Oceanic water cycle, sea surface salinity, and the implications for extreme precipitation in the US Midwest

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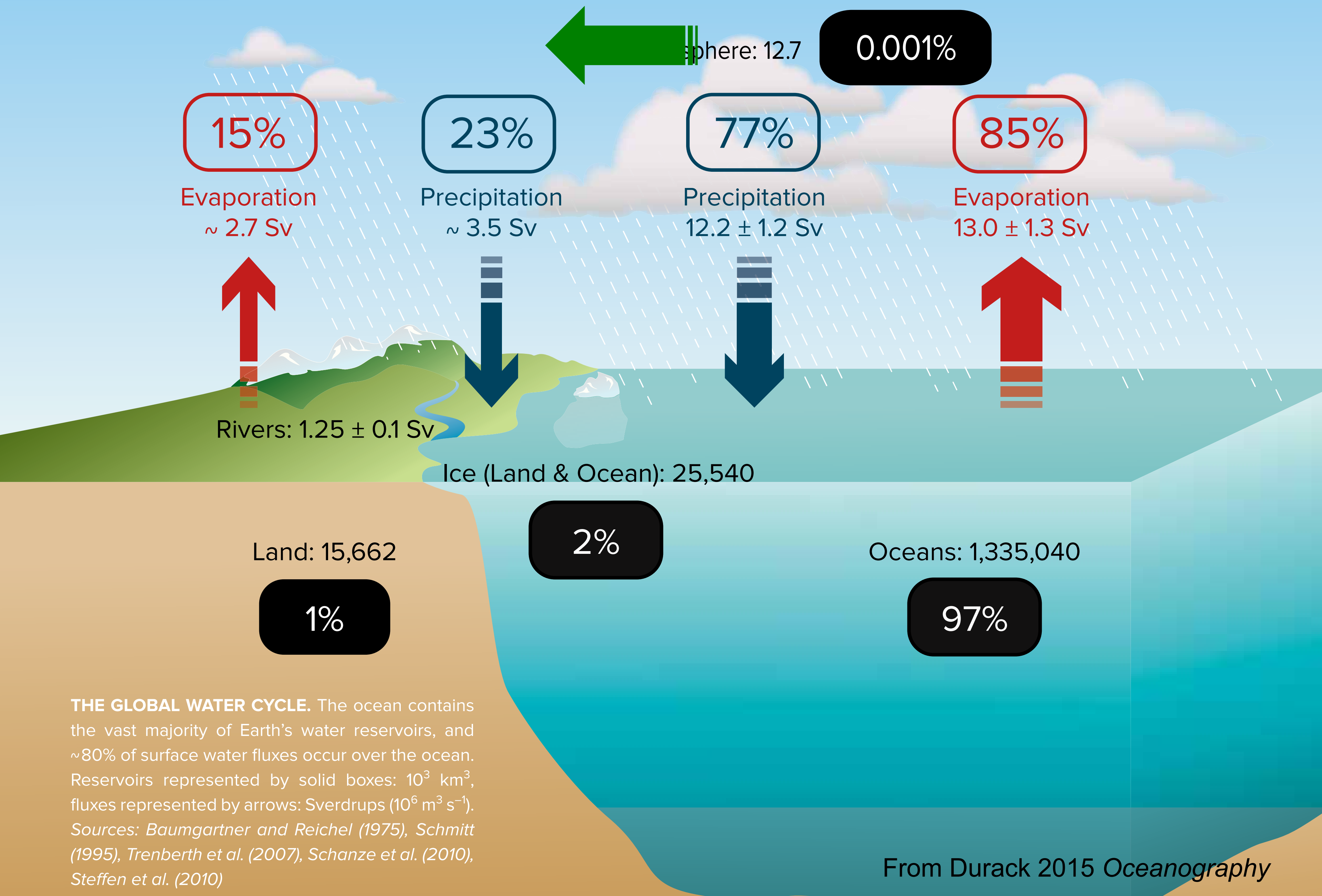
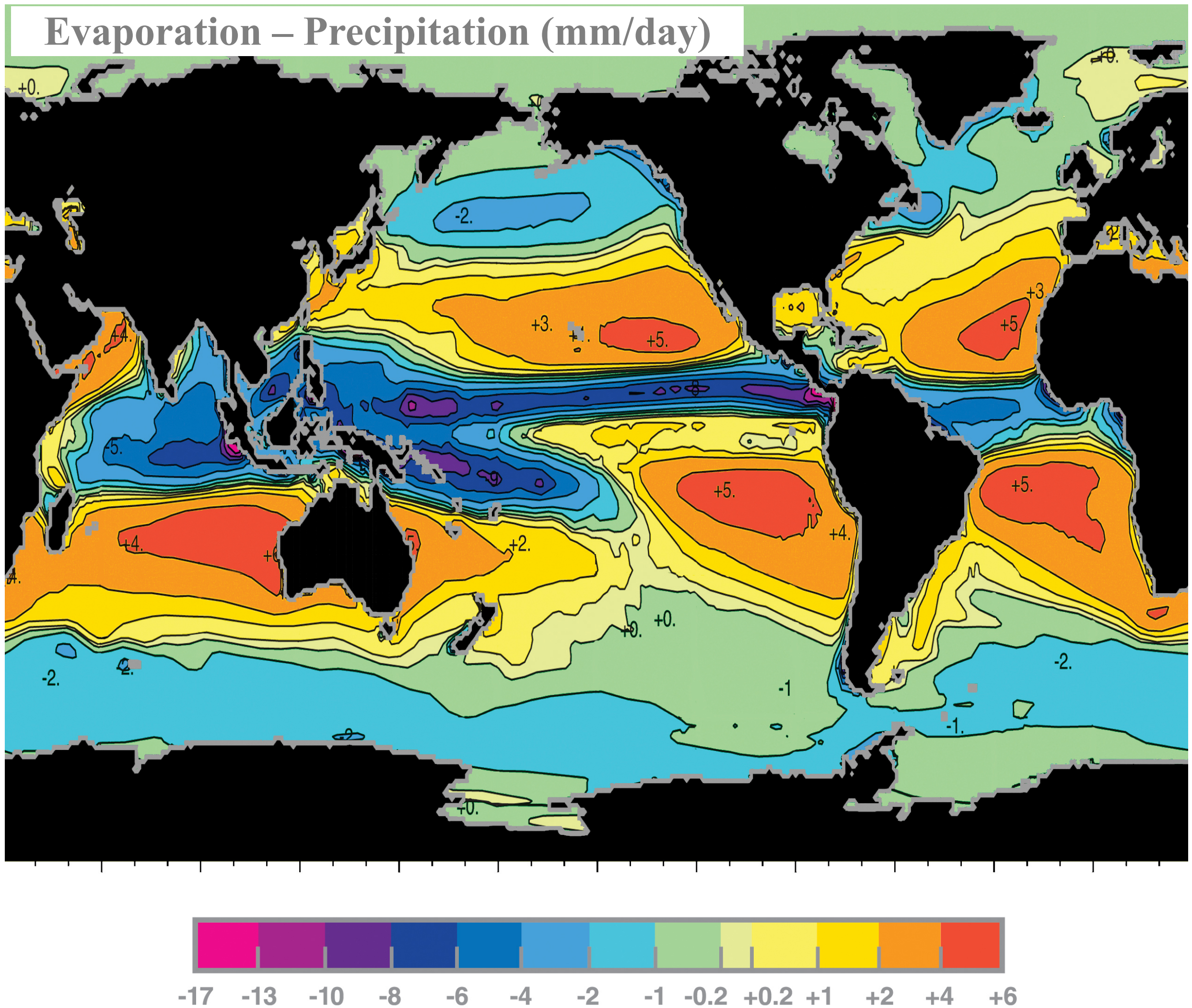
Motivation: Ocean and the global water cycle



THE GLOBAL WATER CYCLE. The ocean contains the vast majority of Earth's water reservoirs, and ~80% of surface water fluxes occur over the ocean. Reservoirs represented by solid boxes: 10^3 km^3, fluxes represented by arrows: Sverdrups (10^6 m^3 s^{-1}). *Sources: Baumgartner and Reichel (1975), Schmitt (1995), Trenberth et al. (2007), Schanze et al. (2010), Steffen et al. (2010)*

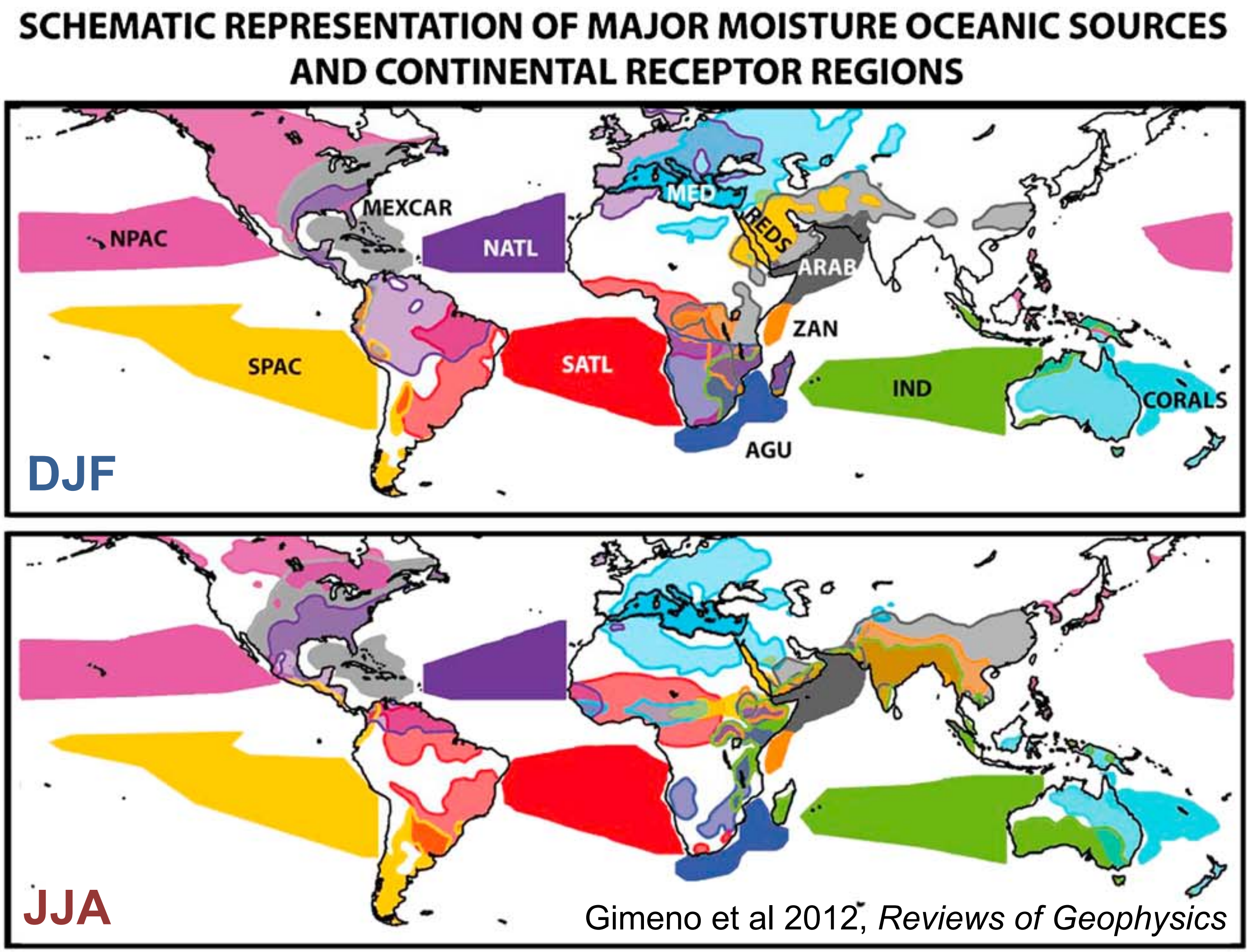
From Durack 2015 *Oceanography*

Moisture source regions: Subtropical oceans



Evaporation>Precipitation→ net moisture export: Moisture sources
Precipitation>Evaporation→ net moisture input: Moisture sinks

Oceanic moisture & terrestrial precipitation

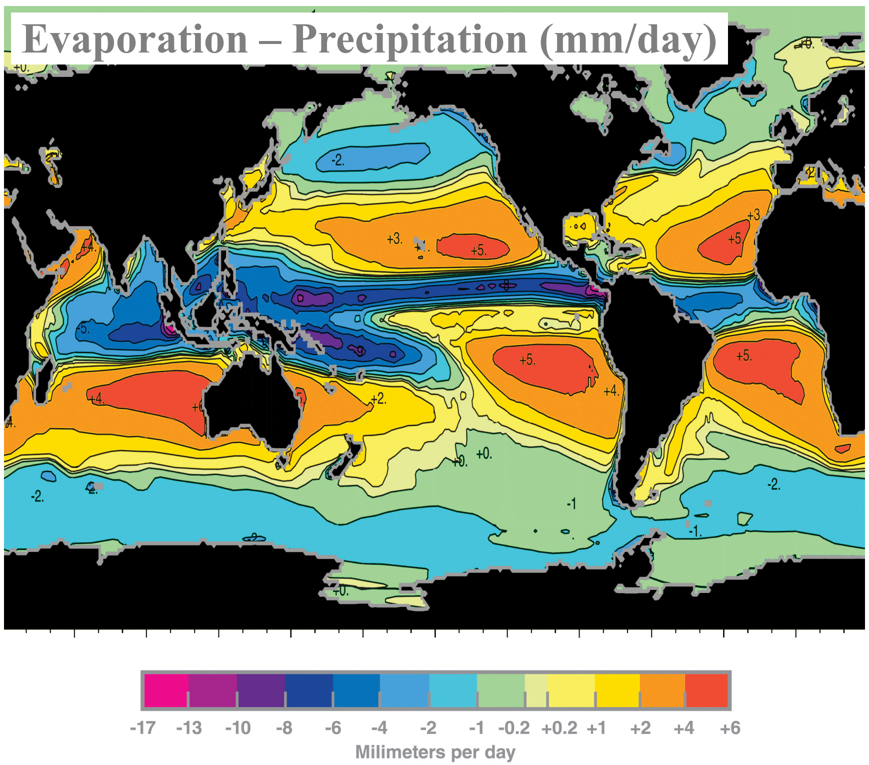


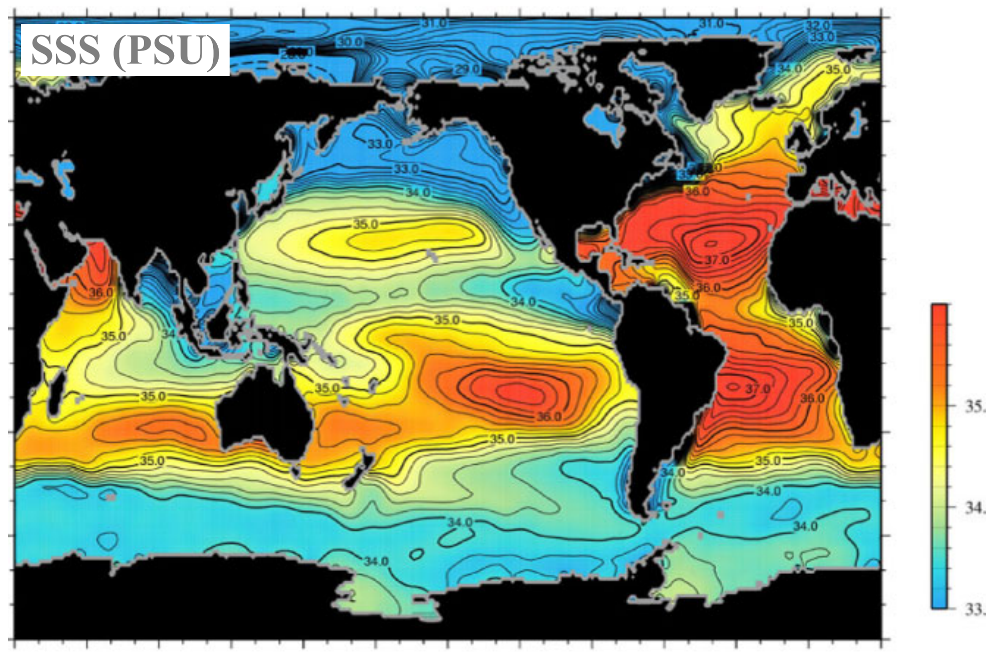
Gimeno et al 2012, *Reviews of Geophysics*

