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

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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$^{-1}$).

Moisture source regions: Subtropical oceans

Evaporation > Precipitation → net moisture export: Moisture sources
Precipitation > Evaporation → net moisture input: Moisture sinks
Oceanic moisture & terrestrial precipitation

Evaporation $\rightarrow$ Precipitation $\rightarrow$ net moisture export: Moisture sources
Precipitation $\rightarrow$ Evaporation $\rightarrow$ 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.
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:

\[ P \sim -\frac{1}{g} \nabla \cdot \int_{0}^{p_s} \bar{q} \bar{V} dp \]

\[ -\frac{1}{g} \nabla \cdot \int_{0}^{p_s} \bar{q} \bar{V} dp = -\frac{1}{g} \int_{0}^{p_s} \bar{q} \nabla \cdot \bar{V} dp - \frac{1}{g} \int_{0}^{p_s} \bar{V} \cdot \nabla \bar{q} dp \]

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

\(_c: \text{climatology; } _a: \text{anomalies}\)

\[ -\frac{1}{g} \int_{0}^{p_s} q \nabla \cdot \bar{V} dp = -\frac{1}{g} \int_{0}^{p_s} q_c \nabla \cdot \bar{V}_c dp - \frac{1}{g} \int_{0}^{p_s} q_c \nabla \cdot \bar{V}_a dp - \frac{1}{g} \int_{0}^{p_s} q_a \nabla \cdot \bar{V}_c dp - \frac{1}{g} \int_{0}^{p_s} q_a \nabla \cdot \bar{V}_a dp \]

Mass Divergence

\[ -\frac{1}{g} \int_{0}^{p_s} \bar{V} \cdot \nabla q dp = -\frac{1}{g} \int_{0}^{p_s} \bar{V}_c \cdot \nabla q_c dp - \frac{1}{g} \int_{0}^{p_s} \bar{V}_a \cdot \nabla q_c dp - \frac{1}{g} \int_{0}^{p_s} \bar{V}_c \cdot \nabla q_a dp - \frac{1}{g} \int_{0}^{p_s} \bar{V}_a \cdot \nabla q_a dp \]

Moisture Gradient
What cause rainfall anomaly?

Combination of dynamic and thermodynamic processes

Changes in moisture gradient (Thermodynamic)

Changes in mass divergence (Dynamic)

Moisture flux convergence anomaly (mm/day)
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

Data

Subsample-1

\( Y = f_1(X) \)

Subsample-2

\( Y = f_2(X) \)

Subsample-n

\( Y = f_n(X) \)

Subsample-N-1

\( Y = f_{N-1}(X) \)

Subsample-N

\( Y = f_N(X) \)

……

Prediction
Predicting Midwest summer precipitation

Knowledge of NW SSS can improve rainfall prediction in US Midwest

a) Importance of Predictor

![Importance of Predictor Graph]

- SSSA
- Nino34
- TSA
- WHWP
- AO
- PDO
- NAO
- TNA
- AMO
- Persistence
- Nino4

b) All Predictors

![All Predictors Graph]

1993
2008

R² = 0.41

R² = 0.16

95% confidence interval

- Red: Observations
- Black: Predictions
Case Study: 2015 US Summer Precipitation

Salty subtropical N. Atl. ~ wet summer in Midwest

2015 Precipitation Anomaly

From Li et al. (2018), Climate Dynamics
Salinity precursor & extreme daily precipitation

Probability Density Function

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.

![Graph showing likelihood of extreme precipitation and normalized SSS](image)

- **SSSA PDF (low precipitation)**
- **SSSA PDF (high precipitation)**
- **Frequency of extreme daily precipitation**
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.
North Atlantic salinity as a predictor of Sahel rainfall

A) SSSA and ENSO

B) SSSA

C) ENSO

\[
R^2 = 0.40
\]

\[
R^2 = 0.34
\]

\[
R^2 = 0.06
\]
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.

![Map showing moisture flux divergence anomalies](image)
Puzzle 2: What Cause Rainfall Anomaly?

Methods: Thermodynamic and dynamic decomposition of regional water cycle

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

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

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

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

- \frac{1}{g} \int_0^{p_s} q \nabla \cdot \vec{V} dp = -\frac{1}{g} \int_0^{p_s} q_c \nabla \cdot \vec{V}_c dp - \frac{1}{g} \int_0^{p_s} q_a \nabla \cdot \vec{V}_a dp

- \frac{1}{g} \int_0^{p_s} \vec{V} \cdot \nabla q dp = -\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_a dp
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 (GPLLLJ) ➔ *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

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.
Springtime NW SSS and US Precipitation

(a) MAM
(b) MAM
(c) JJA
(d) JJA

Precipitation Anomaly (mm/day)
Predicting Midwest Precipitation Using NW SSS:
Random Forest Algorithm

Data → Subsample-1 → Y = f1(X) → Prediction
Data → Subsample-2 → Y = f2(X) → Prediction
Data → Subsample-n → Y = fn(X) → Prediction
Data → Subsample-N-1 → Y = fN-1(X) → Prediction
Data → Subsample-N → Y = fN(X) → Prediction
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

<table>
<thead>
<tr>
<th>Climate Indice</th>
<th>Correlation with NW SSS</th>
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<tbody>
<tr>
<td>AMO</td>
<td>-0.09</td>
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<tr>
<td>AO</td>
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<tr>
<td>NAO</td>
<td>-0.06</td>
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<tr>
<td>Nino 3.4</td>
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<td>PDO</td>
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<td>WHWP</td>
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</tr>
</tbody>
</table>

- $R^2 = 0.41$
- 95% confidence interval
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.
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.