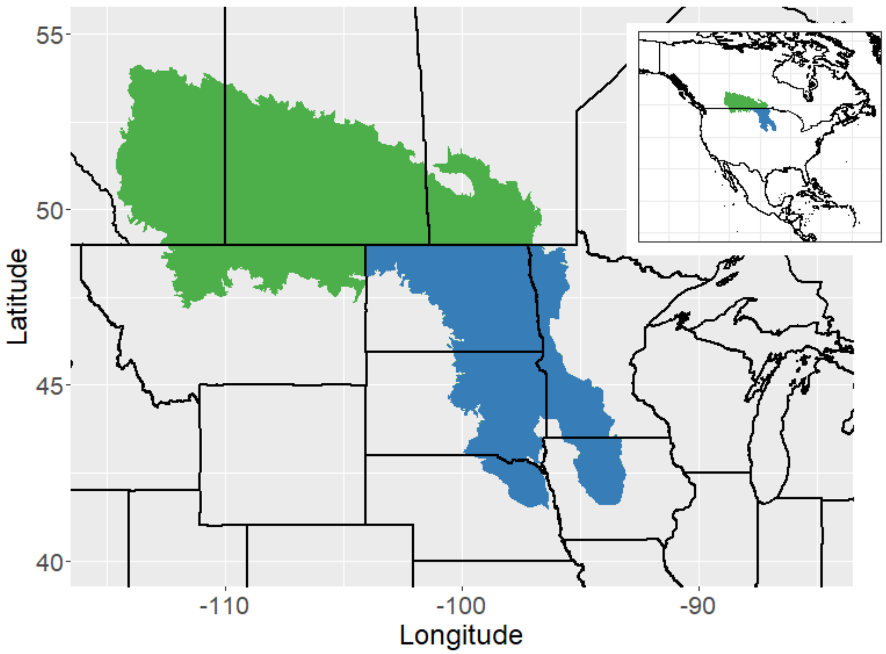

Understanding and projections of space-time variability of summer hydroclimate and ecology in the United States Prairie Pothole Region

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University of Colorado Boulder

CIRES

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THE EARTH INSTITUTE AT COLUMBIA UNIVERSITY

NOAA

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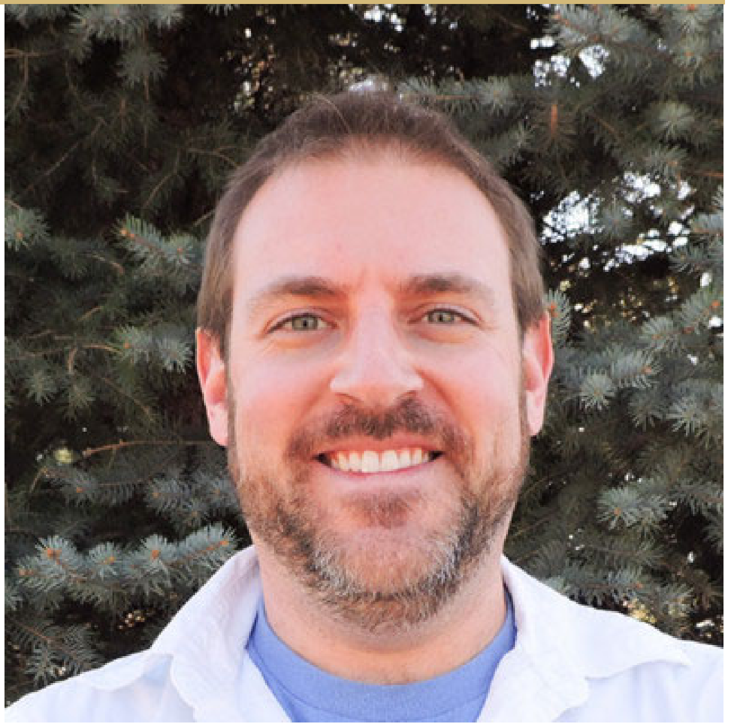
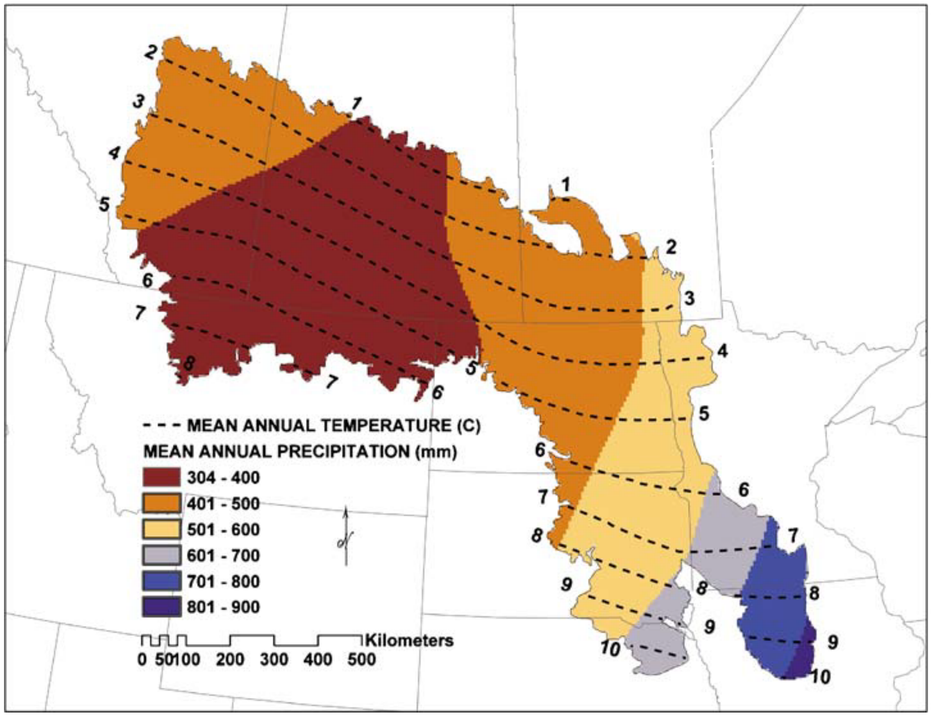


The Prairie Pothole Region (PPR)

- Unique, important habitat in northern Great Plains
  - Millions of wetlands, vast grasslands
- Many species not found elsewhere
- Waterfowl breeding grounds, floodwater storage, carbon storage
- Pheasants, deer, over 300 other species depend on wetlands
- Vegetation used for nesting, foraging, and shelter