Evaporation>Precipitation→ net moisture export: Moisture sources
Precipitation>Evaporation→ net moisture input: Moisture sinks

Sea surface salinity: Indicator of oceanic water cycle

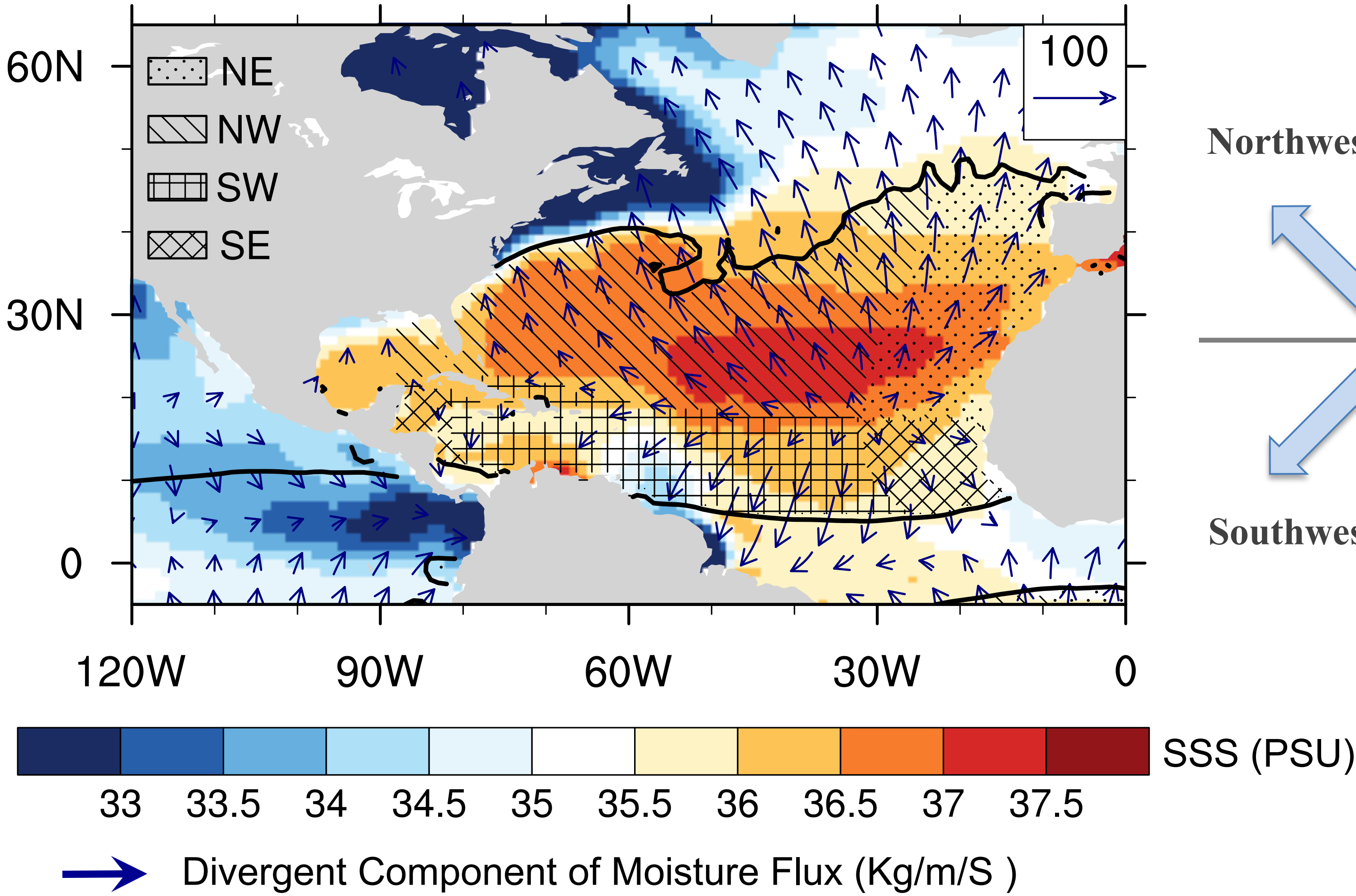
The oceanic water cycle leaves an imprint on SSS, making SSS "nature's rain gauge".

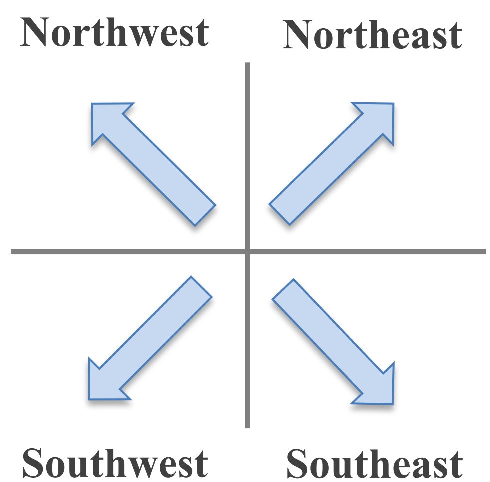




Q: Is SSS a predictor of terrestrial precipitation?

Definition of North Atlantic SSS indices

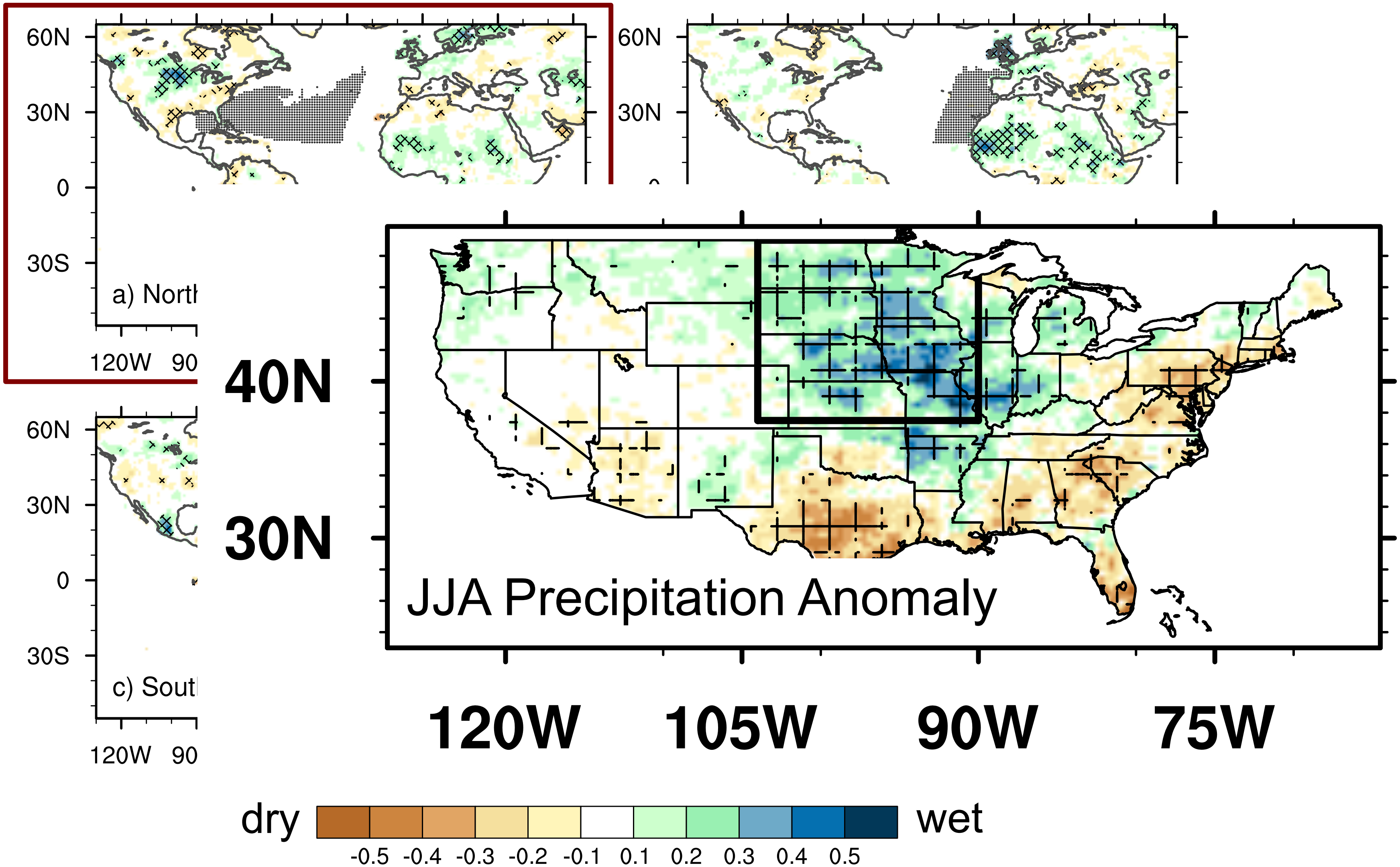




March-April-May (MAM) climatology (1950-2009) of SSS (shaded, unit: PSU), moisture flux divergence (contours, unit: mm/day) and the divergent component of moisture flux (vectors, unit: Kg/m/S) over the North Atlantic. The bold contours are the moisture flux divergence = 0 isoline.

N. Atl. SSS & terrestrial precipitation: Midwest

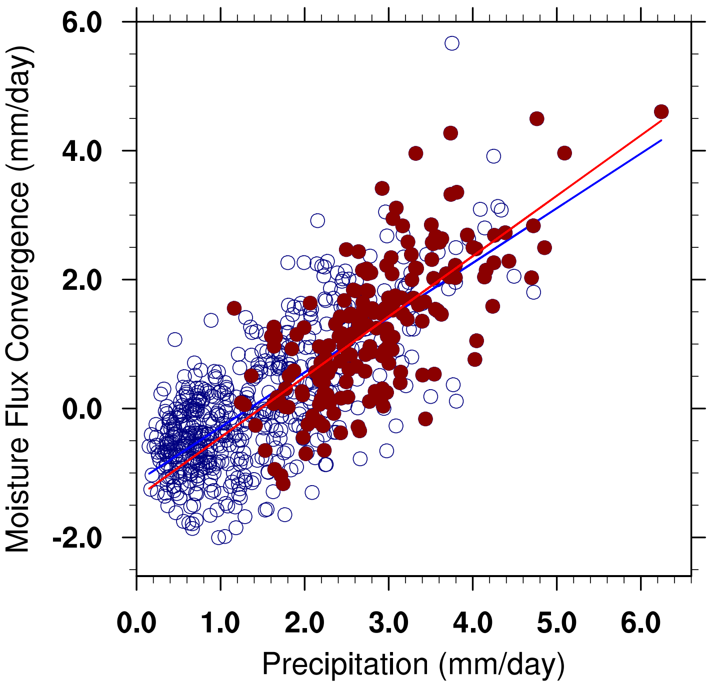
SSS in NW subtropical N. Atl. leads Midwest summer precipitation



Correlation between Springtime North Atlantic SSS and Warm season (JJA) precipitation: a) Northwest index; b) Northeast index; c) Southwest index; and d) Southeast index.

What cause rainfall anomaly?

Methods: Thermodynamic and dynamic decomposition of the regional water cycle



In US Midwest: $P \sim -\frac{1}{g}\nabla \cdot \int_0^{p_s} \overline{q}\vec{\overline{V}}dp$

$$-\frac{1}{g}\nabla \cdot \int_0^{p_s} \overline{q}\vec{\overline{V}}dp = \underbrace{-\frac{1}{g}\int_0^{p_s} \overline{q}\nabla \cdot \vec{\overline{V}}\,dp}_{\text{mass divergence}} \underbrace{-\frac{1}{g}\int_0^{p_s} \vec{\overline{V}} \cdot \nabla \overline{q}\,dp}_{\text{moisture gradient}}$$

Thermodynamic and Dynamic Decomposition: $q = q_c + q_a$; $\vec{V} = \vec{V}_c + \vec{V}_a$

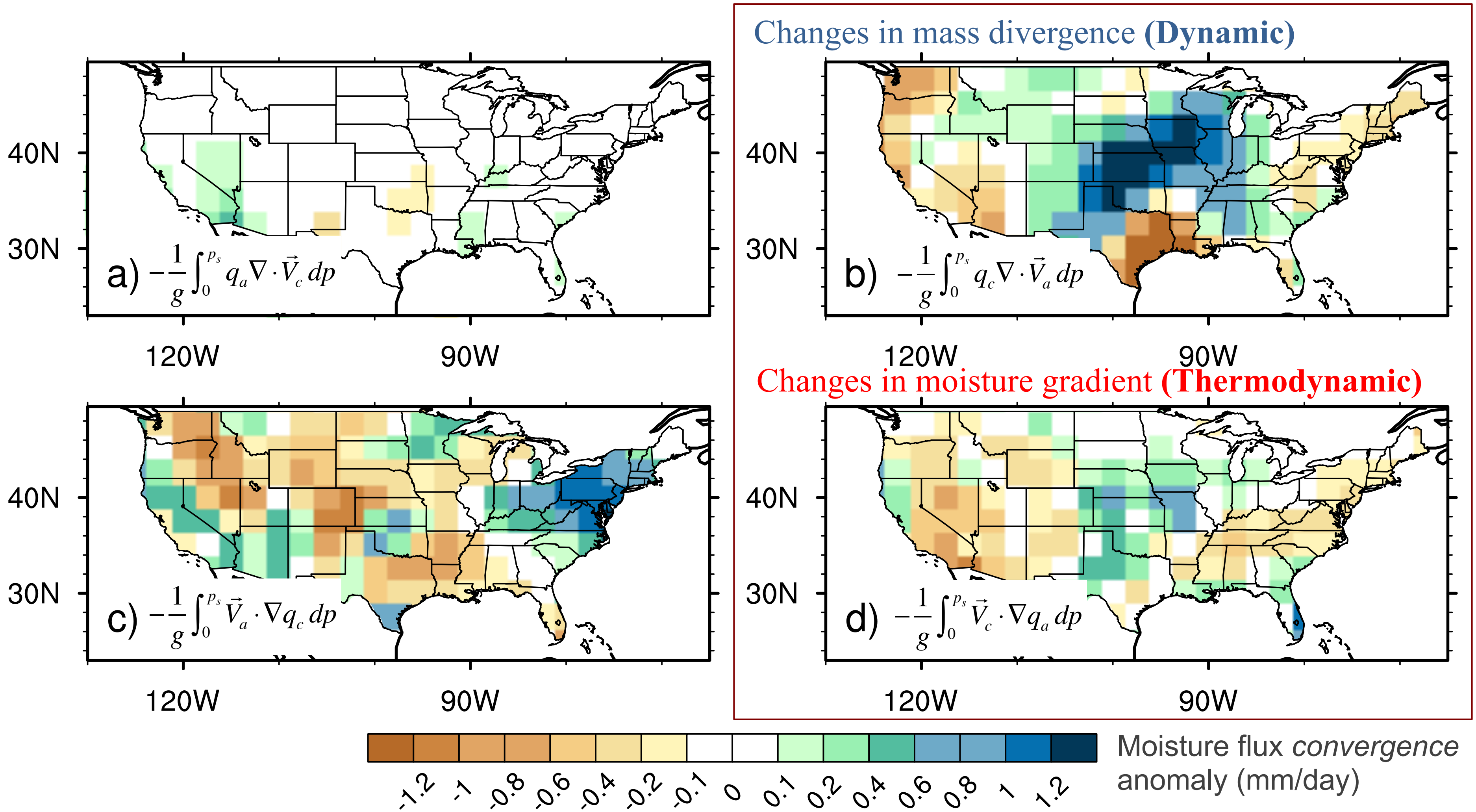
(_c: climatology; _a: anomalies)

$$\underbrace{-\frac{1}{g}\int_0^{p_s} q\nabla \cdot \vec{V}\,dp}_{\text{Mass Divergence}} = -\frac{1}{g}\int_0^{p_s} q_c\nabla \cdot \vec{V}_c\,dp - \frac{1}{g}\int_0^{p_s} q_c\nabla \cdot \vec{V}_a\,dp - \frac{1}{g}\int_0^{p_s} q_a\nabla \cdot \vec{V}_c\,dp - \frac{1}{g}\int_0^{p_s} q_a\nabla \cdot \vec{V}_a\,dp$$

$$\underbrace{-\frac{1}{g}\int_0^{p_s} \vec{V} \cdot \nabla q\,dp}_{\text{Moisture Gradient}} = -\frac{1}{g}\int_0^{p_s} \vec{V}_c \cdot \nabla q_c\,dp - \frac{1}{g}\int_0^{p_s} \vec{V}_a \cdot \nabla q_c\,dp - \frac{1}{g}\int_0^{p_s} \vec{V}_c \cdot \nabla q_a\,dp - \frac{1}{g}\int_0^{p_s} \vec{V}_a \cdot \nabla q_a\,dp$$

