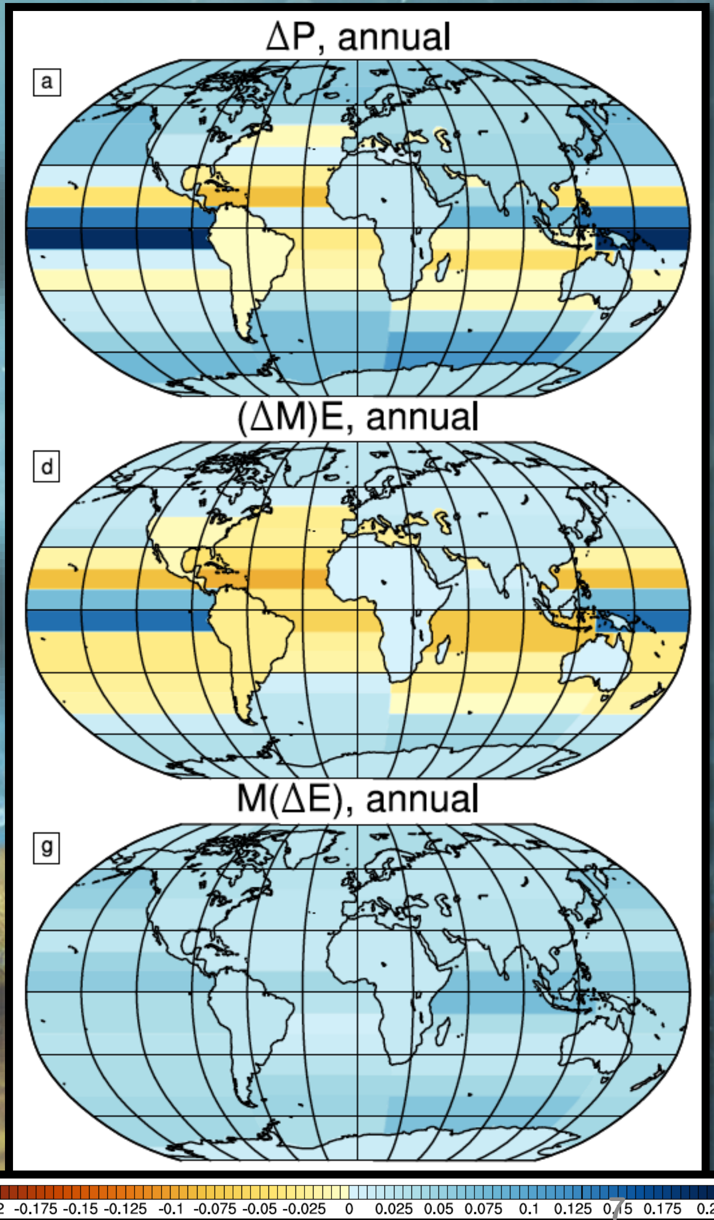
Change in Precipitation

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

Change in Transport

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

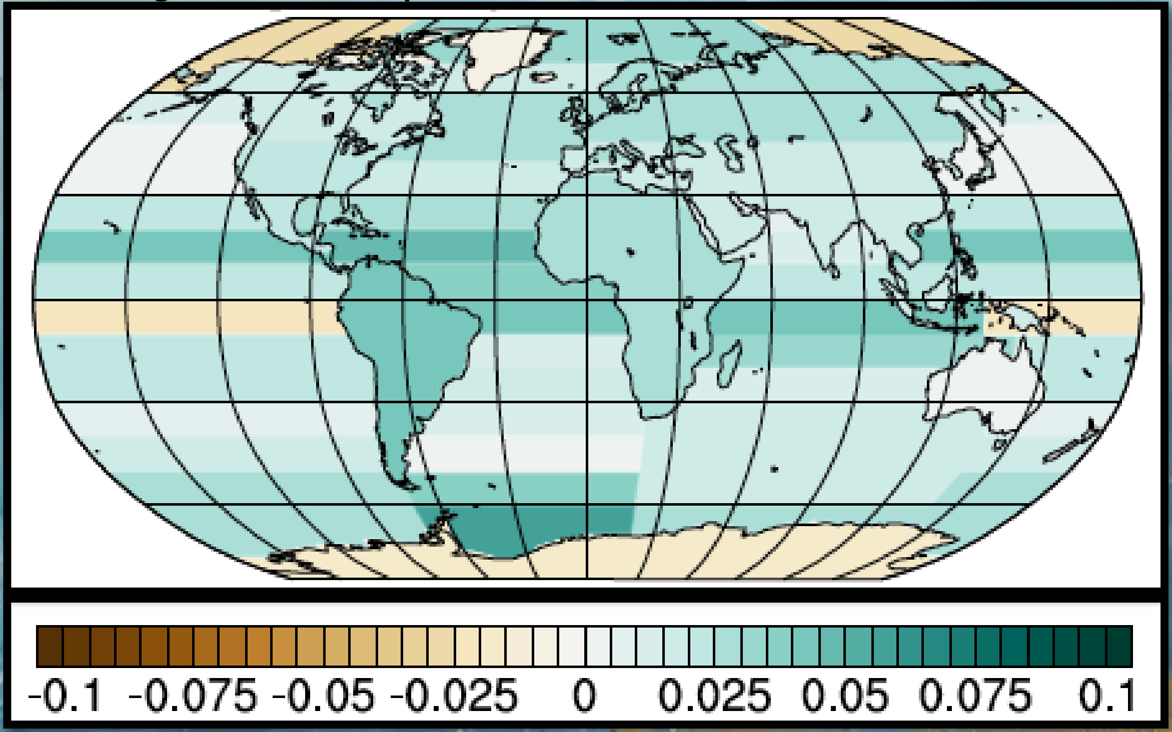
Change in Evaporation



Singh et al (2016B)