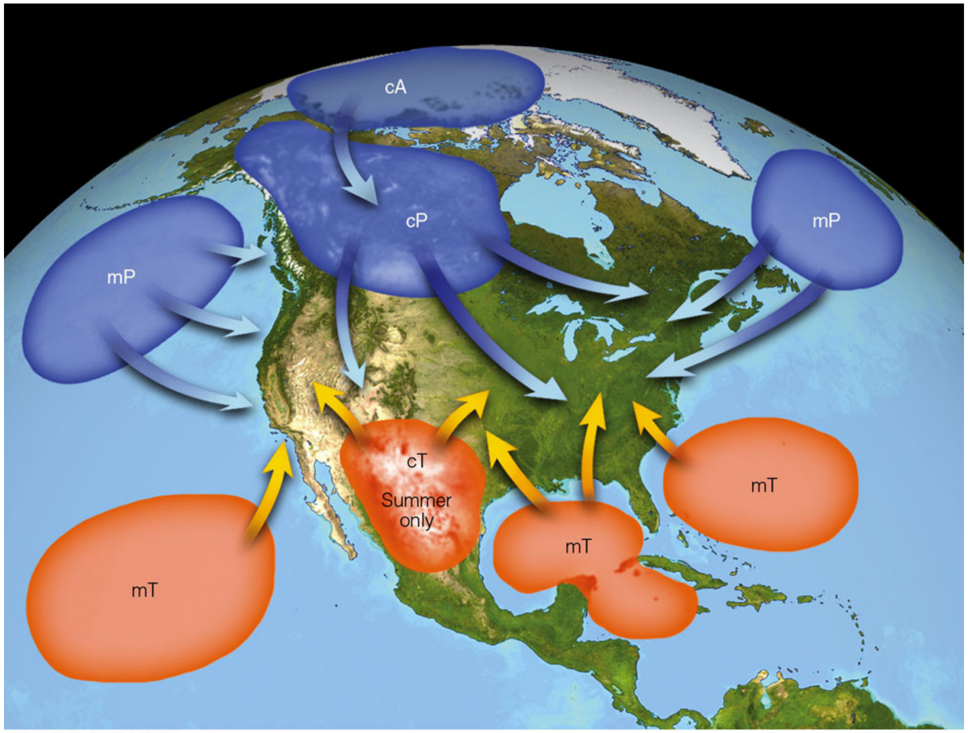
PPR Climate

- Dry (potential evapotranspiration > precipitation) (Winter 1989)
- Cold winters –> snow accumulation (Hayashi 2016)
- Average temperature and precipitation increasing (Millett et al 2009)
  - Differences in this trend at finer temporal and spatial scale (e.g. T_{min} warmed, T_{max} cooled)
- East-west precipitation gradient
  - Steepened over past century - northwest precipitation decreasing, southeast precipitation increasing
- North-south temperature gradient



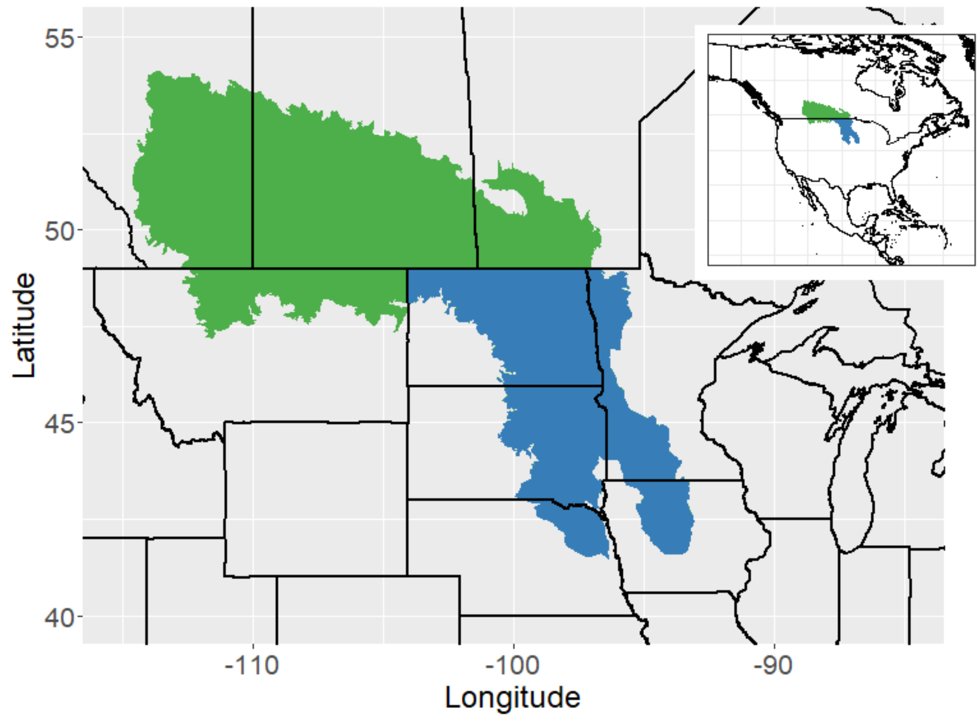
PPR Climate Variability

- Temperature and precipitation variability
  - Temporal and spatial
- Three competing air masses (cP, mP, mT) (Brunnschweiler 1954, Bryson and Hare 1974)
- Missouri River basin – flood in 2011, drought in 2012 (Conant et al 2018)
- Climate change and variability expected to increase
  - Droughts and heat waves projected to occur more frequently (Conant et al 2018)

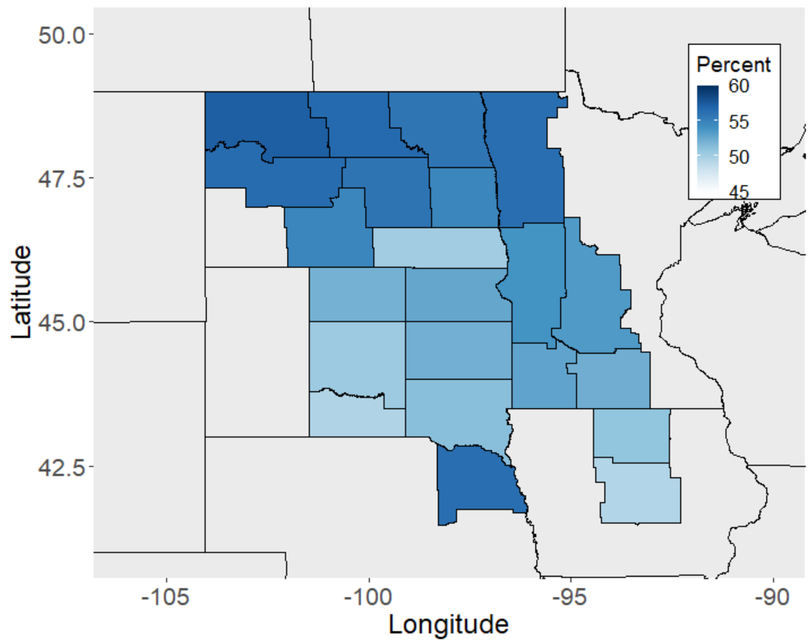


Southeast PPR (SEPPR)