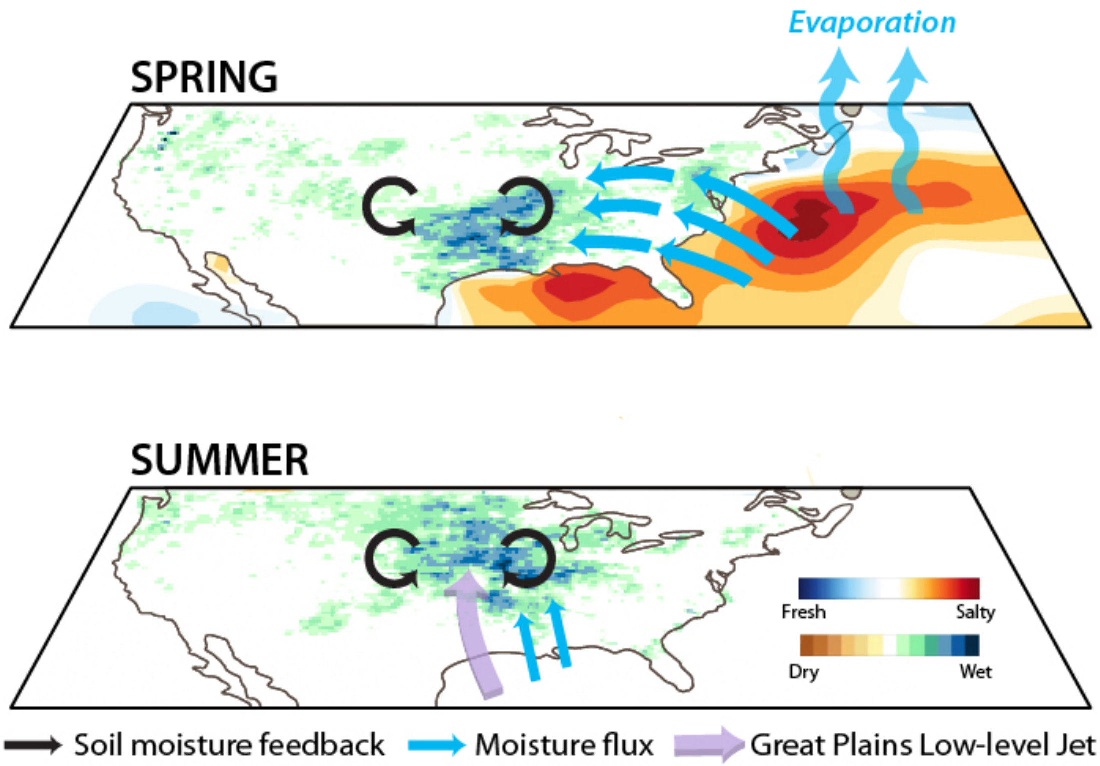
What cause rainfall anomaly?

Combination of dynamic and thermodynamic processes

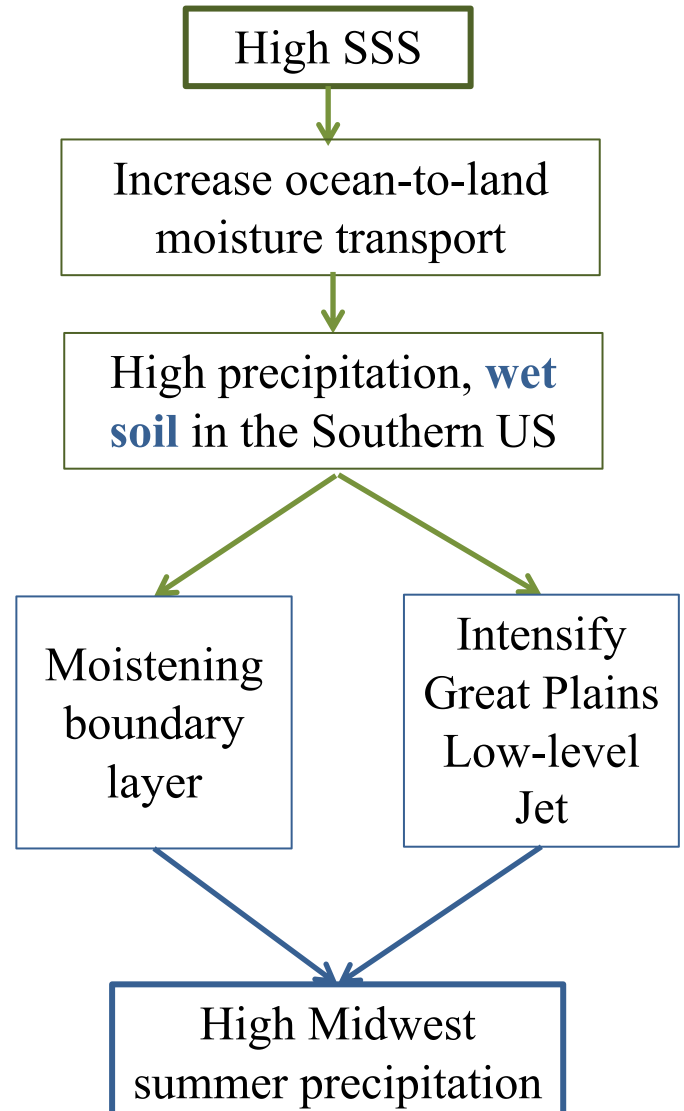


Physical mechanism

Dual effects of soil moisture on regional water cycle

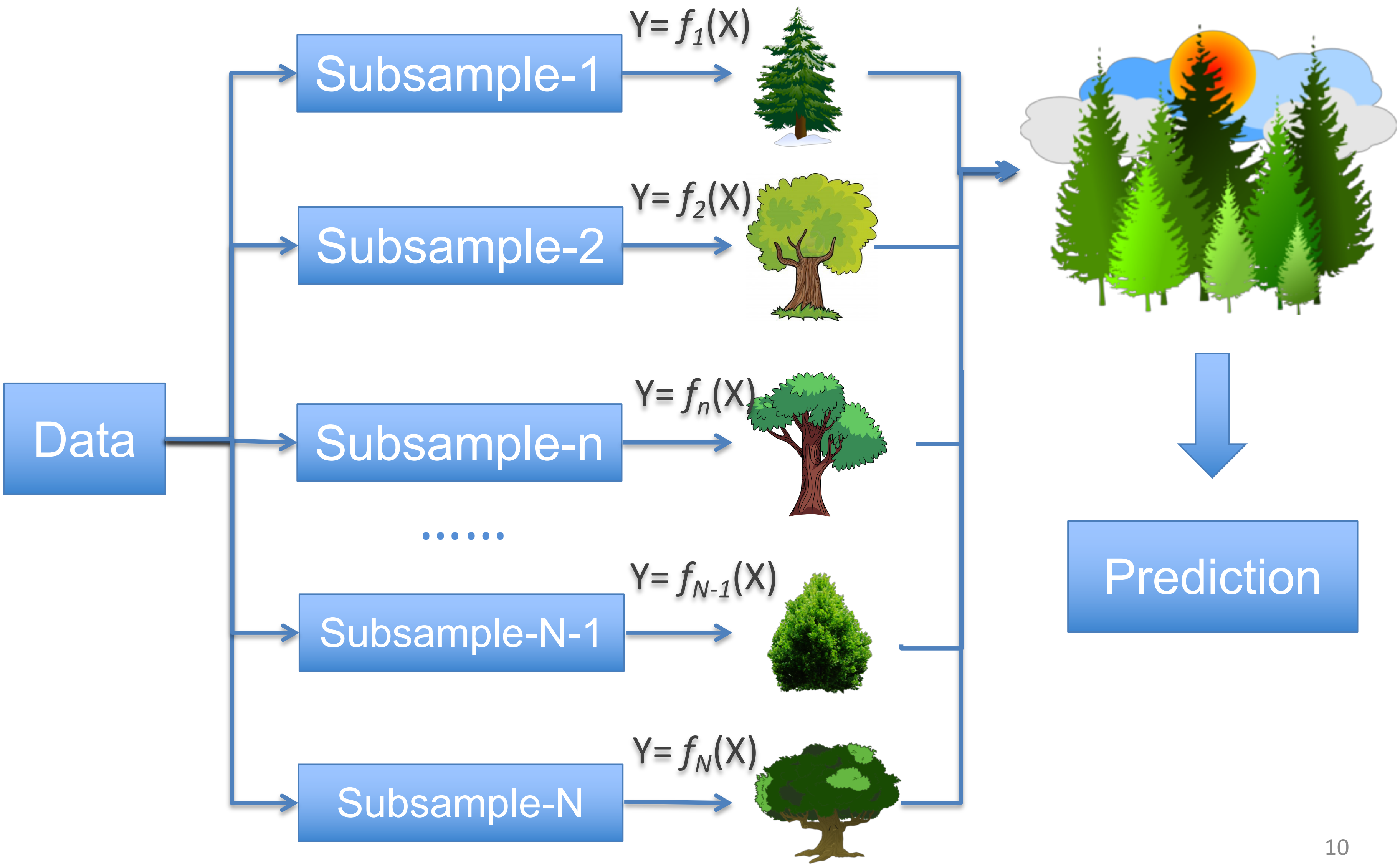


Schematic figure showing the mechanism of North Atlantic SSS-Midwest precipitation relationship. (See Li et al., 2016 *J. Climate*, **29**, 3143-3159. [Illustration by Jack Cook, WHOI]).



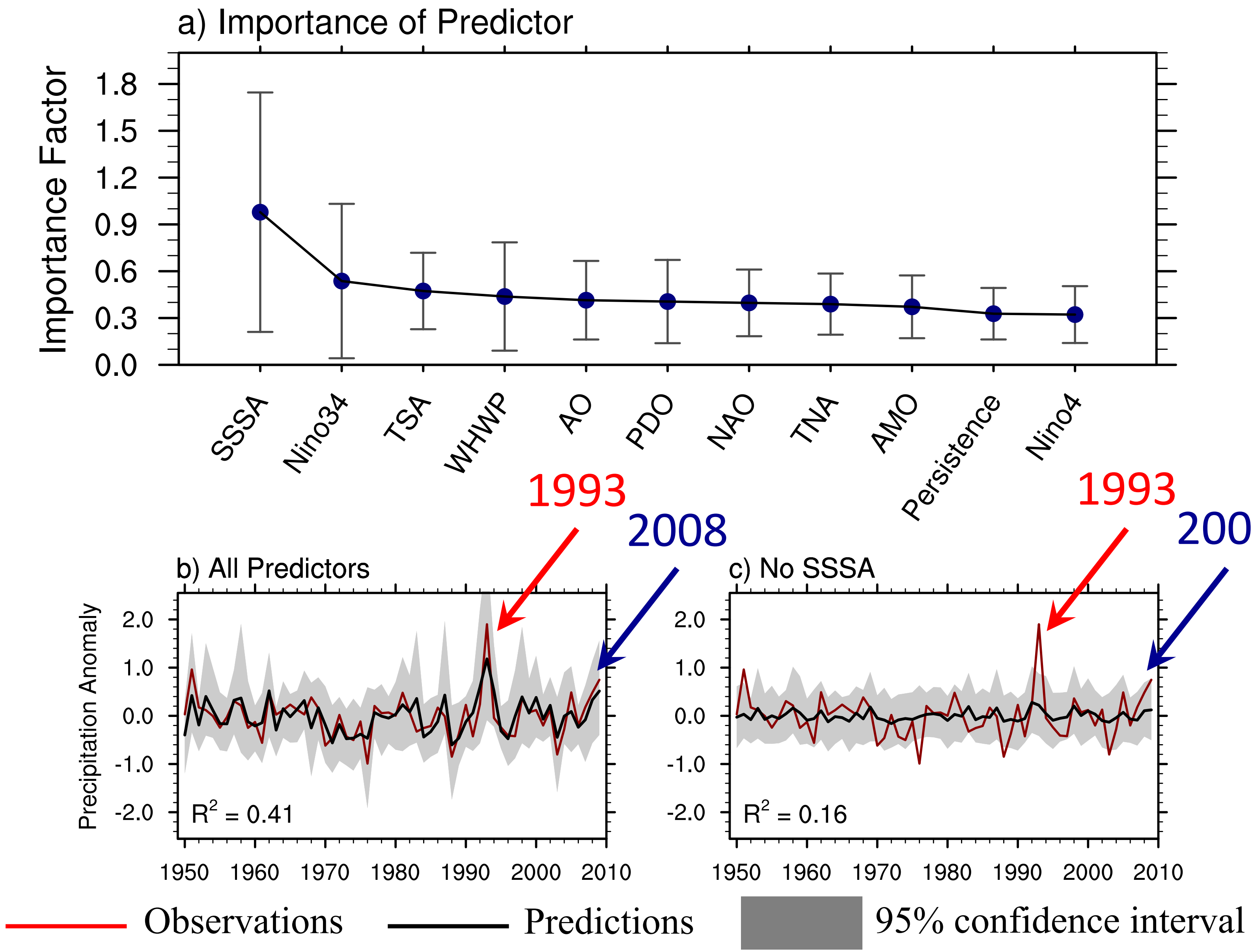
Predicting Midwest precipitation using salinity