Altered Transport: Moisture export increases everywhere

Change in the Export Fraction



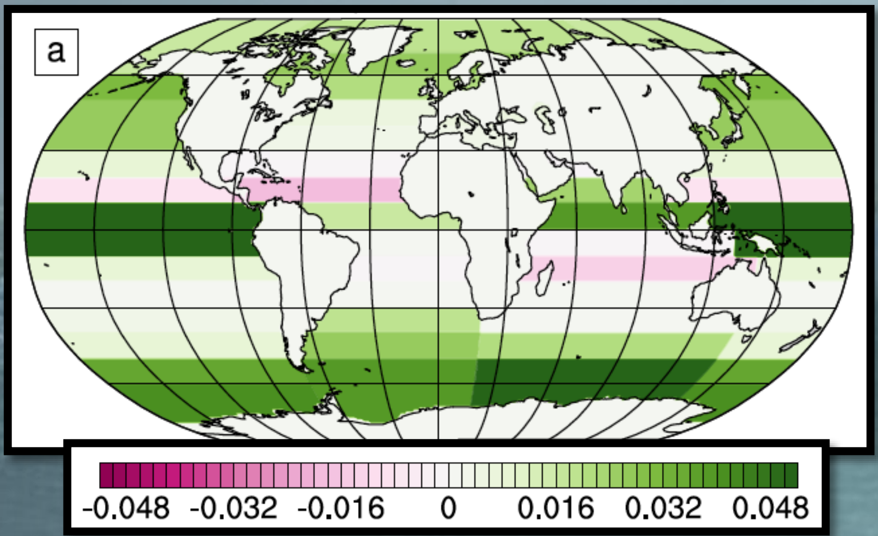
$$\vec{P} - \vec{E} = \mathbf{FT}\vec{E} - \mathbf{T}\vec{E}$$

Export Fraction = Fraction of Locally-Evaporated Moisture that Precipitates Remotely

The export fraction increases (nearly) everywhere.