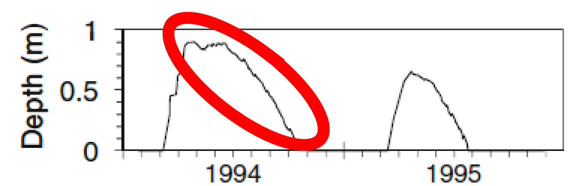
- "Shift" in precipitation southeast (Ballard et al 2014, Johnson and Poiani 2016, McKenna et al 2017)
- Most productive habitat for breeding waterfowl – shift from center to southeast (Johnson et al 2005)
- Agricultural modifications – numerous and impactful

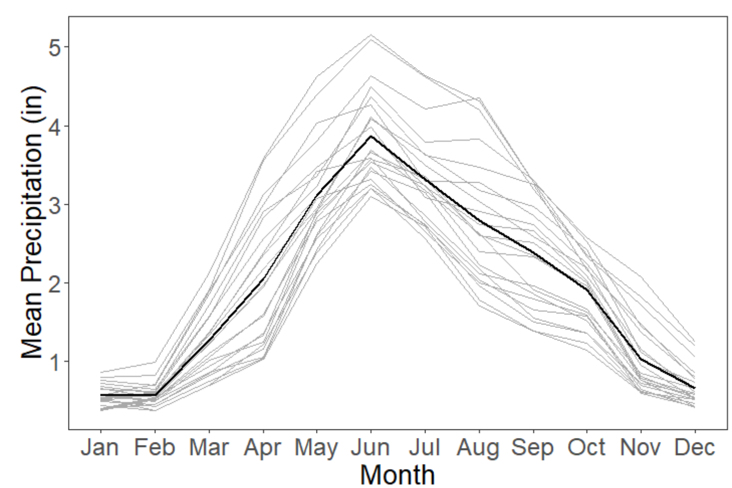


Importance of Summer



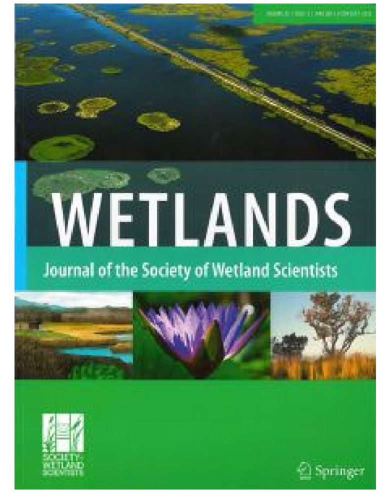
- Can contribute approximately **<u>half of the annual precipitation</u>** (Rosenberry 2003, Vecchia 2008)
- June, July, August – first, second, and fourth wettest months historically (Rosenberry 2003)





- Ponds **<u>receive most inflows</u>** from snowmelt and ***summer precipitation*** (Winter et al 2000)
  - Summer rainfall **<u>sustains wetlands</u>** (Hayashi et al 2016)

PPR Past Work



Climate change and variability

- Millett et al. 2009 – climate trends of PPR
- 25-year modeling study (Johnson and Poiani 2016) – physical model built from ground up; grew in complexity over time
  - Wetlands **sensitive to climate change and variability**
  - Shorter wetland hydroperiods **affect vertebrates**
  - Warmer, drier climate will **decrease functional wetlands and associated habitat**
- Ballard et al. 2014 – analysis of hydroclimate variability and change using CMIP5
  - Precipitation will increase in all seasons **except summer**, but offset by increased evapotranspiration

Moisture sources and pathways

- **Great Plains Low Level Jet (GPLLJ)** – Song et al. 2019 found GPLLJ patterns
- **Land** as moisture source (Brubaker et al. 2001, Dirmeyer and Kinter 2010)
- **GoM** – 1993 and 2008 Midwest floods sourced all the way from GoM (Dirmeyer and Kinter 2009)

Point of Departure

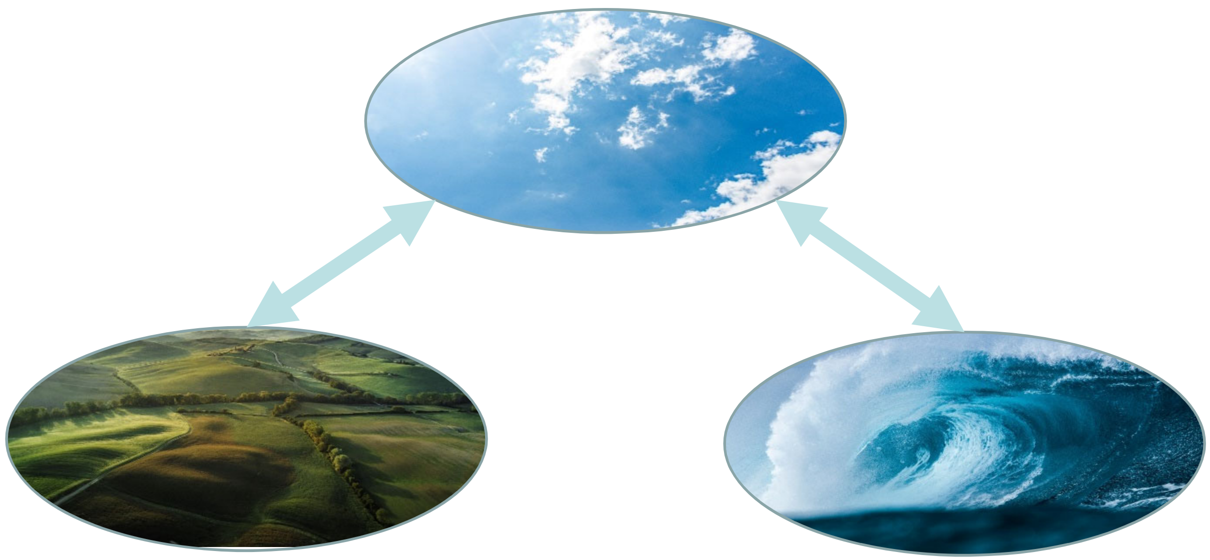
Though a great deal of research has been done on the PPR, a crucial gap for summer hydroclimate and ecology in the SEPPR exists:

- Lack of direct investigation into large-scale teleconnections and potential mechanisms of climate variability
- Studies identifying primary moisture sources for Great Plains summer precipitation exist, but none have focused on the SEPPR
- Currently available pond count predictive tools are outdated, lacking complexity
- Other available vegetation models are focused on hydrology and therefore do not directly simulate vegetation and typically do not include enough versatility

Research Questions

- What large-scale mechanisms and teleconnections influence summer precipitation variability?
- What are the dominant sources and pathways of moisture for the region's summer precipitation and extreme precipitation events?
- How well does a predictive model for pond counts perform using large-scale climate variables as predictors?
- Can wetland vegetation be adequately modeled using a point-based, physical numerical model coupled with climate information?