Random Forest Algorithm



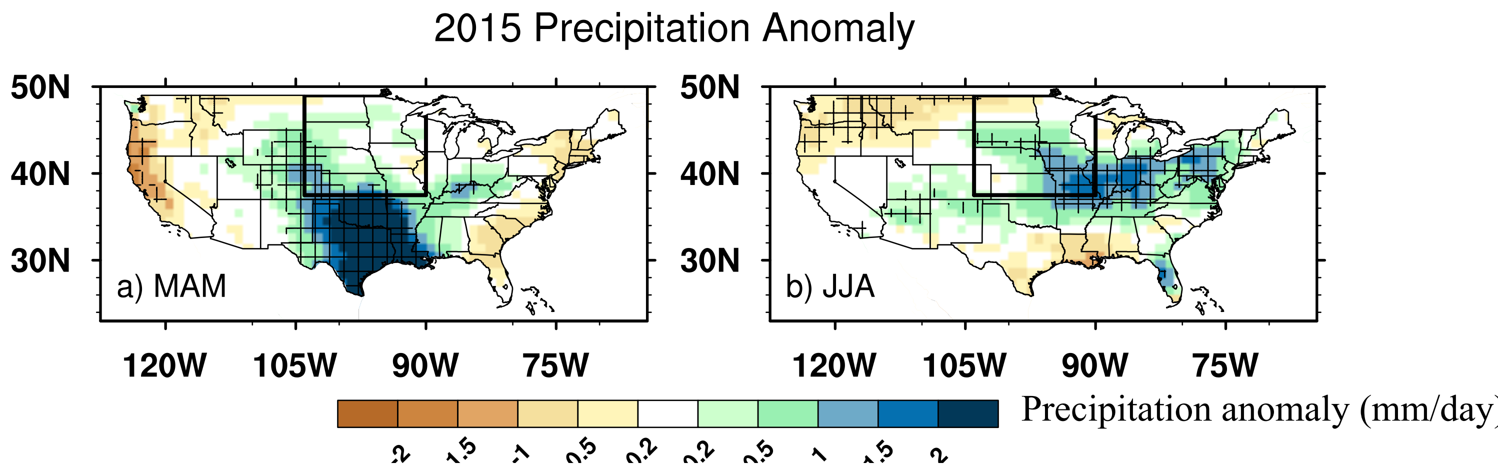
Predicting Midwest summer precipitation

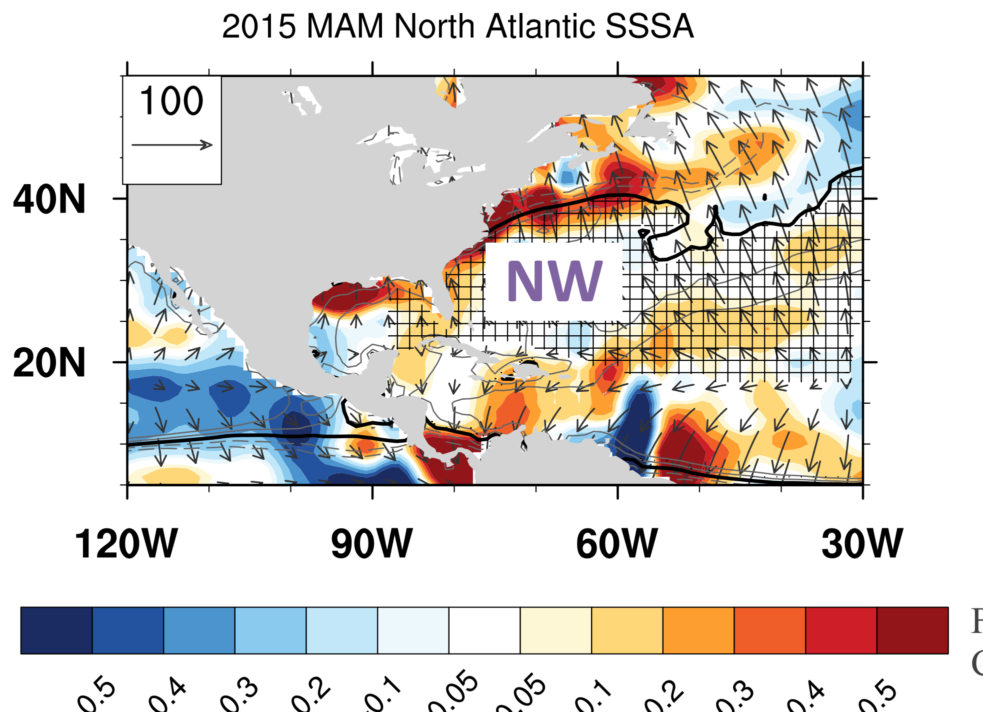
Knowledge of NW SSS can improve rainfall prediction in US Midwest



Case Study: 2015 US Summer Precipitation

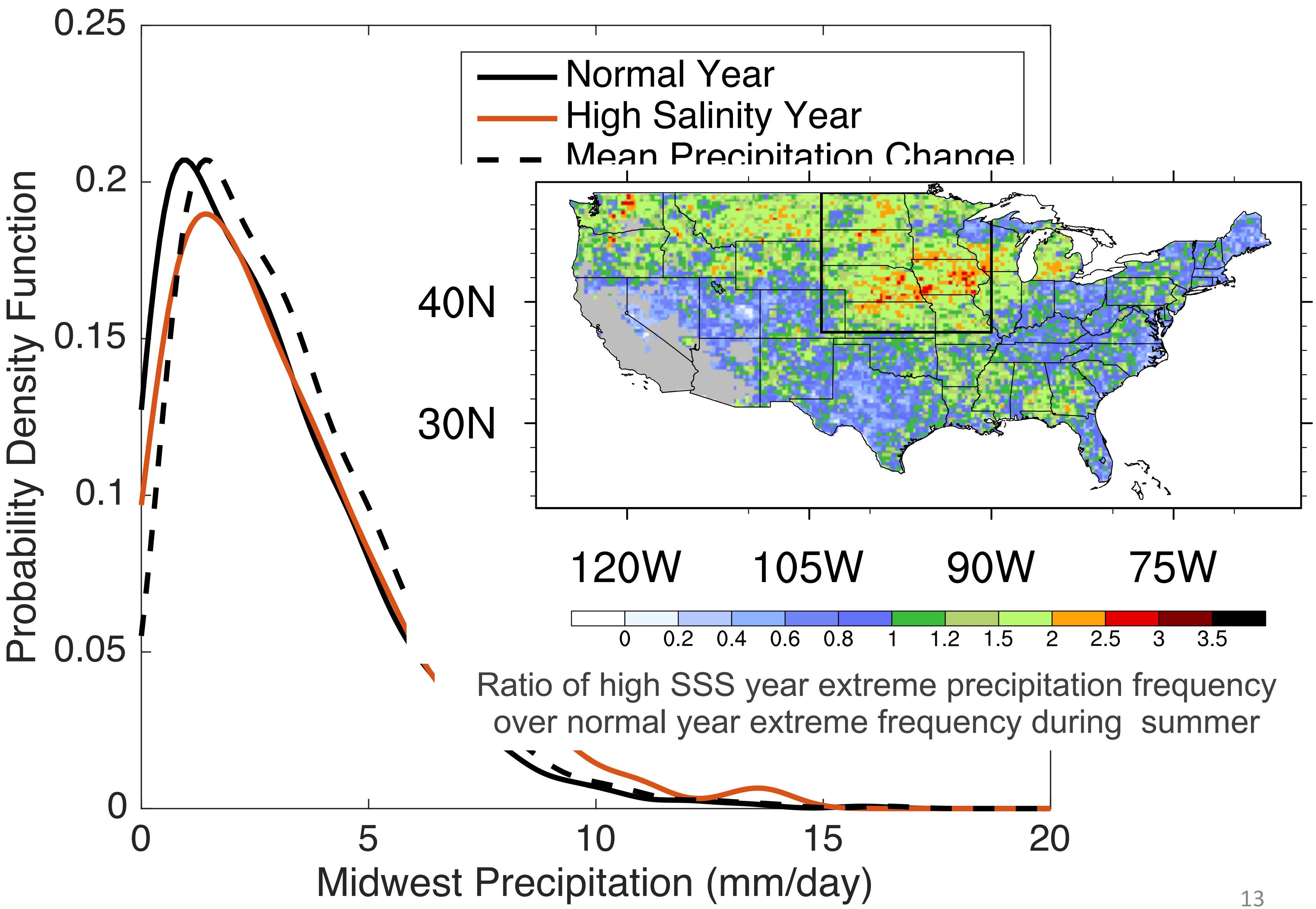
Salty subtropical N. Atl. ~ wet summer in Midwest





From Li et al. (2018), Climate Dynamics

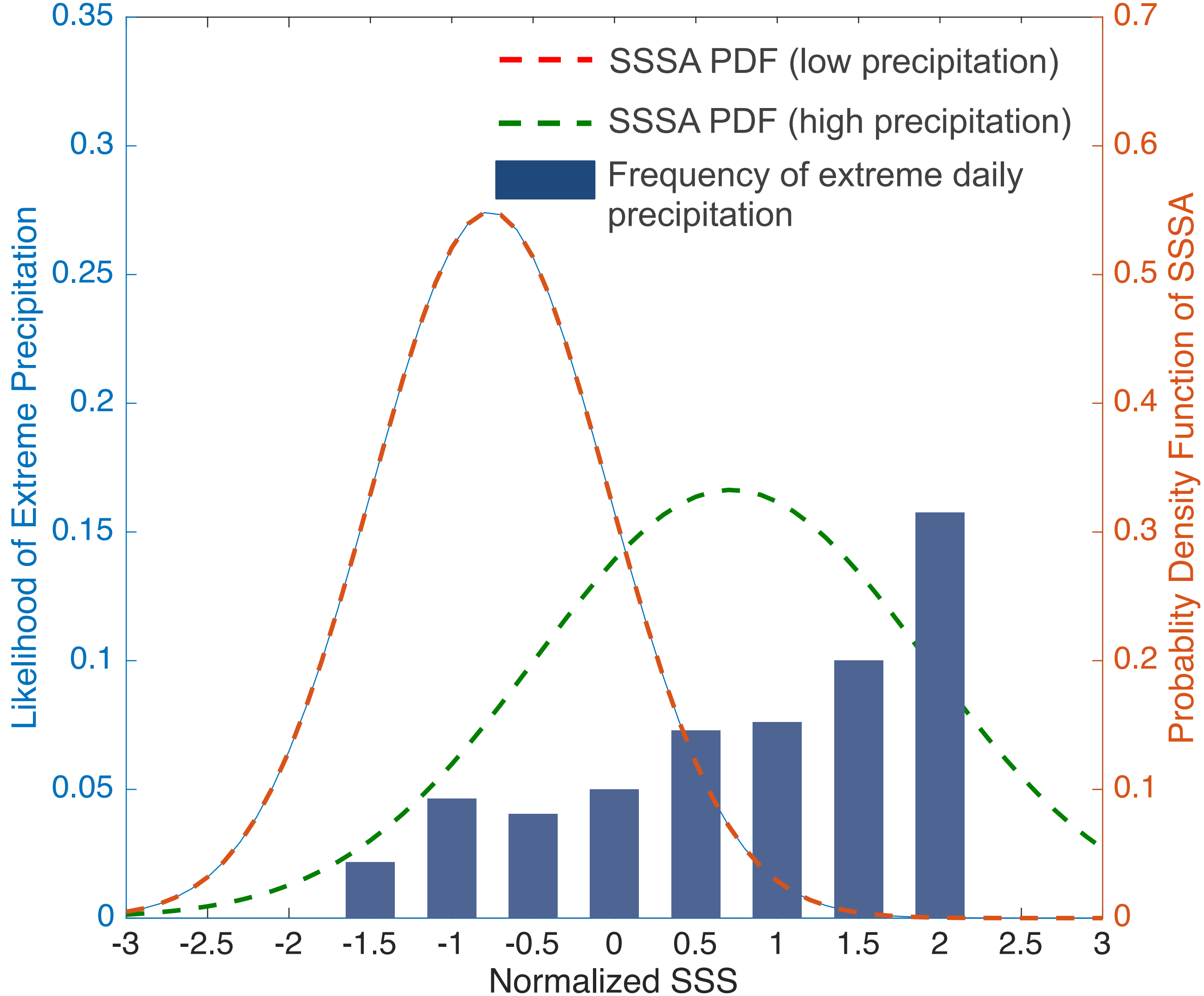
Salinity precursor & extreme daily precipitation



Ratio of high SSS year extreme precipitation frequency over normal year extreme frequency during summer

Concluding Remarks

Salinity provides predictive values to Midwest extreme rain.

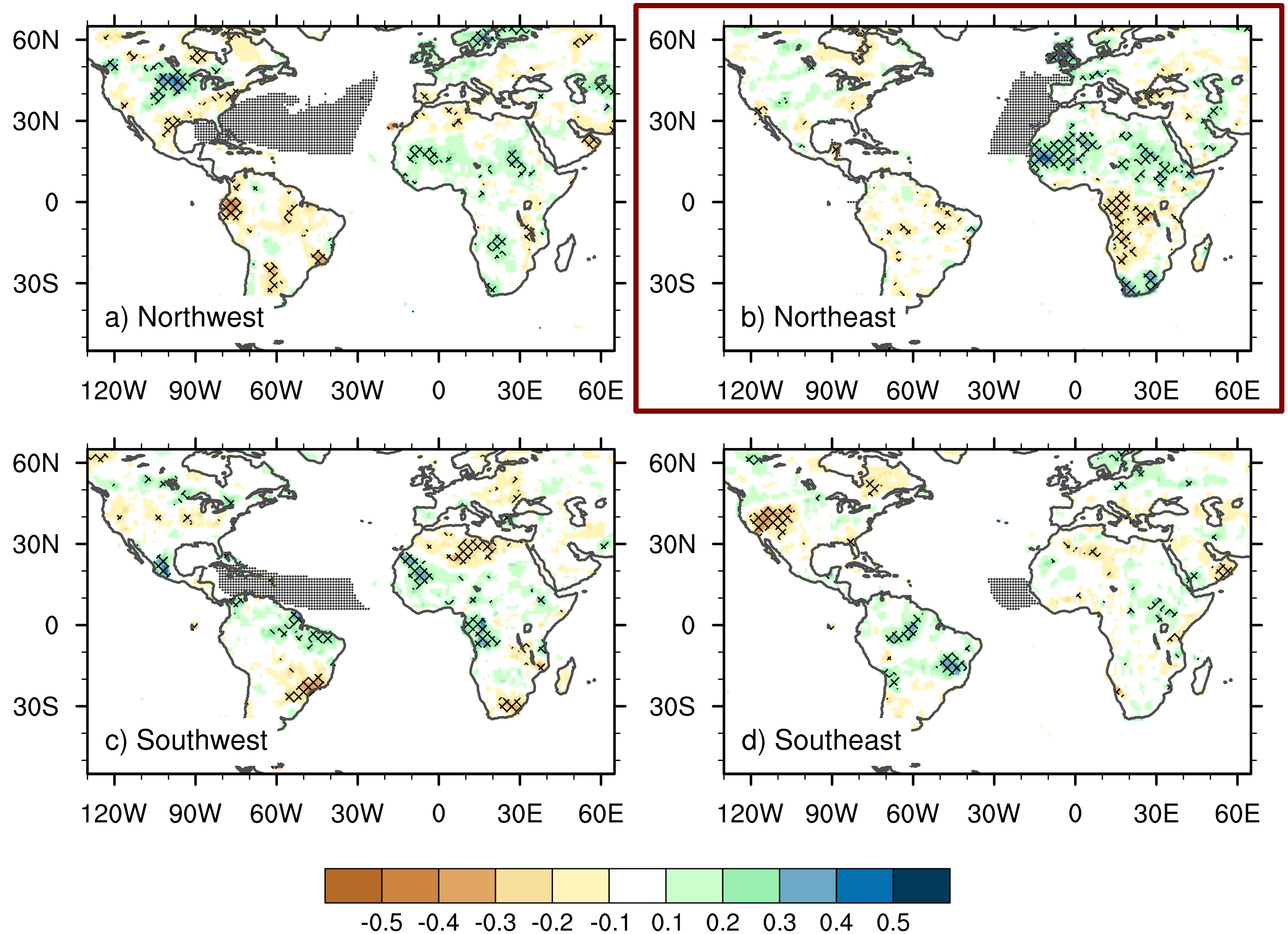


THANK YOU!

SUPPLEMENTARY FIGURES

N. Atl. SSS and Terrestrial Precipitation: Sahel

SSS in NE subtropical N. Atl. leads Sahel monsoon precipitation



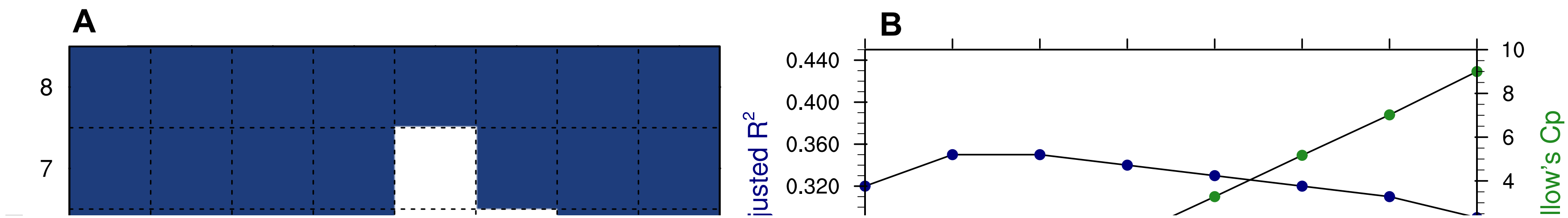
Correlation between Springtime North Atlantic SSS and Warm season (JJA) precipitation: a) Northwest index; b) Northeast index; c) Southwest index; and d) Southeast index.