Singh et al (2016B)

Altered Transport: Interbasin Moisture Convergence Increases Everywhere



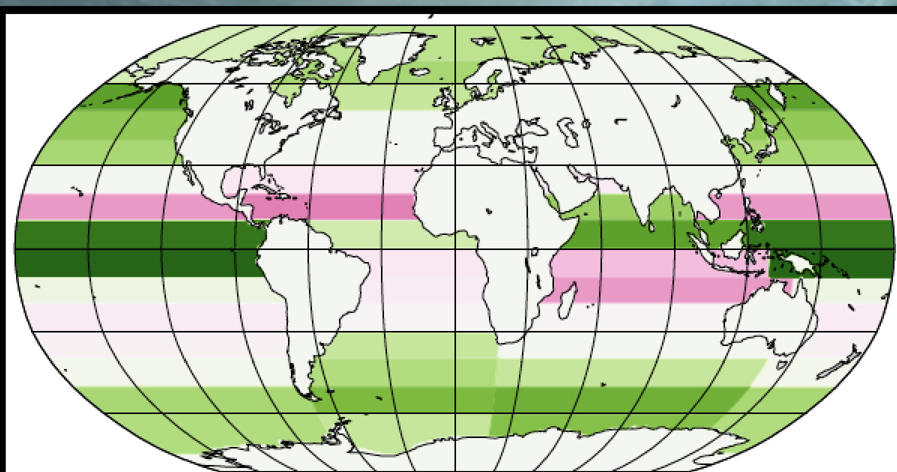
← Total Change in Remote Moisture Convergence

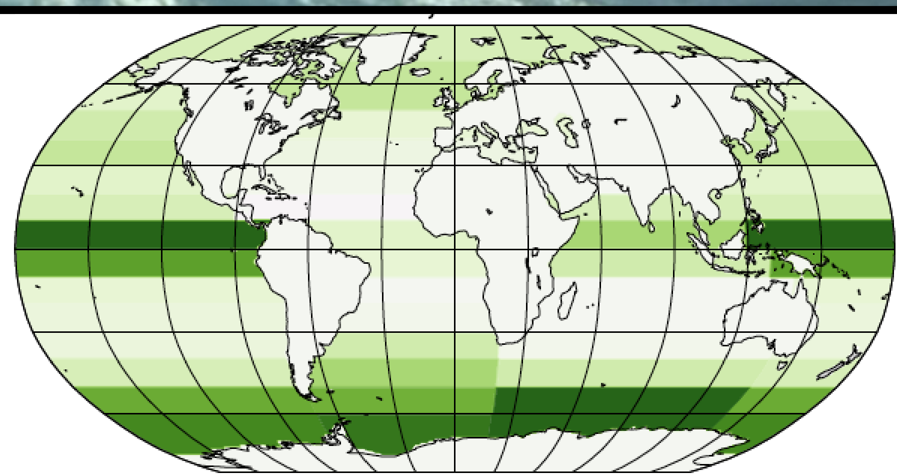
$$\vec{P} - \vec{E} = \mathbf{FT}\vec{E} - \mathbf{T}\vec{E}$$

$$\Delta(\mathbf{FT}\vec{E}) = \Delta(\mathbf{FT}\vec{E})_{intrabasin} + \Delta(\mathbf{FT}\vec{E})_{interbasin}$$