Important Connections



Research Question 1

What large-scale mechanisms and teleconnections influence summer precipitation variability?

Data

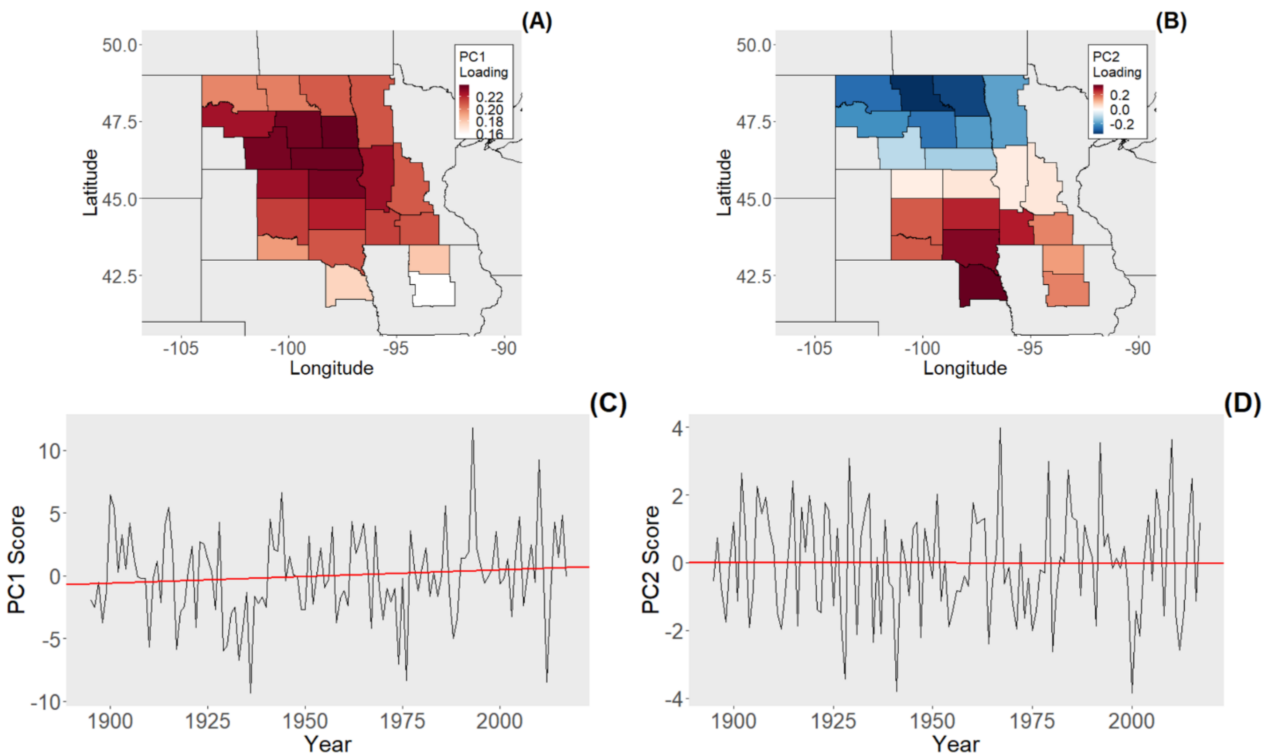
- Precipitation
  - NOAA NCEI nClimDiv
- Sea Surface Temperature (SST), 500 mb heights
  - International Research Institute (IRI) Data Library
- Palmer Drought Severity Index (PDSI)
  - NOAA ESRL PSL Climate Data Repository

Methods

- Determine main modes of variability
  - Principal Component Analysis (PCA, von Storch 1999)
- Determine teleconnections and potential mechanisms
  - Correlation maps – principal components (PCs) with SSTs, 500 mb heights, and PDSI
  - Composite analysis – top and bottom 0.15 quantile of PC1 used to extract wet and dry years and composite variables

Abel, B. D., Rajagopalan, B., Ray, A. J., 2021. Space-time variability of summer hydroclimate in the United States Prairie Pothole Region. Earth Interactions (Manuscript in peer review)

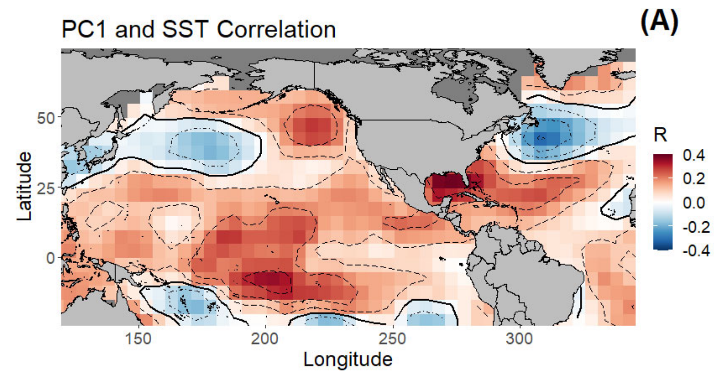
Principal Component Analysis

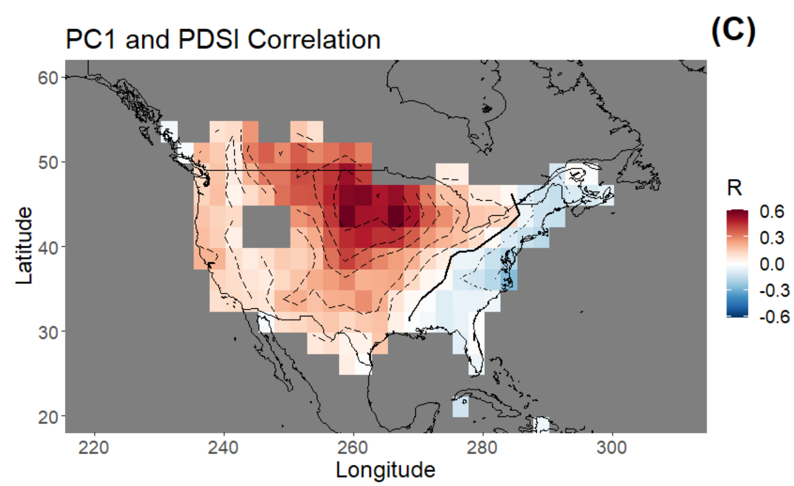


- PCA of summer precipitation by climate division
- PC1 – **54.3% of variance**; PC2 – 11.8%
  - Jana (2018) PC1, 2 – 26.97%, 12.17%
- PC1 – spatial loadings (A) indicate one causal mechanism – trend (C)
- PC2 – N-S dipole (B) indicates two primary mechanisms