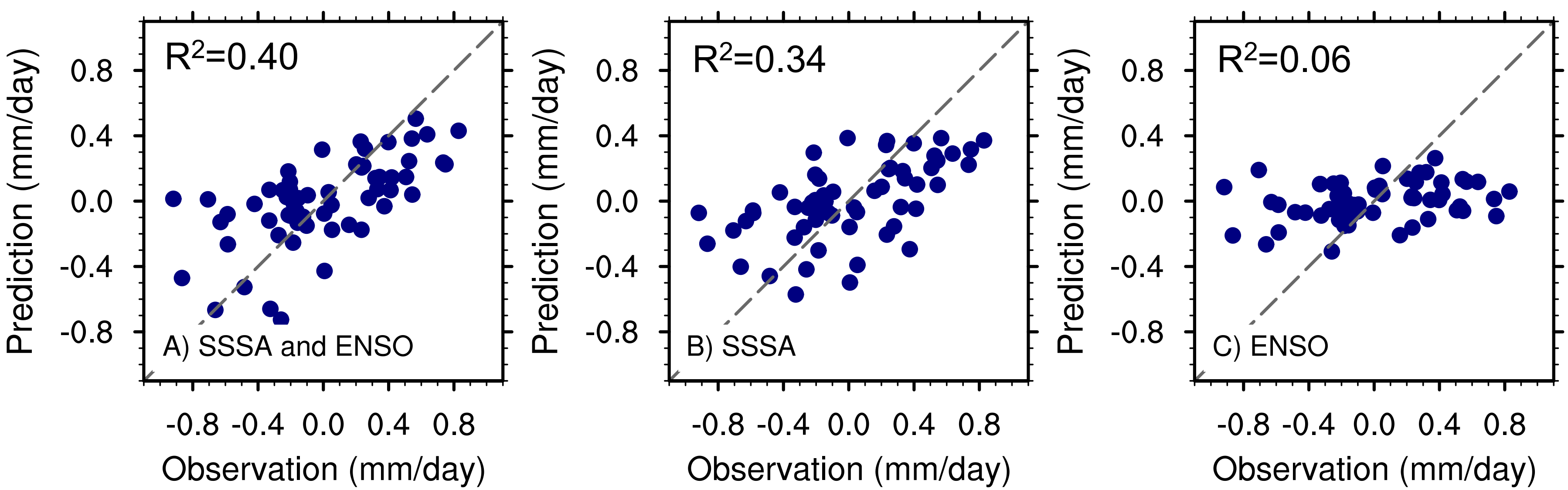
RESEARCH ARTICLE

OCEANOGRAPHY

North Atlantic salinity as a predictor of Sahel rainfall

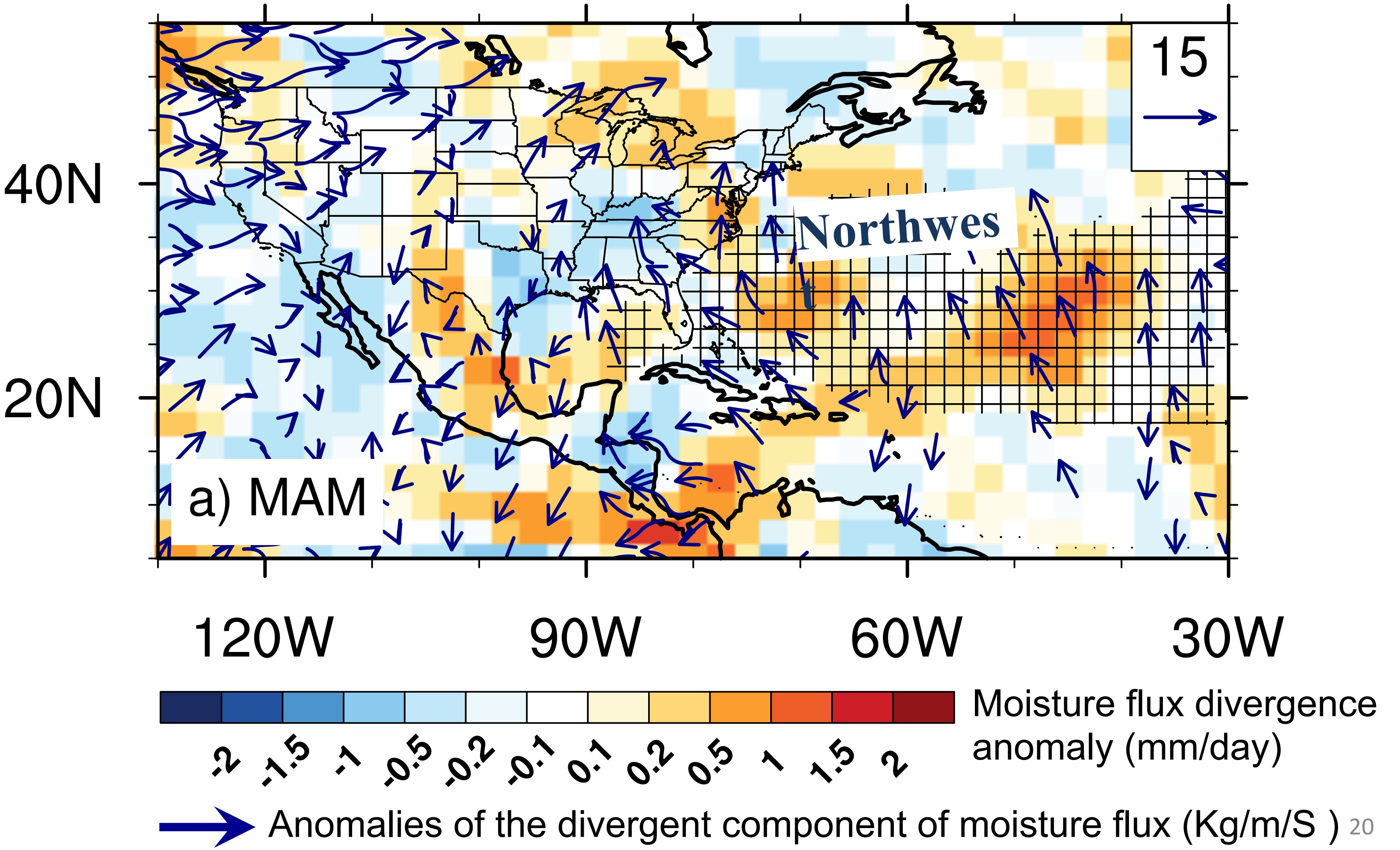
10.1126/sciadv.1501588





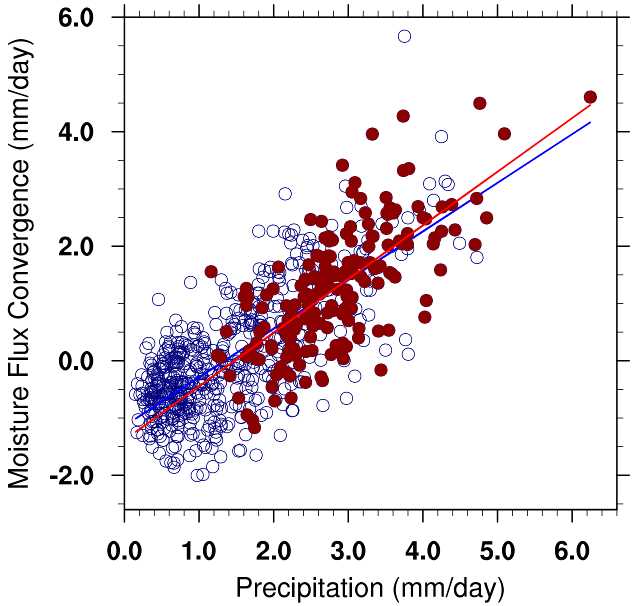
Puzzle 1: What Causes SSS Anomalies?

Increased moisture flux divergence away from the local ocean results in higher SSS over the NW subtropical North Atlantic



Puzzle 2: What Cause Rainfall Anomaly?

Methods: Thermodynamic and dynamic decomposition of regional water cycle



$$P - E = -\frac{1}{g}\overline{\nabla \cdot \int_0^{p_s} q\vec{V}dp} = -\frac{1}{g}\nabla \cdot \int_0^{p_s} \overline{q}\overline{\vec{V}}dp - \frac{1}{g}\overline{\nabla \cdot \int_0^{p_s} q'\vec{V}'dp}$$

In US Midwest: $P \sim -\frac{1}{g}\nabla \cdot \int_0^{p_s} \overline{q}\overline{\vec{V}}dp$

$$-\frac{1}{g}\nabla \cdot \int_0^{p_s} \overline{q}\overline{\vec{V}}dp = \underbrace{-\frac{1}{g}\int_0^{p_s} \overline{q}\nabla \cdot \overline{\vec{V}}\,dp}_{\text{mass divergence}} \underbrace{-\frac{1}{g}\int_0^{p_s} \overline{\vec{V}} \cdot \nabla \overline{q}\,dp}_{\text{moisture gradient}}$$

Thermodynamic and Dynamic Decomposition: $q = q_c + q_a$; $\vec{V} = \vec{V}_c + \vec{V}_a$

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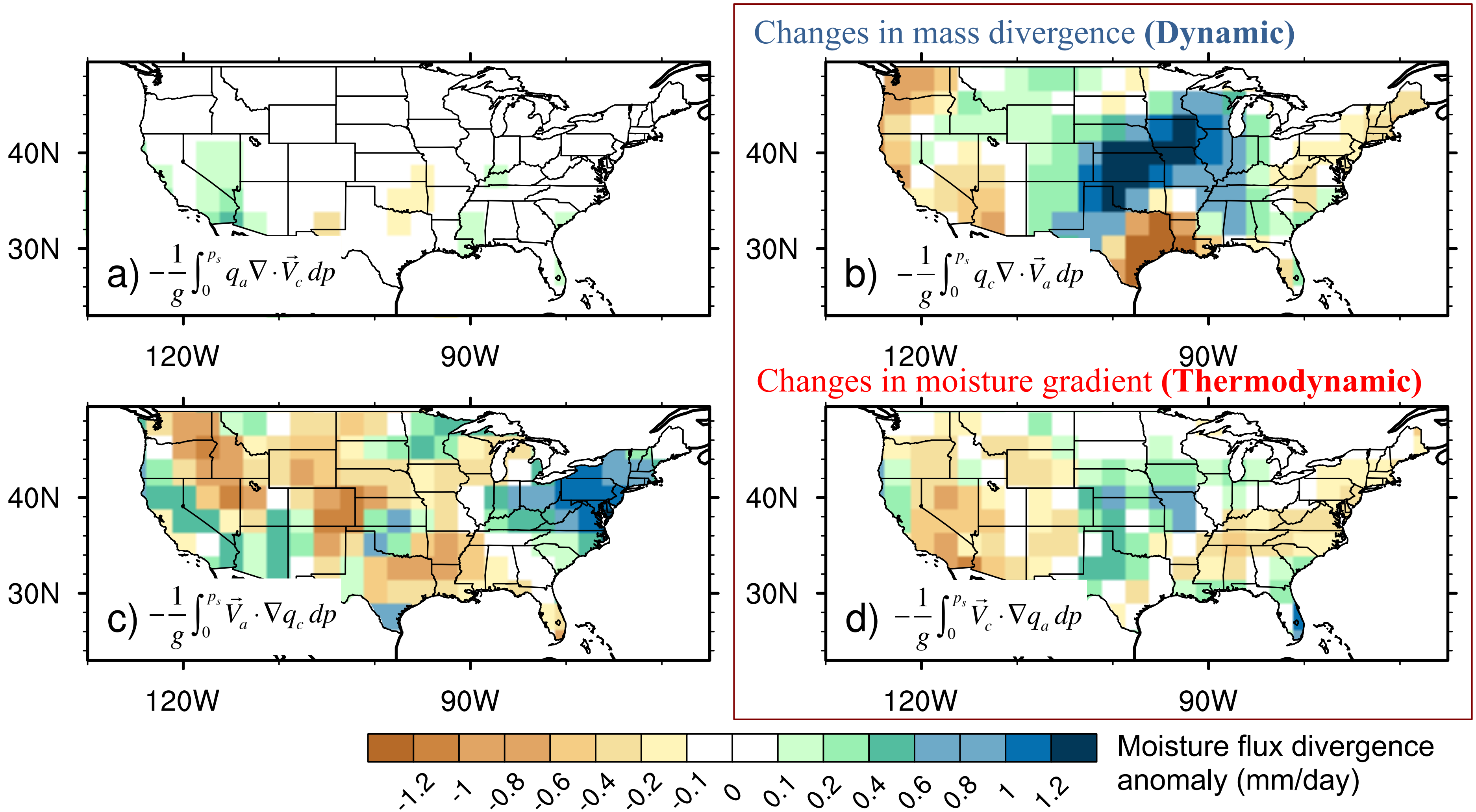
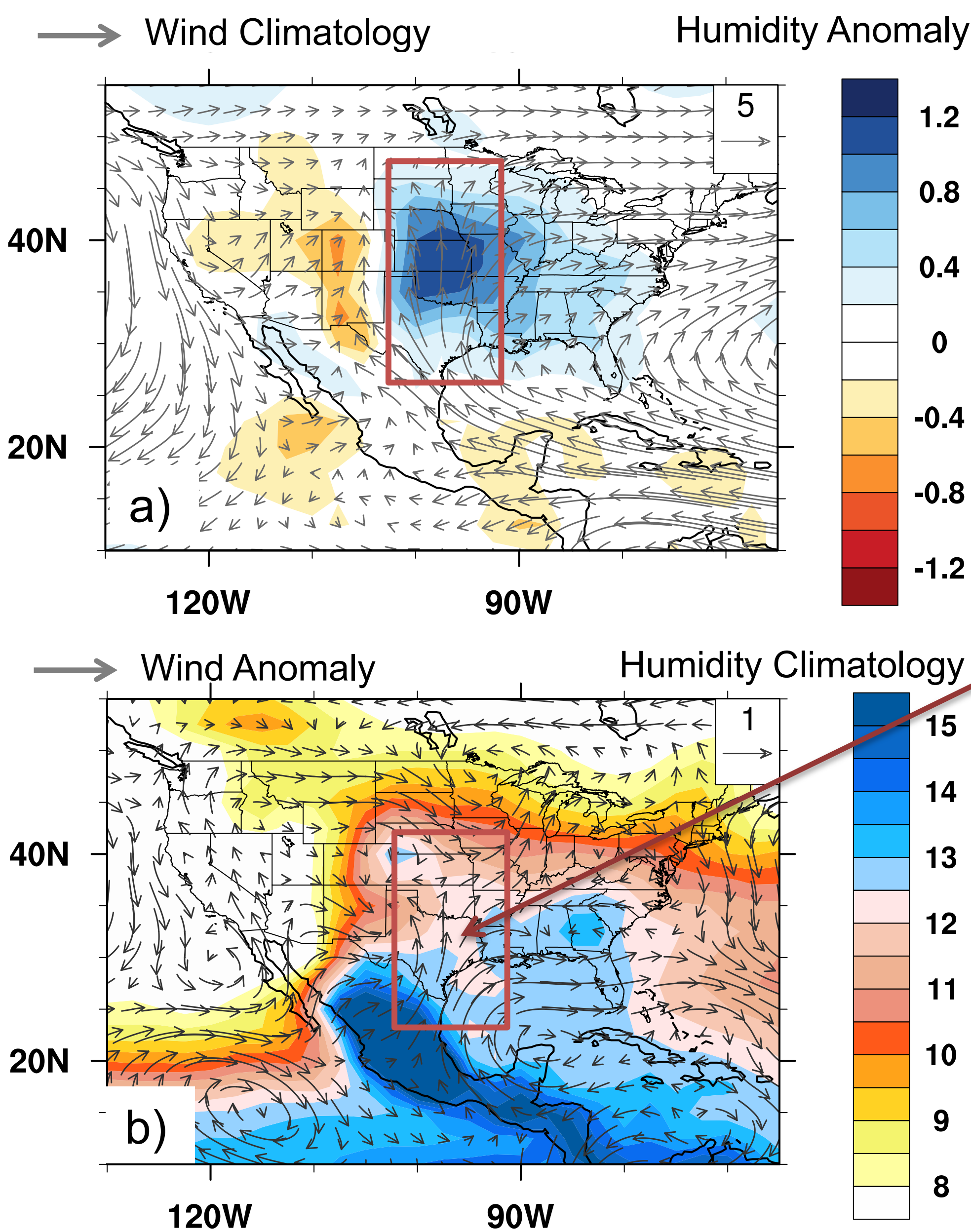
Puzzle 2: What Cause Rainfall Anomaly?