Change in INTRAbasin Moisture Convergence

Change in INTERbasin Moisture Convergence





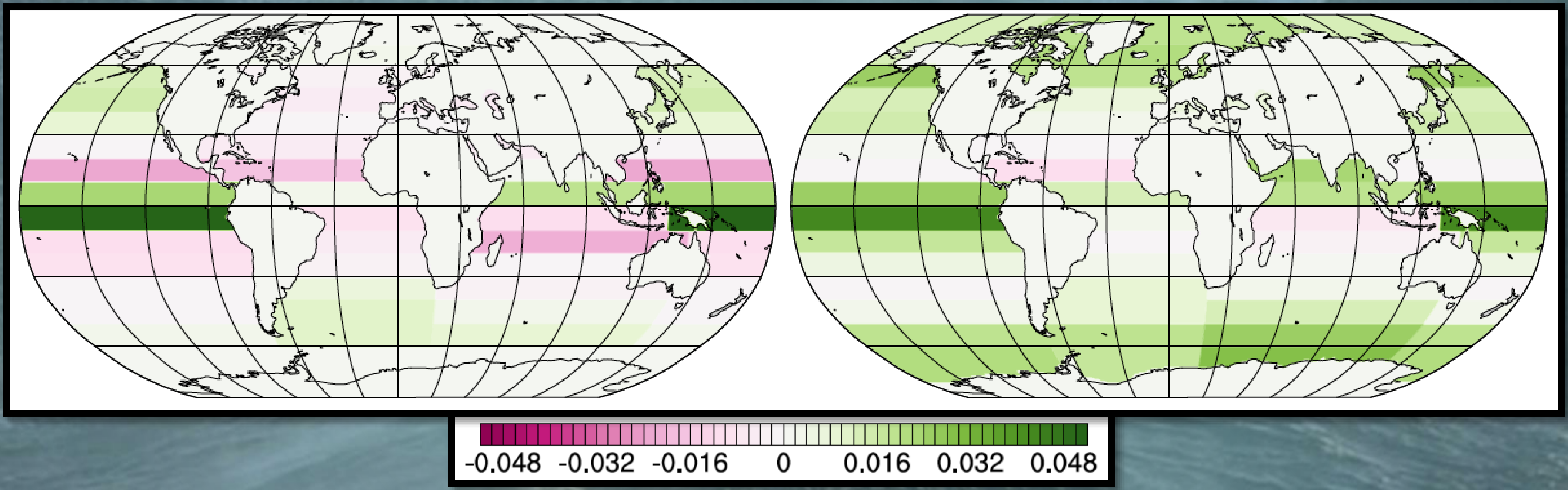
Interbasin moisture convergence increases everywhere.

Singh et al (2016B)

Altered Transport: Near (Far) Intrabasin Moisture Convergence Decreases (Increases) Almost Everywhere

Change in NEAR Intrabasin Moisture Convergence

Change in FAR Intrabasin Moisture Convergence



Convergence from adjacent regions mostly decreases.

Convergence from remote regions increases.

Singh et al (2016B)

Altered Transport: Due to an INCREASE in the Moisture Transport Length Scale

Precipitation Efficiency $\gamma \equiv \frac{P}{Q}$

E and ***P*** increase at only ~2.5% per K

Boer (1992) Mitchell et al (1987)

Q increases at ~7% per K

Precipitation Efficiency MUST decrease $\delta\gamma < 0$

Consider the fundamental equation of hydrology over a 1-D domain

$$\frac{\partial Q}{\partial t} = E(x) - v\frac{\partial Q}{\partial x} - \gamma Q$$

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

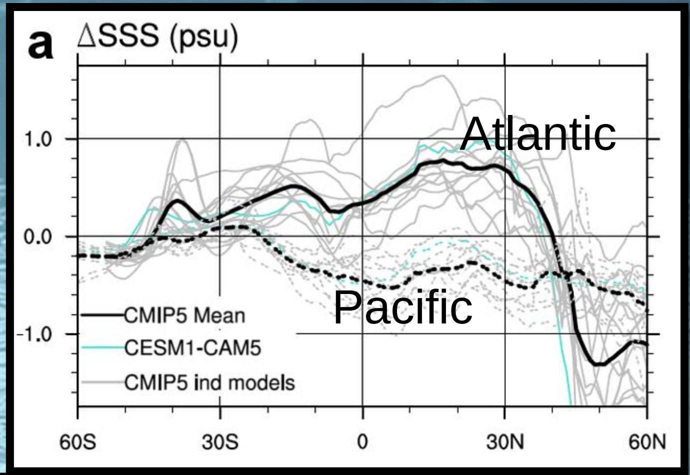
The moisture transport length scale MUST increase