Teleconnections

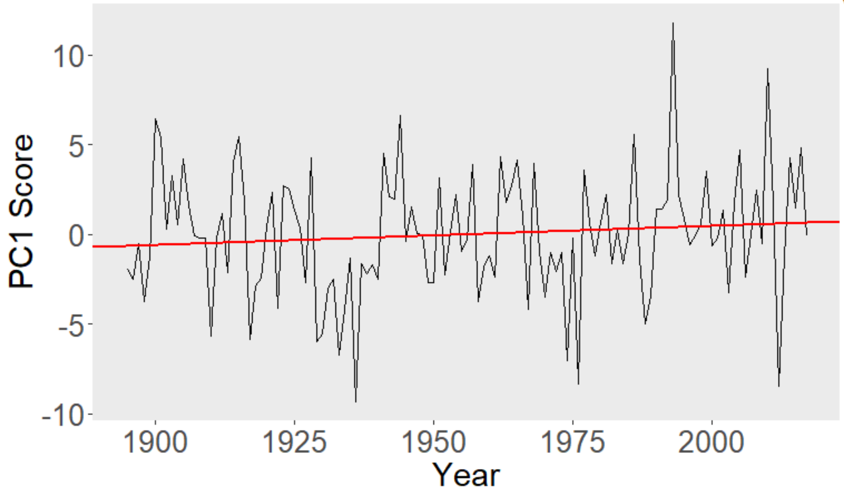
- SST teleconnections (right, top)
  - Signatures in Atlantic and northern, equatorial Pacific Ocean
    - Atlantic Ocean (including Gulf of Mexico, **GoM**)
    - **Pacific Decadal Oscillation (PDO)** pattern in Pacific Ocean
  - **El Niño Southern Oscillation (ENSO)** pattern
- PDSI (right, bottom)
  - Positive correlation **over SEPPR, S, and W**
    - Wet PDSI – wet years
- 500 mb heights (not shown)
  - Negative correlation over **northwestern U.S.**
    - Low pressure system

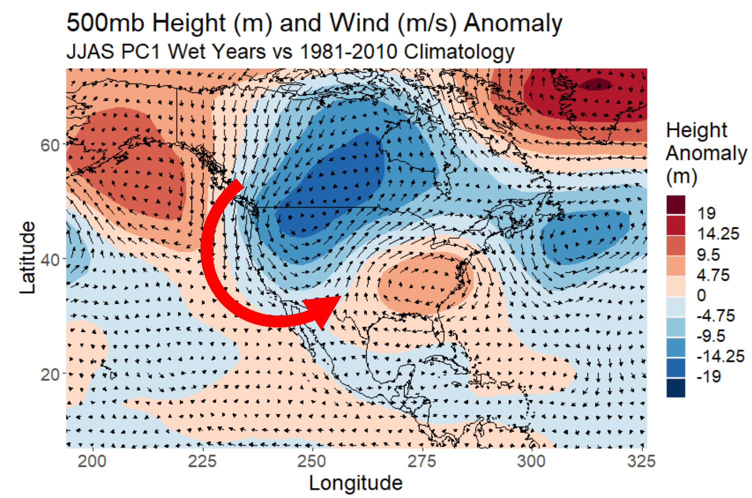




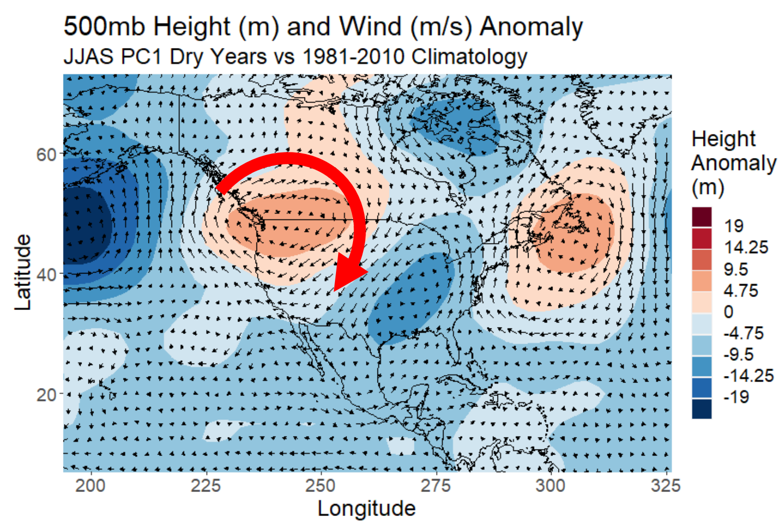
Potential Mechanisms

(C)



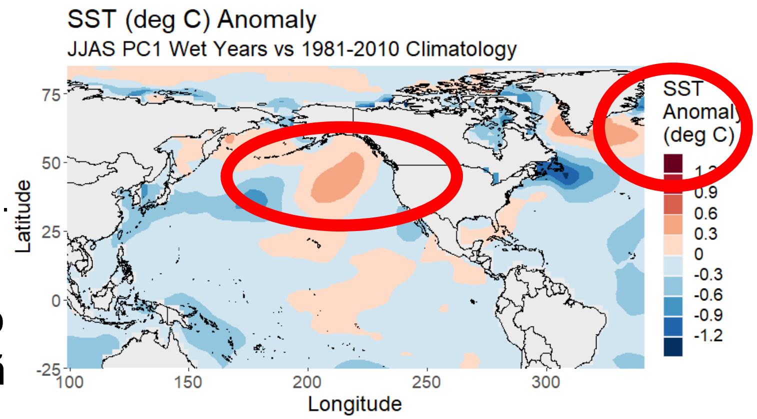


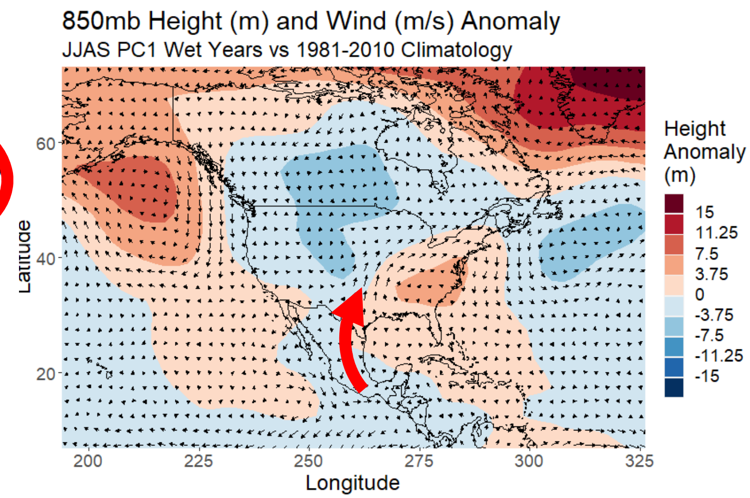
- Wet and dry years determined using PC1 (see below)
  - Composite to find potential mechanisms
- 500 mb heights and associated winds
  - Wet (right, top) – **anomalous low over NW U.S.**
    - Cyclonic (counterclockwise) winds – favorable for bringing in moisture, storm creation
  - Dry (right, bottom) – mirror image (**symmetry**)