Increased summer rainfall in the Midwest results from a combination of dynamic and thermodynamic processes



Lower Tropospheric Circulation Features



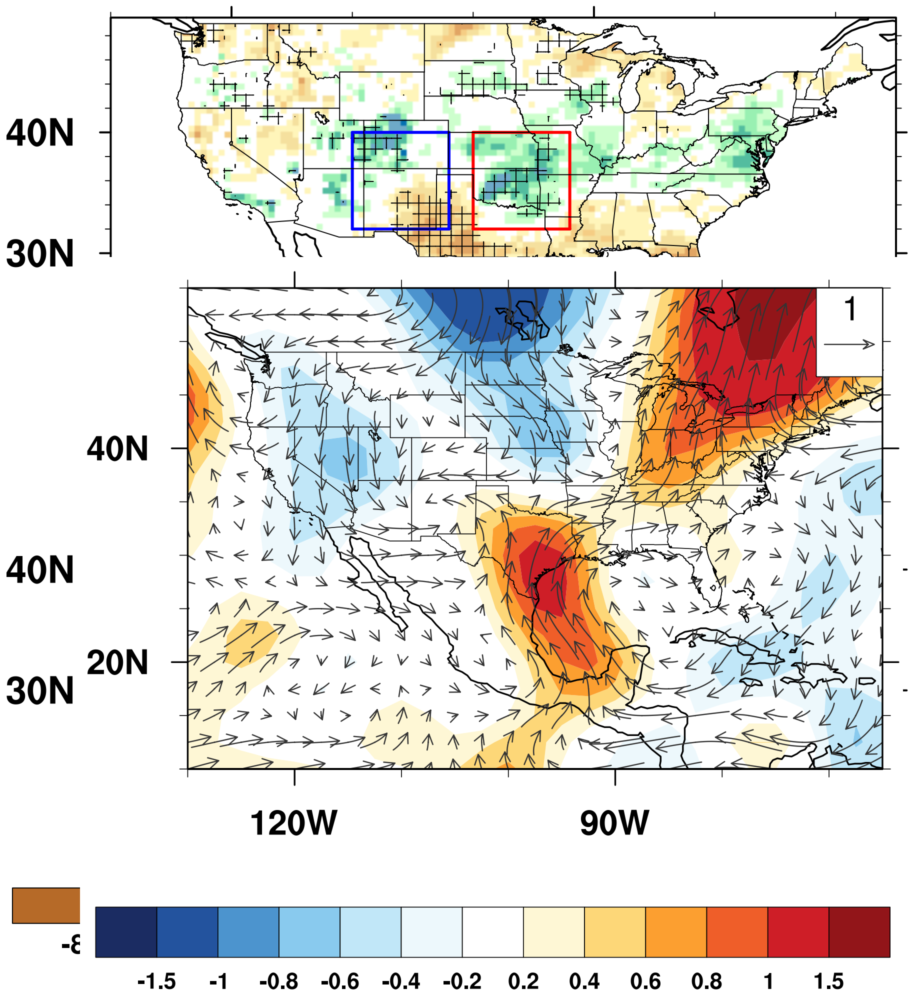
Intensification of meridional moisture gradient along 36N → ***Thermodynamically*** increase moisture convergence in the Midwest

Intensification of Great Plains Low-Level Jet (GPLLJ) → ***Dynamically*** increase moisture convergence in the Midwest

JJA Lower tropospheric a) wind anomalies (vectors, units: m/S) and b) moisture content anomalies (shaded, units: g/Kg) composite on North Atlantic northwest SSS index. In a) the shaded is the climatology of JJA moisture content (unit: g/Kg); and in b) the vectors are the climatology of lower-tropospheric wind.

Puzzle 3: What Extend Springtime SSS Signal to Summer Precipitation?

Springtime SSS signal is extended to summer precipitation due to the dual effects of soil moisture on regional water cycle.



Effects #1:

Increased soil moisture → moisten the lower troposphere → Thermodynamic effects on moisture flux convergence

Effects #2:

Increased east-west ***soil moisture gradient*** along the southern slope of the Rockies→ intensify GPLLJ → Dynamic effects on moisture flux convergence

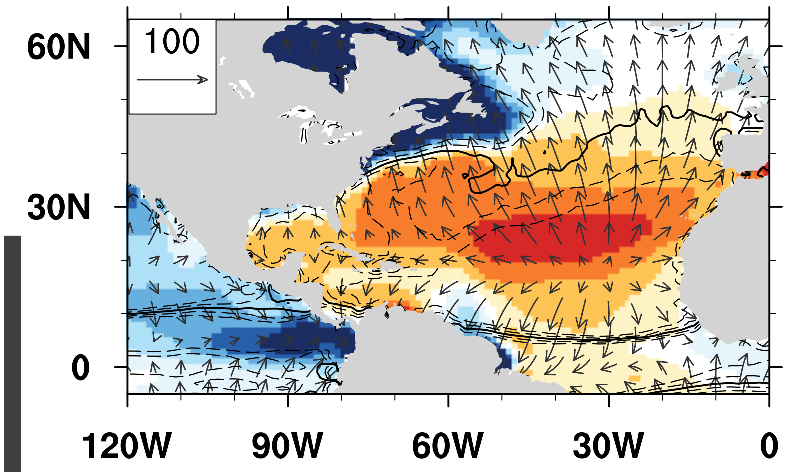
Summary: “SSS-Midwest Rainfall Relationship”

NW SSS is a physically meaningful predictor of Midwest rainfall

Spring to Summer

Puzzle 3: What extend the springtime signal?

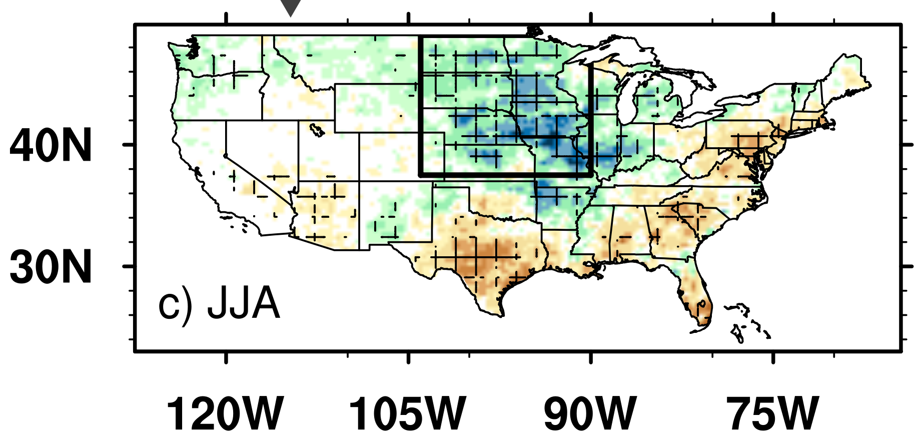
Soil moisture extends the initial moisture flux signal and provides dual effects on rainfall.



Spring SSS

Puzzle 1: What cause SSS anomalies?

Increased local moisture export results in higher SSS over the NW subtropical North Atlantic



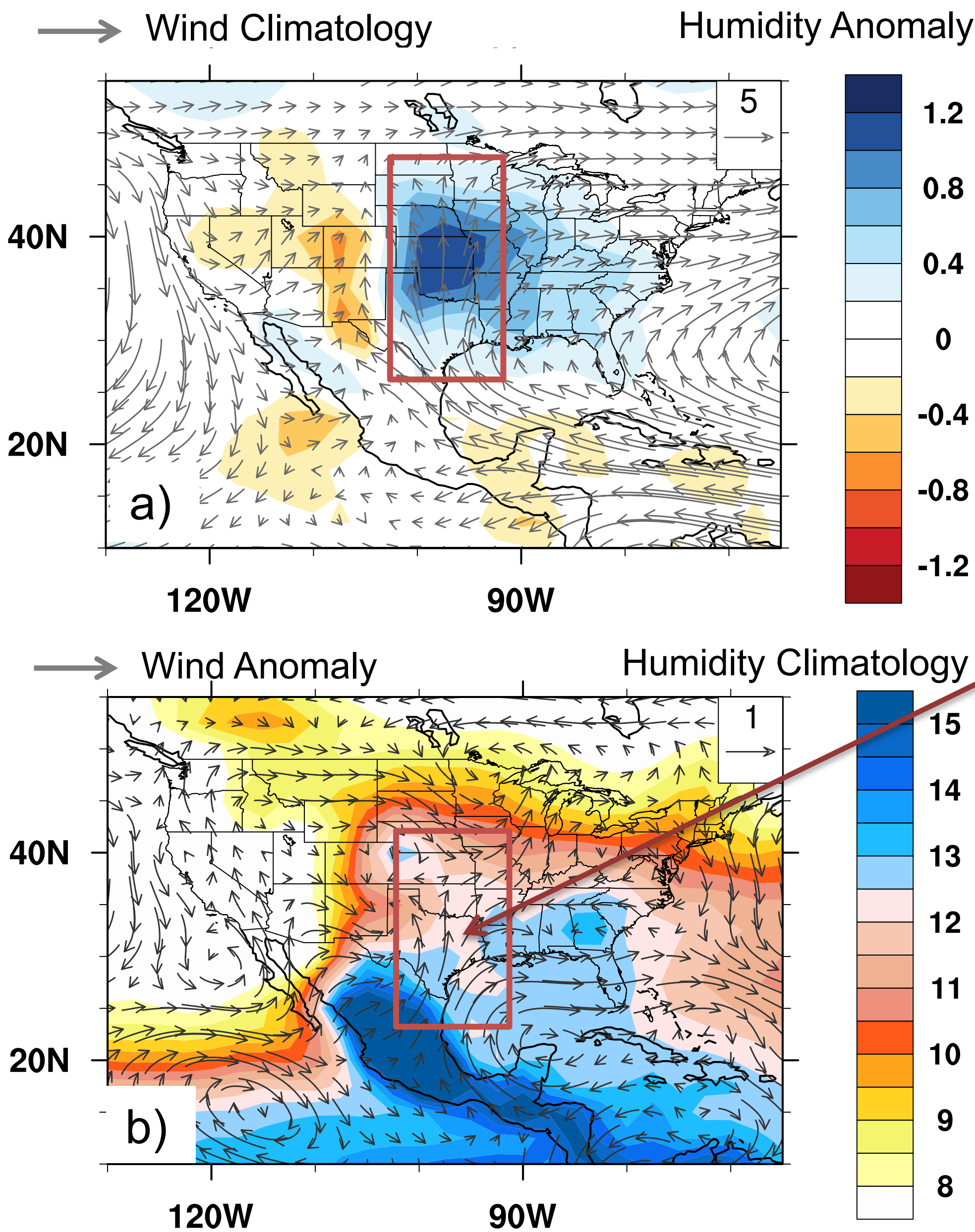
Summer Precipitation

Puzzle 2:

What causes rainfall anomalies?

Both atmospheric dynamics (intensification of low-level jet) and thermodynamics (increases in moisture content) contributes to increased precipitation in the Midwest

Lower Tropospheric Circulation Features



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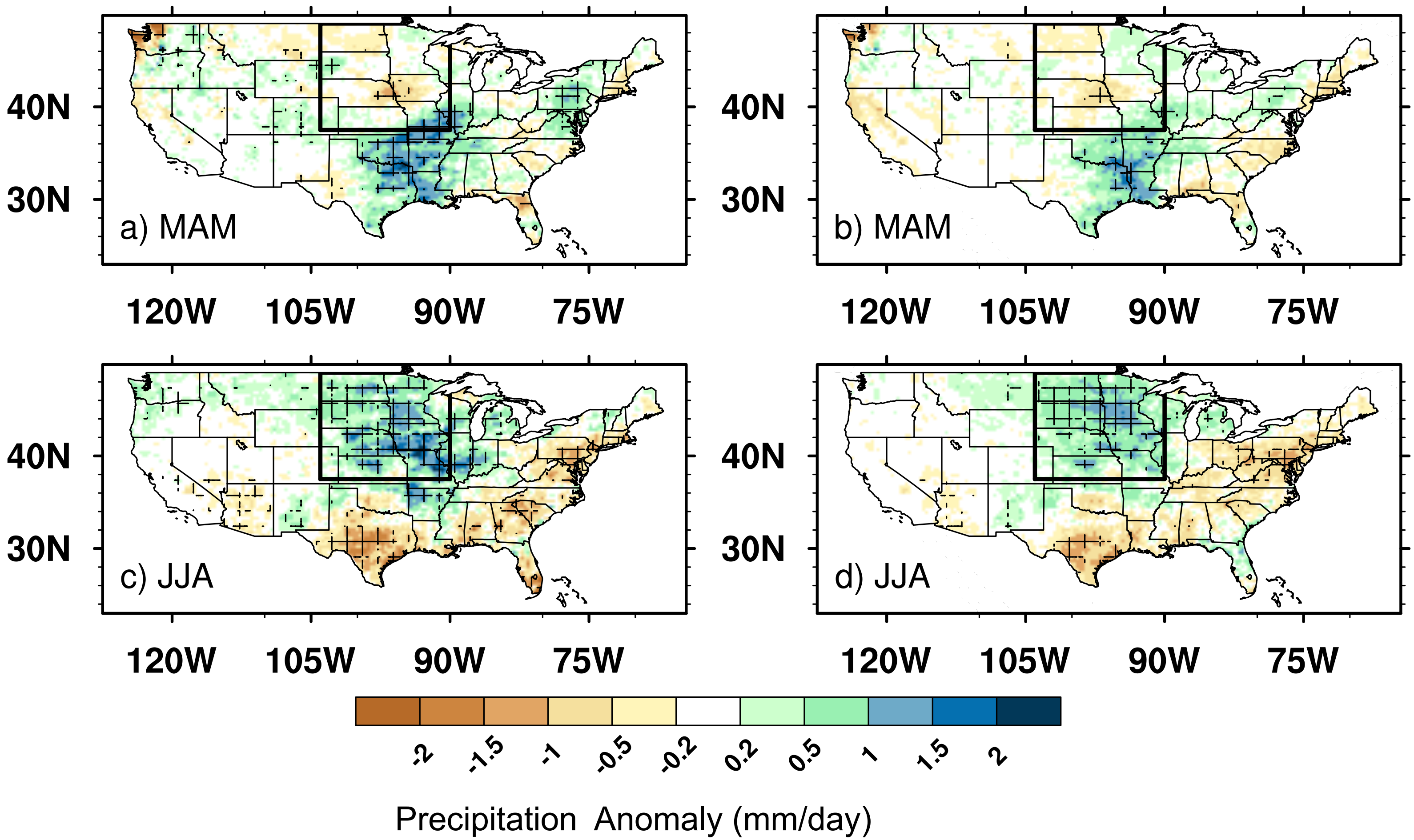
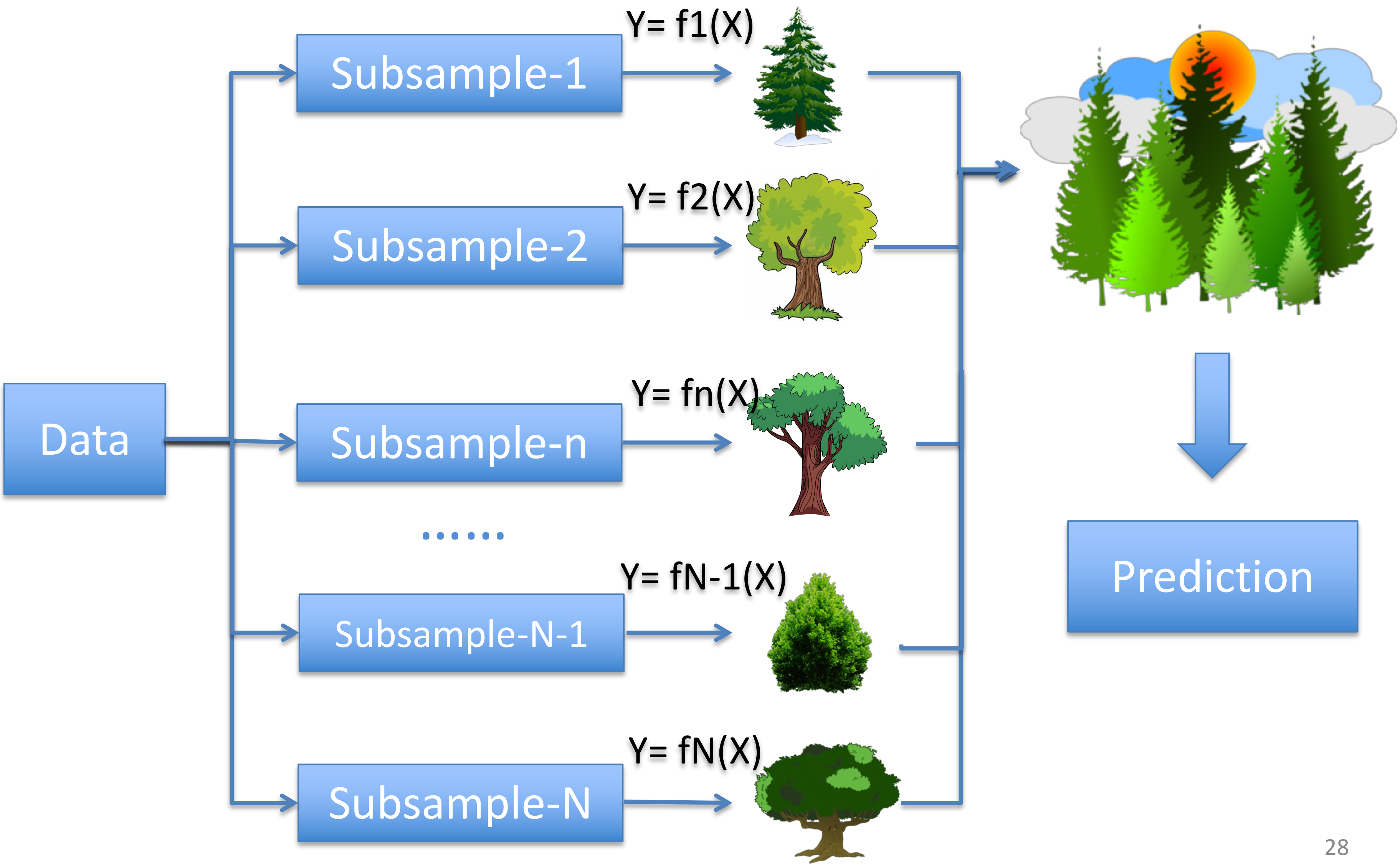
Springtime NW SSS and US Precipitation