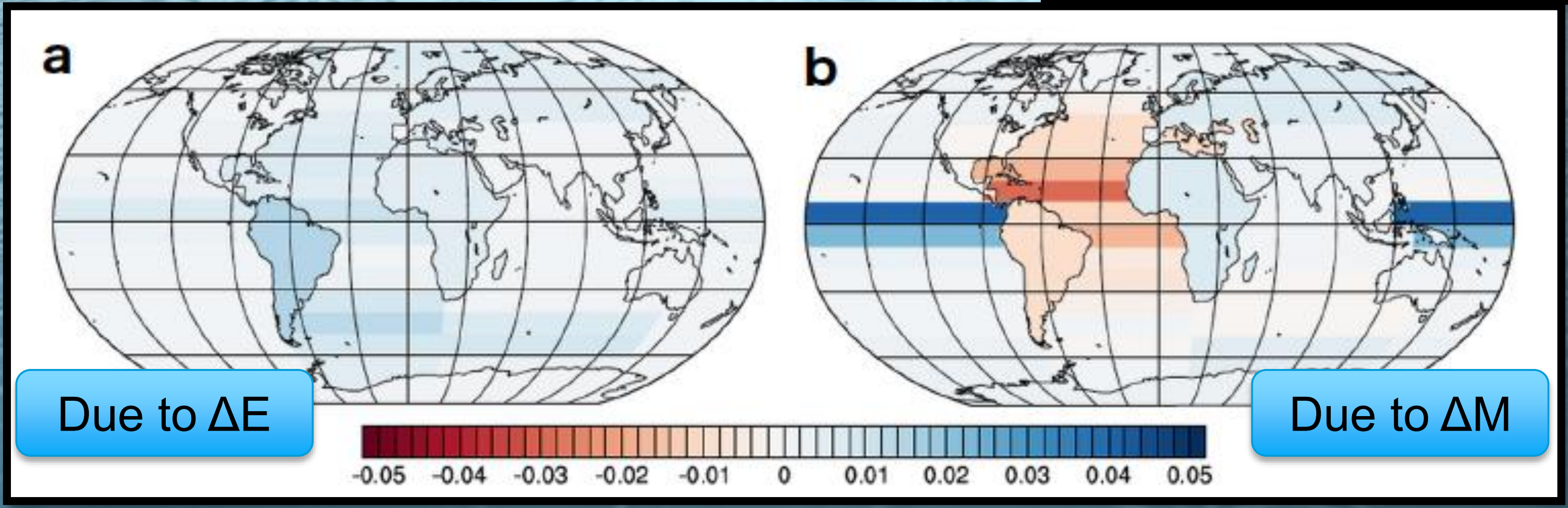
Singh et al (2016C)

An Increase in the Moisture Transport Length Scale explains why the Atlantic will get Saltier with Warming