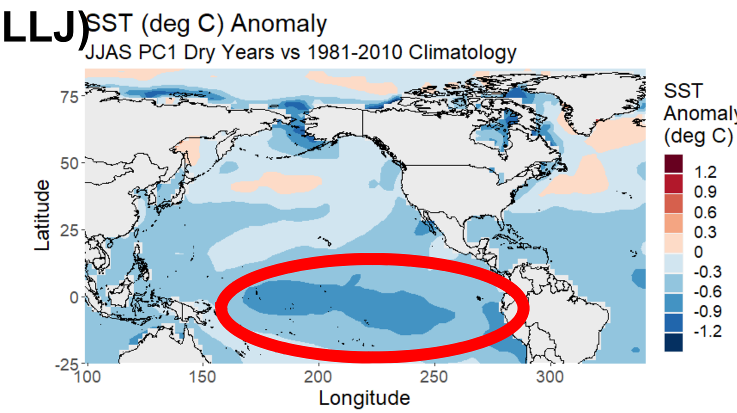


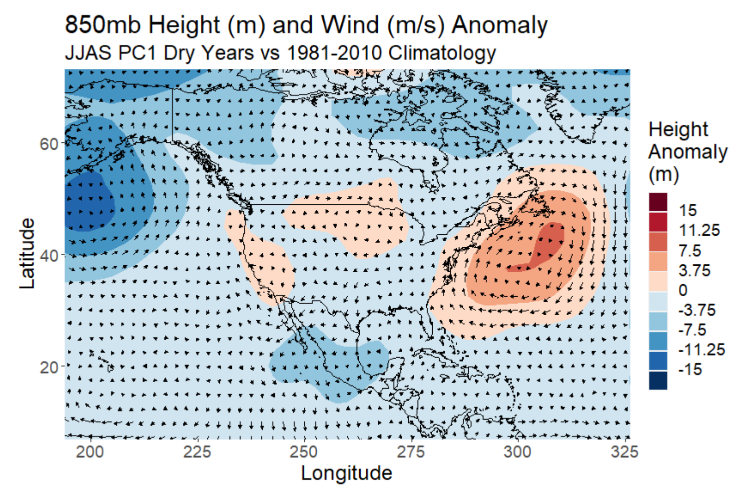
Potential Mechanisms

- SSTs
  - Wet (left, top) – **PDO**
  - Dry (left, botto **ENSO** (La Niñ
- 850 mb heights an associated winds
  - Wet (right, top) – anomalous low
  - **Great Plains Low Level Jet (GPLLJ)**
- **Asymmetry**





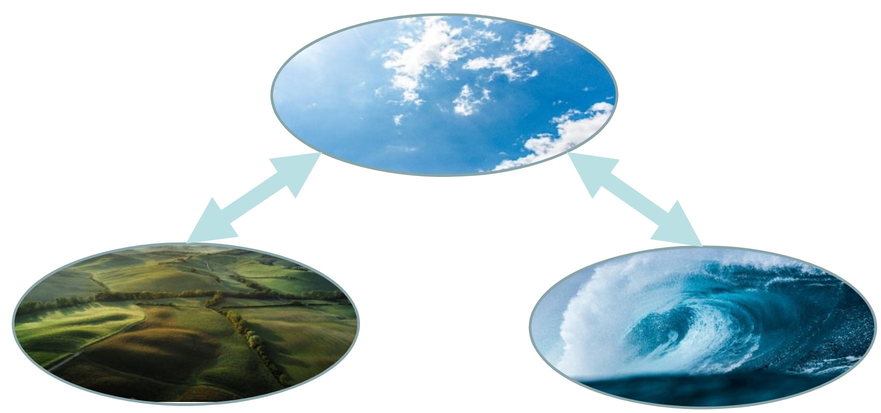




Summary and Impacts

- Dominant mode of variability captures over half the variance
- Identified large-scale teleconnections
  - SSTs (ocean) – PDO and ENSO, Atlantic SSTs (GoM)
  - PDSI (land) – over SEPPR, S, and W
  - Geopotential heights (atmosphere) – 500 mb low
  - Convey a coupling between land (PDSI), atmosphere (heights), and ocean (SST)
- Potential mechanisms
  - GPLLJ
  - Cooler tropical Pacific (La Niña)

- Predictability
  - Large-scale variable persistence
- Inform management
  - Longer lead times



Research Question 2

What are the dominant sources and pathways of moisture for the region's summer precipitation and extreme precipitation events?

Data

- Daily precipitation data
  - Global Historical Climatology Network (GHCN) (Menne et al 2012, Durre et al 2010, Durre et al 2008)
- Gridded meteorological data
  - North American Regional Reanalysis (NARR)
- SSTs and 850 mb heights
  - IRI Data Library
- PDSI
  - NOAA PSL Climate Data Repository

Methods

- Moisture trajectories
  - Choose weather stations
  - Determine rainy days and extreme event dates
  - Run back trajectories
- Trajectory analysis
  - Determine trajectories producing moisture
  - Determine moisture source location
  - Determine pathways for moisture
  - Analyze large-scale setups
  - Large-scale climate connections

Abel, B. D., Rajagopalan, B., Ray, A. J., 2021. Understanding the dominant moisture sources and pathways of summer precipitation in the southeast Prairie Pothole Region. Earth and Space Science (Manuscript in peer review)