Predicting Midwest Precipitation Using NW SSS:

Random Forest Algorithm



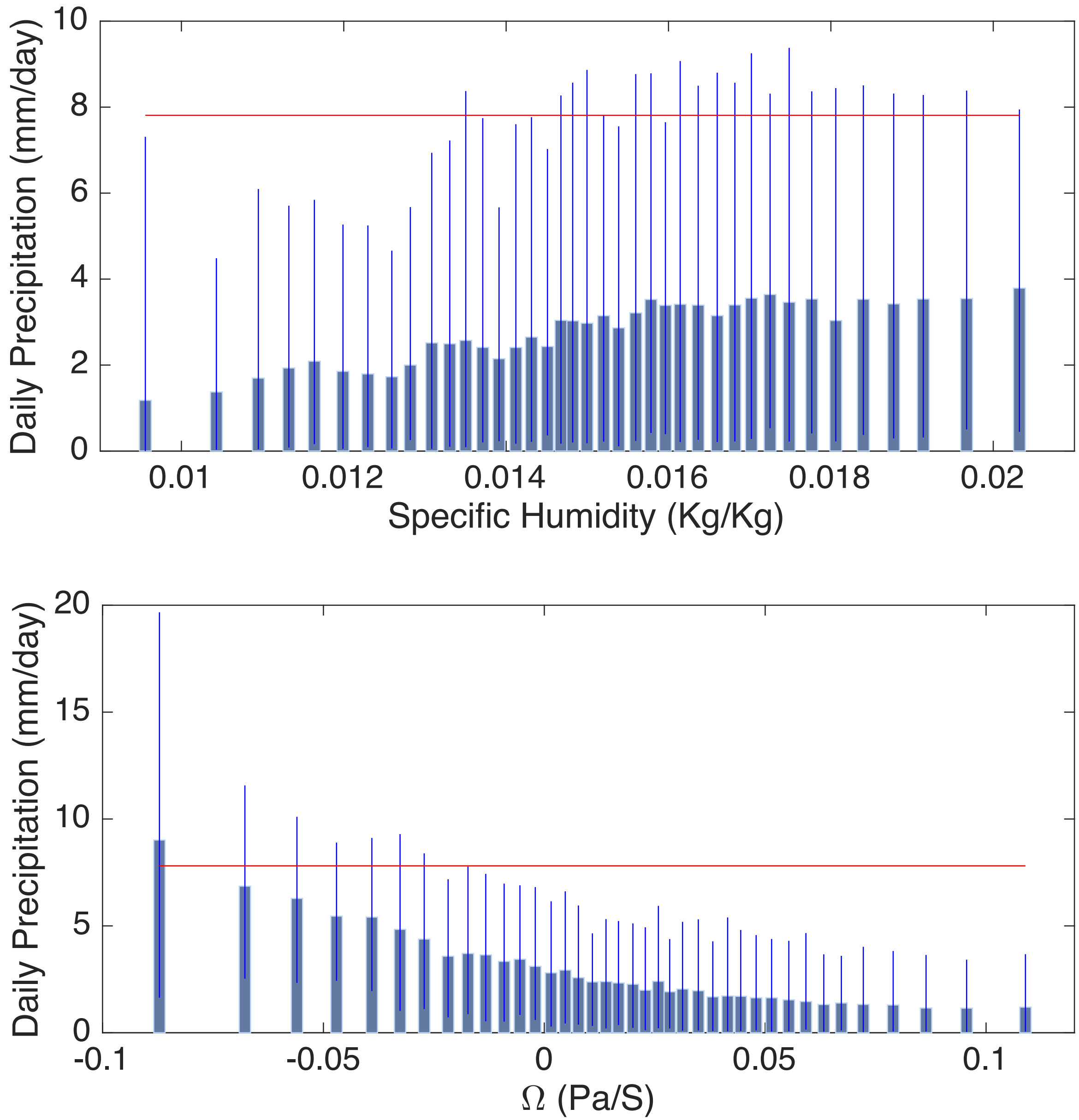


Figure 2 | US Midwest daily precipitation versus specific humidity (upper panel) and 500hPa vertical motion (lower panel). The bars are averaged precipitation rate at each humidity and vertical motion quantile. The error bars are the 95% uncertainty range of the precipitation. The red lines are the threshold value of US Midwest extreme precipitation.

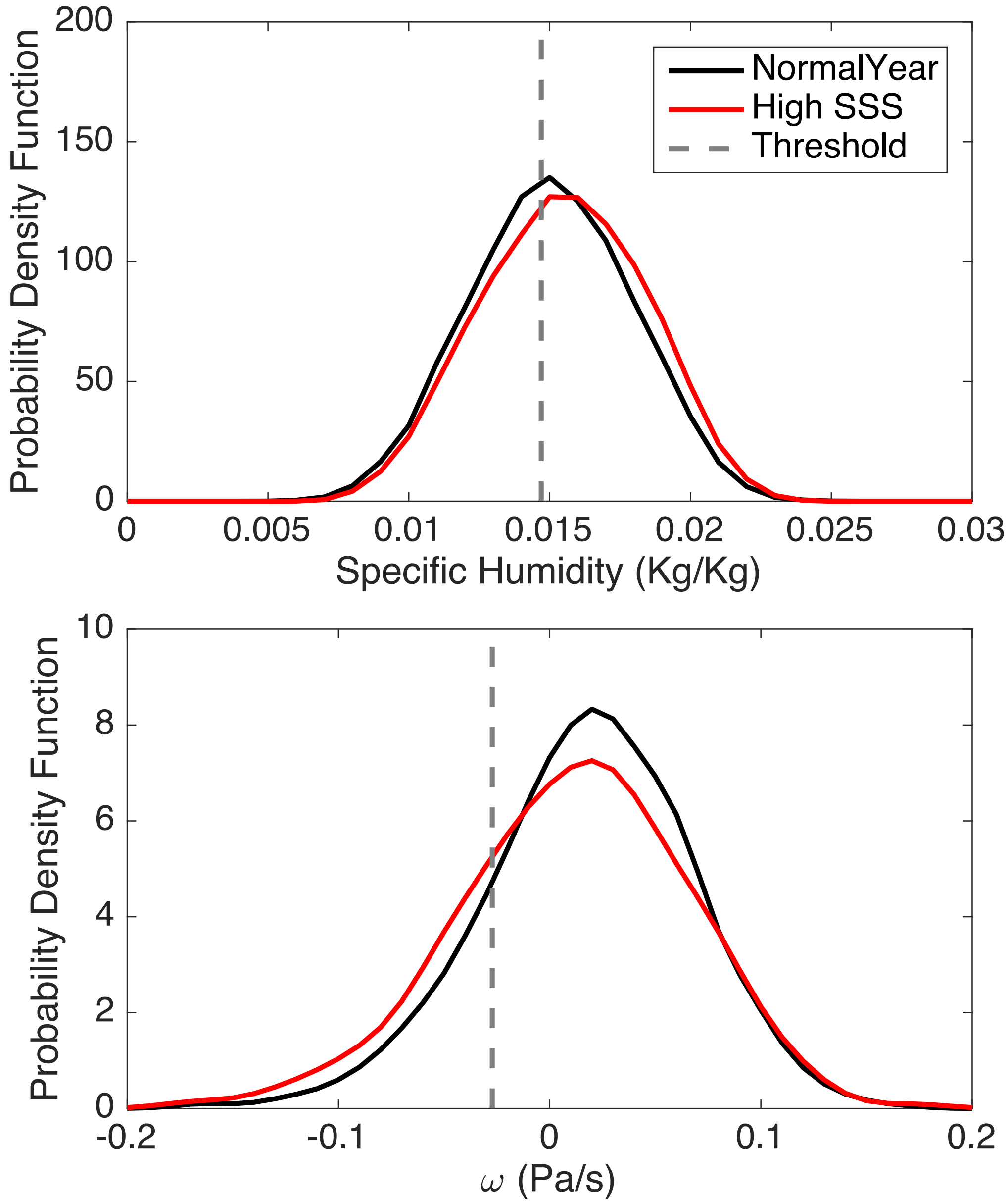
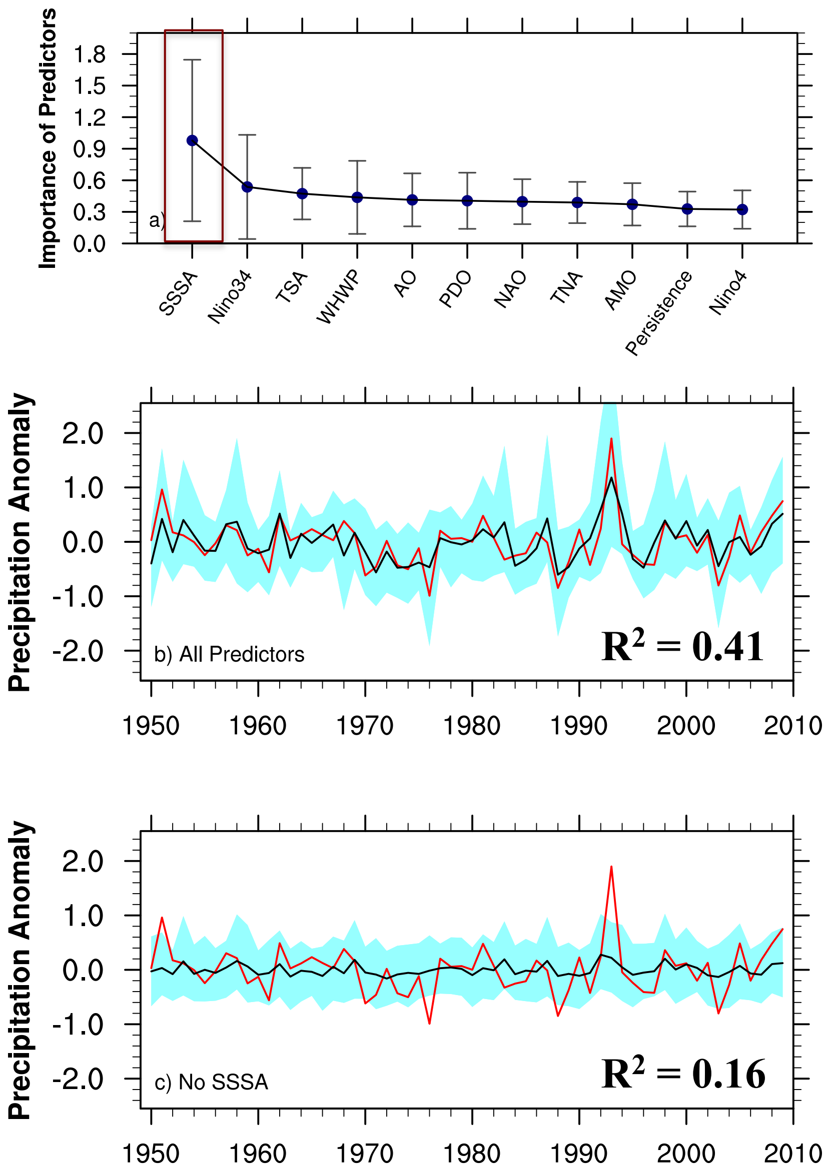


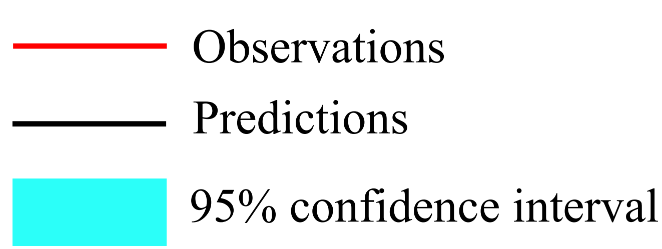
Figure 3 | Probability density function of US Midwest specific humidity (upper panel) and 500hPa vertical motion (lower panel) in the summer season. The black curves are the normal year condition. The red curves are the years with top decile SSS in the subtropical North Atlantic. The dashed line is the threshold value of thermodynamic and dynamic condition needed for extreme precipitation.