CMIP5

Δ Salinity
Ab4$\times CO_2$ - piC



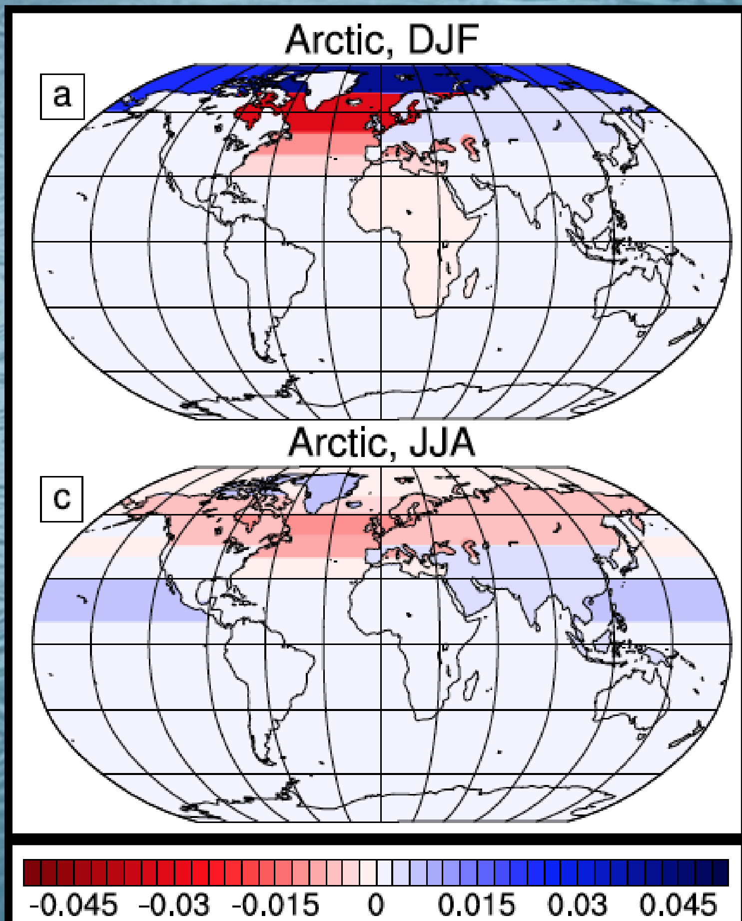


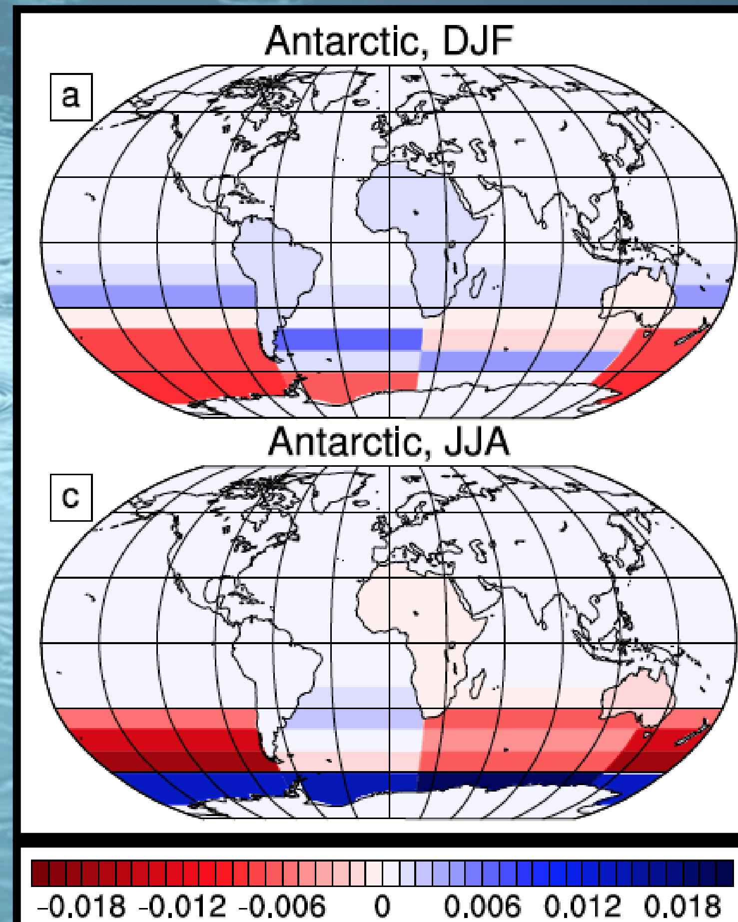
Changes in transport explain why the Atlantic (Pacific) is getting saltier (fresher).

Singh et al (2016C)

The Polar Regions in Winter are an Exception.

Fractional Change in Polar Precipitation Source Regions





In winter, an increase in local moisture sources dominates.
In summer, remote sources increase in relative importance.

Singh et al (2016D)

Thank you!

Questions?

Increased evaporation, given that transport remains constant, can only increase precipitation.

Altered moisture transport with CO_2-induced warming is due to a robust increase in the moisture transport length scale.

The increase in the moisture transport length scale has important implications for ocean basin salinity.

The polar regions in winter are unique in that locally-sourced precipitation increases.

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