HYSPLIT

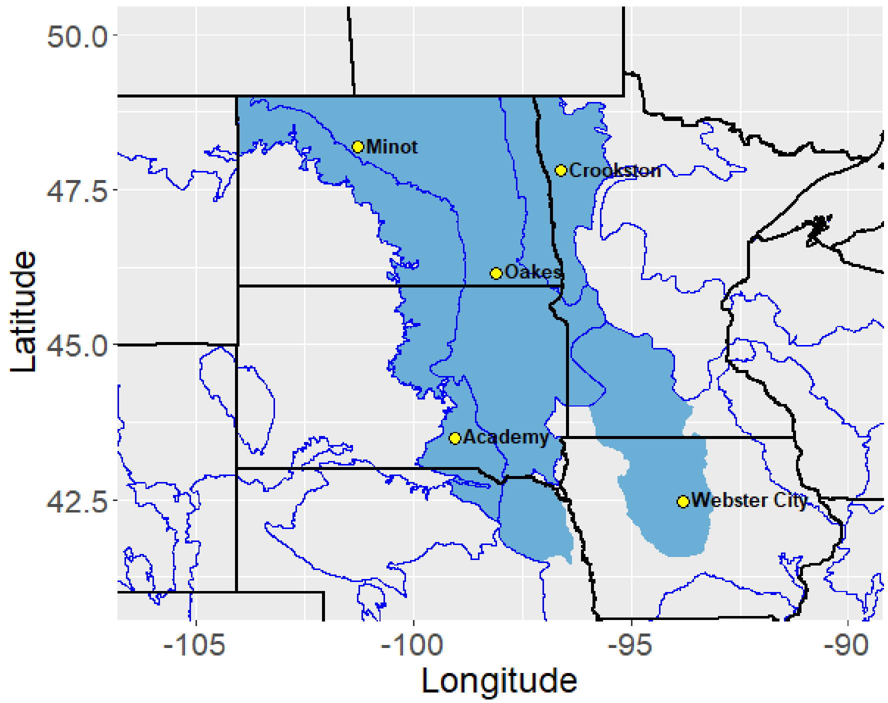
- HYbrid Single-Particle Lagrangian Integrated Trajectory model (Draxler et al 2014, Draxler and Hess 1997, 1998)
  - High-resolution, Lagrangian, particle(parcel)-tracking model
- Uses reanalysis data to track movement of particle
  - 3D winds, pressure, temperature, and relative humidity
  - North American Regional Reanalysis (NARR)
    - Good spatial resolution and ample temporal domain
- Position – average 3D velocity vectors, linearly interpolated in space and time

$$P(t+\Delta t) = P(t) + 0.5[V(P,t) + V(P',t+\Delta t)]\Delta t$$

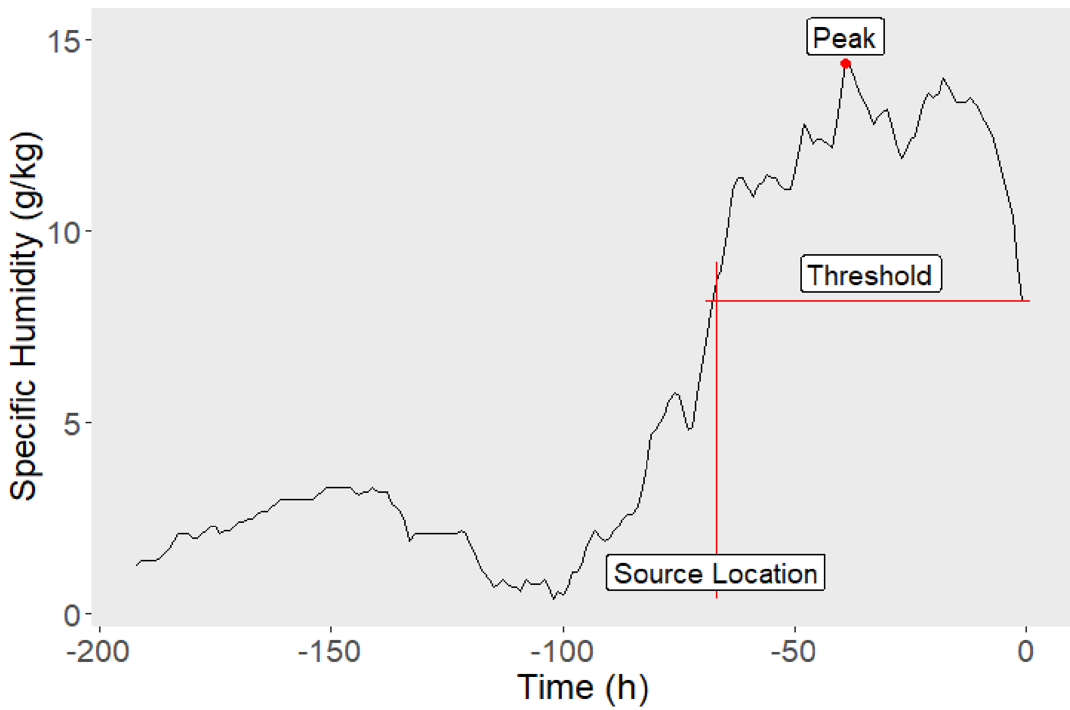
where $P(t+\Delta t)$ is final position, $P(t)$ is initial position, $V(P,t)$ is the velocity vector, and P' is a first-guess position

Generating Back Trajectories

- Five representative weather stations
  - Spatial, ecological, data quality
- Rainy days – >1mm of rainfall, <90th quantile
- Extreme rainfall – >90th quantile for station
- Trajectories
  - Back 8 days (Trenberth 1998)
  - Every 6th hour
  - Every 500 m altitude from 500-5000 m
- 1979-present (restricted by NARR)