Predicting US Midwest Summer Precipitation

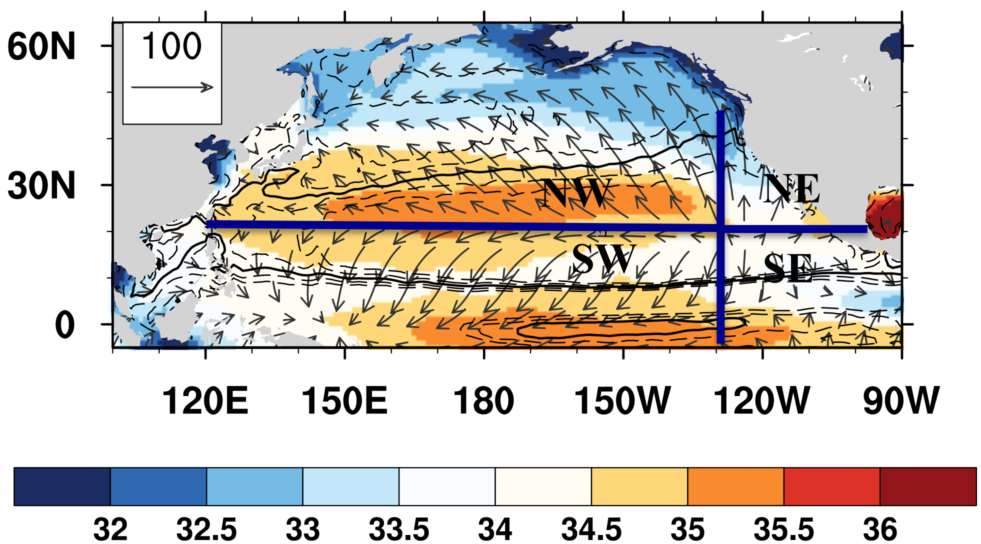
Knowledge of NW SSS can improve rainfall prediction in US Midwest



Climate Indice	Correlation with NW SSS
AMO	-0.09
AO	-0.03
NAO	-0.06
Nino 3.4	0.04
Nino 4	-0.03
PDO	-0.14
TNA	-0.10
TSA	-0.05
WHWP	-0.05



North Pacific Subtropical SSS Indices



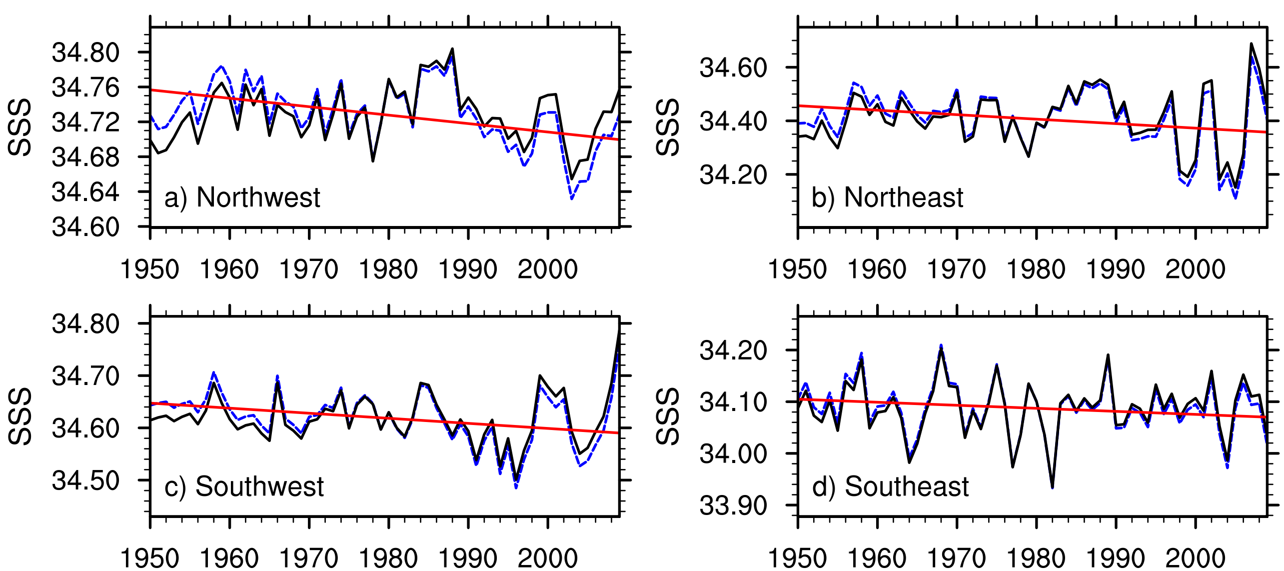


Figure 2 | MAM salinity (blue contours) in the 4 subdomains of subtropical North Pacific: a) Northwest, b) Northeast, c) Southwest, d) Southeast. The red lines are linear trend of the salinity index. The black contours are the detrended salinity time series.

North Atlantic Subtropical SSS Indices

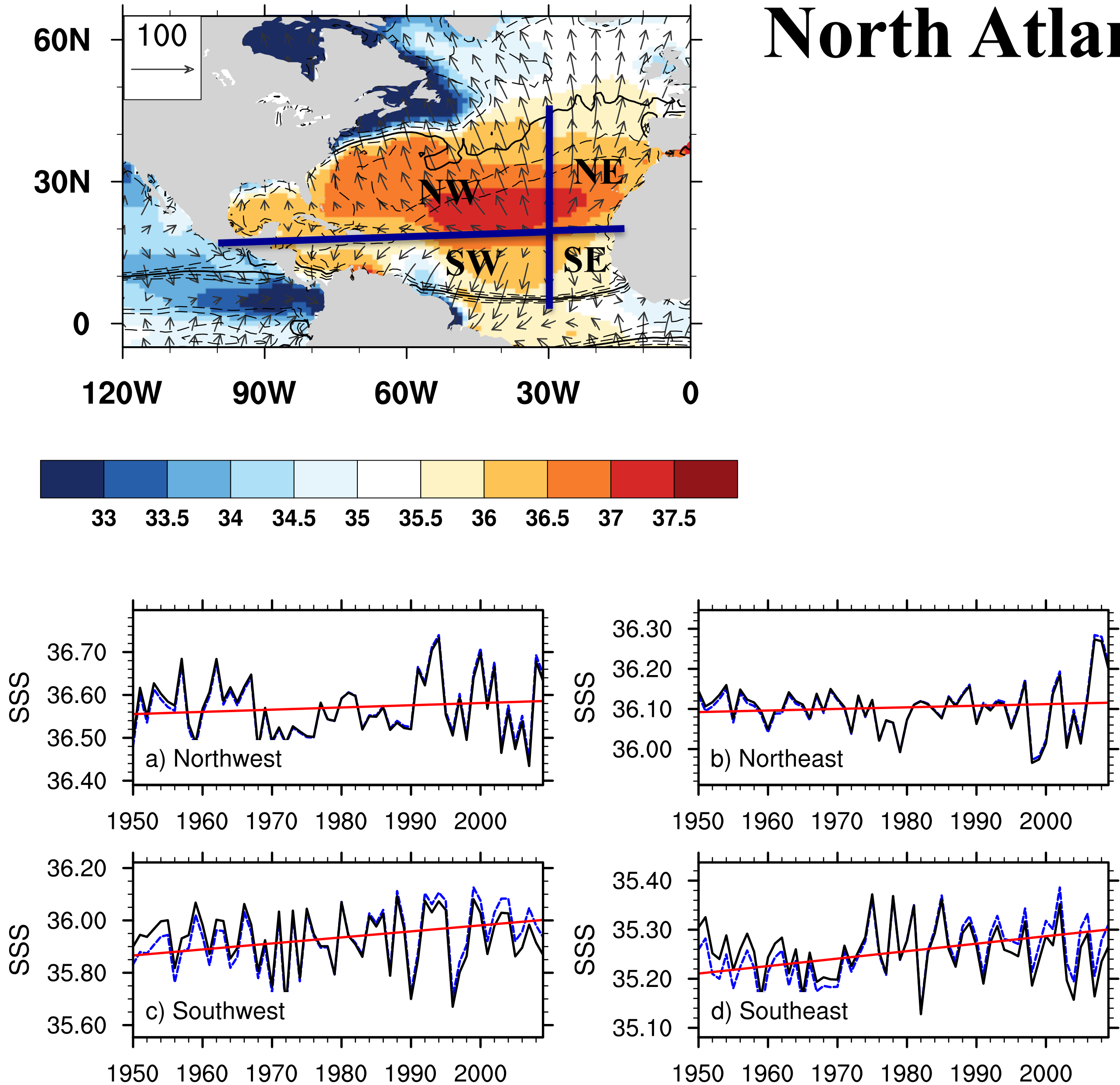
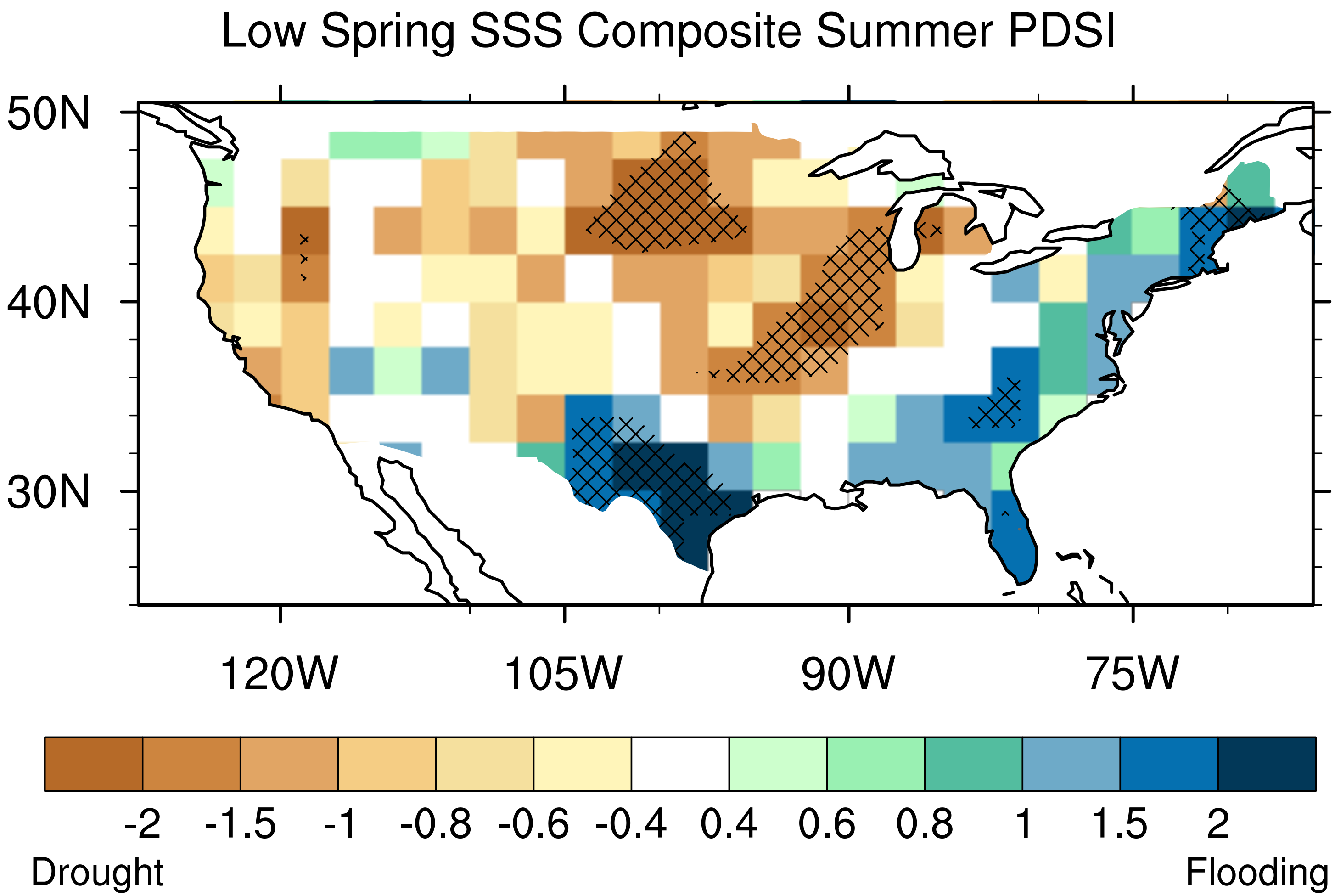


Figure 4 | MAM salinity (blue contours) in the 4 subdomains of subtropical North Atlantic: a) Northwest, b) Northeast, c) Southwest, d) Southeast. The red lines are linear trend of the salinity index. The black contours are the detrended salinity time series.

Salinity Precursor and US Drought



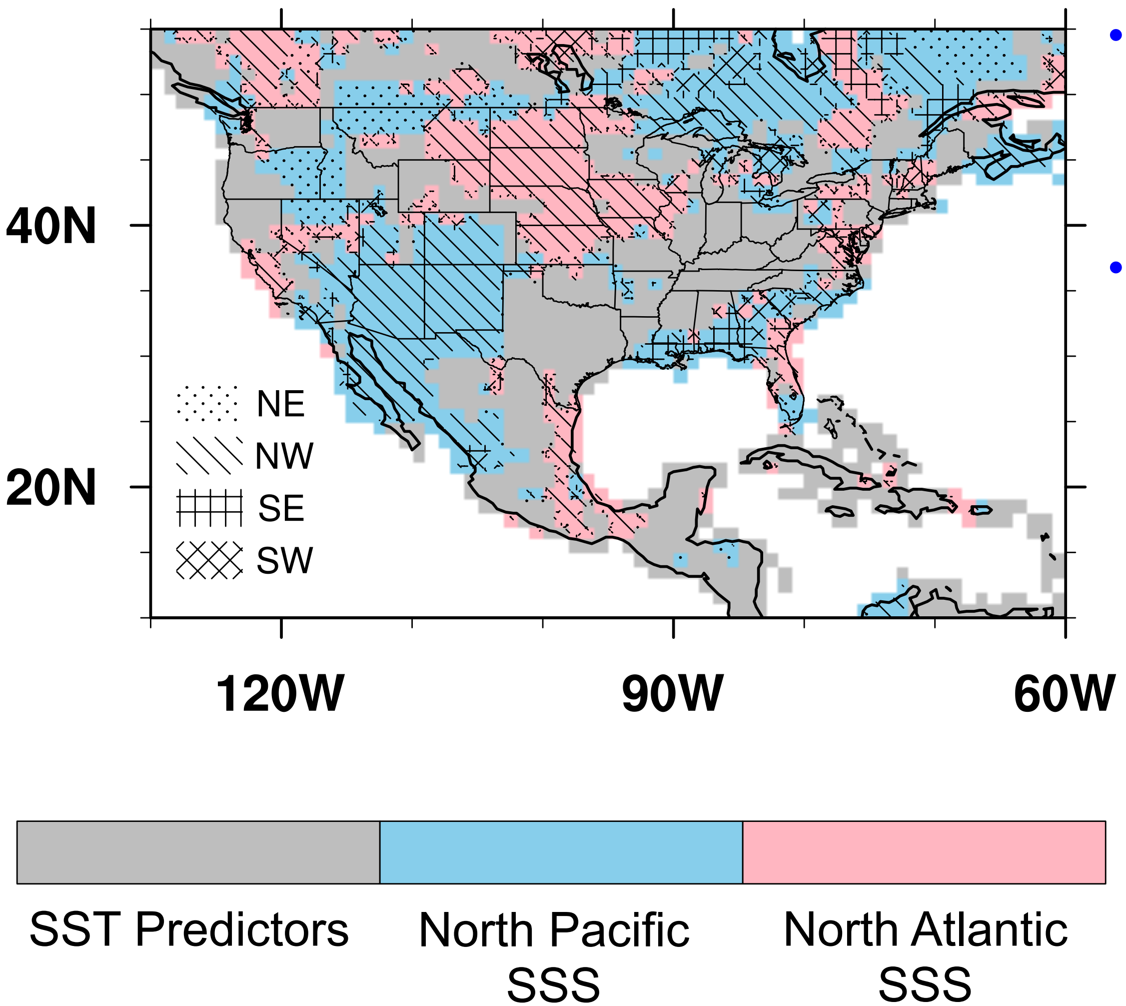
Summary

North Atlantic SSS Provides Predictive Value to summer precipitation over the US Midwest

- SSS over the northwestern portion of the subtropical North Atlantic is indicative of summer precipitation over the US Midwest
- The SSS-Midwest precipitation relationship is established through ocean-to-land moisture transport and the dual effects of soil moisture on regional water cycle
- The SSS indices outweighs SST-based predictors in seasonal forecast of Midwest summer precipitation

Concluding Remarks

SSS provides important skill to predict terrestrial precipitation



- North Atlantic subtropical SSS is most important for prediction precipitation over the US Midwest.
- North Pacific subtropical SSS is the most important predictor for summer precipitation over the North American monsoon region.

The most important predictor for US summer (JJA) precipitation according to the random forest algorithm: gray shaded denotes regions where SST predictors (the first two SSTA mode time series in each of the three ocean basins) have the most skillful prediction. The blue and red shaded are where the most important predictor is North Pacific and North Atlantic SSS, respectively.