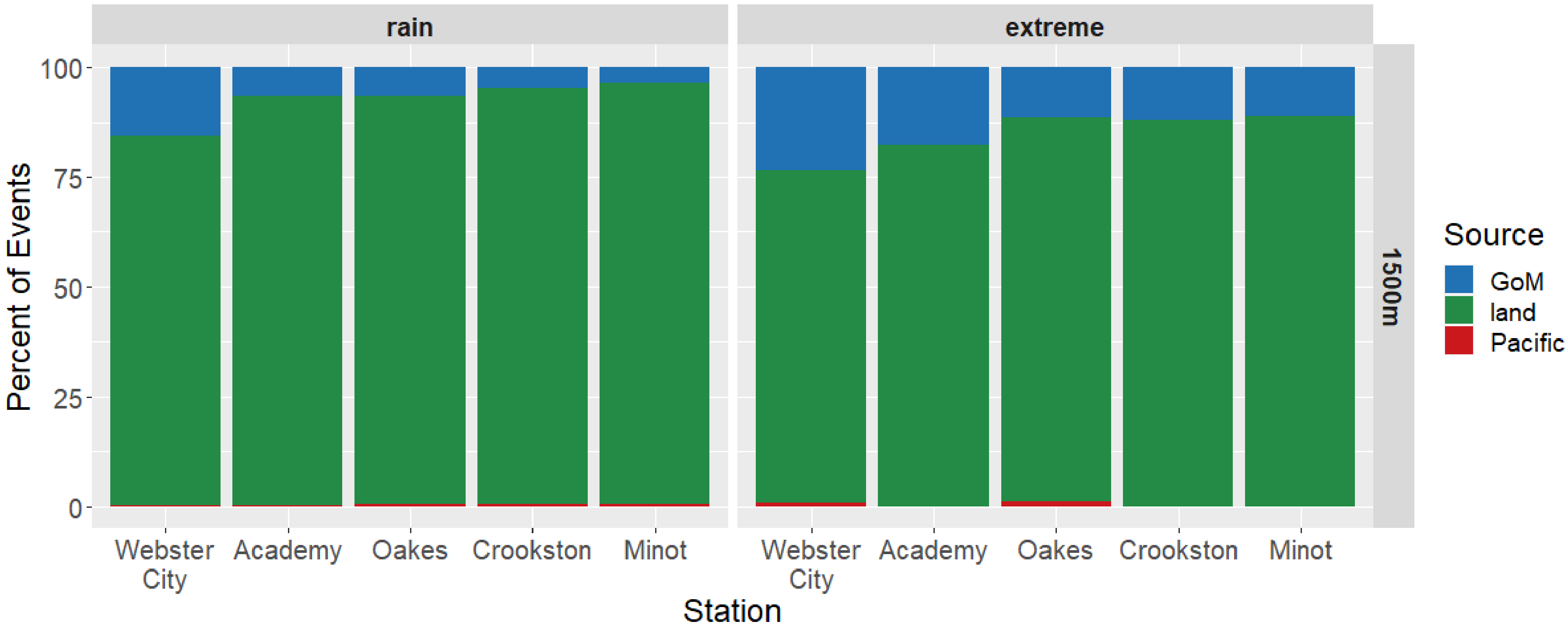


Determining Source Region



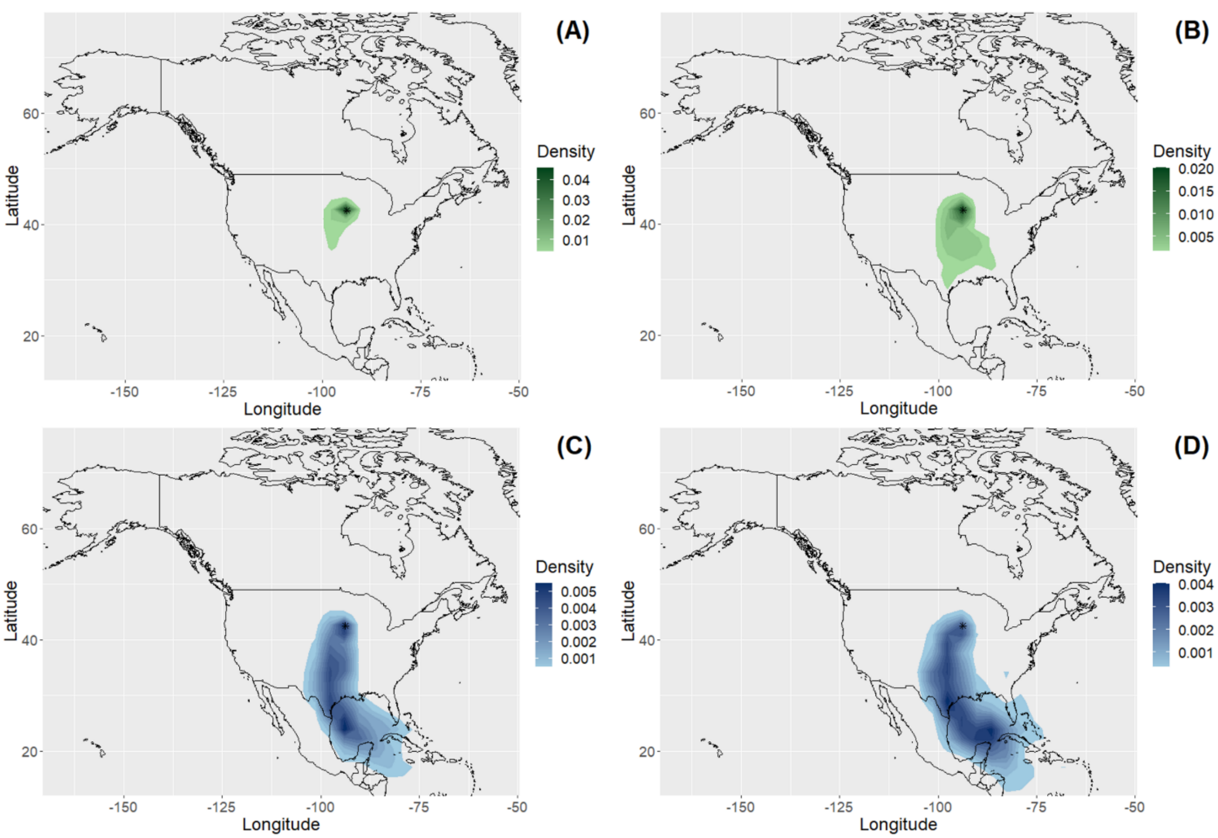
- Use specific humidity (SH) – not affected by temperature
- One trajectory per day with highest drop in SH
  - $SH_{peak} - SH_{hour0}$
- Source location – point where particle drops below SH threshold value, the SH at hour 0
- If SH never drops below threshold, source set to location 8 days prior

Moisture Sources



- 5000m vs 3000m vs **1500m**
- **Land** primary moisture source; Gulf of Mexico (GoM) secondary
- **GoM** more influence the **further south and east** and on **extreme events**

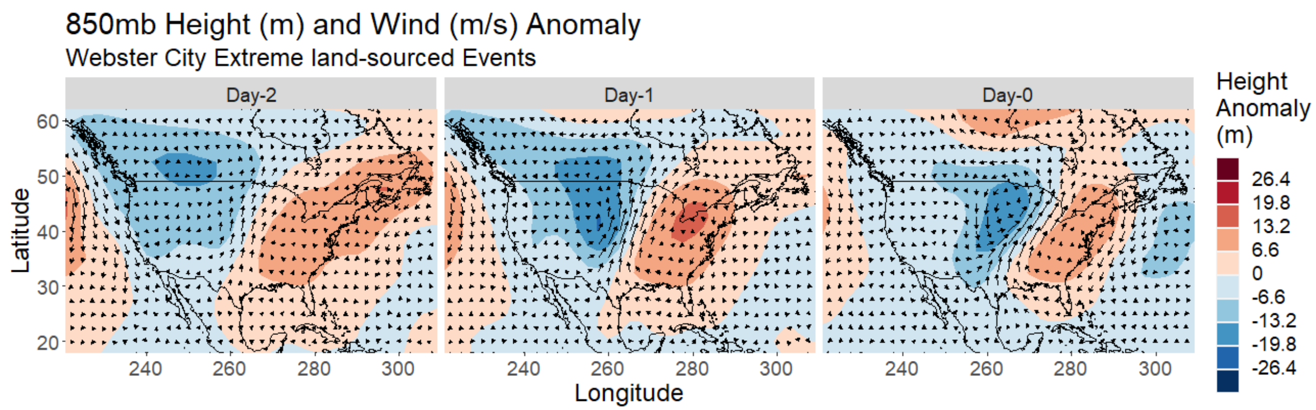
Moisture Pathways

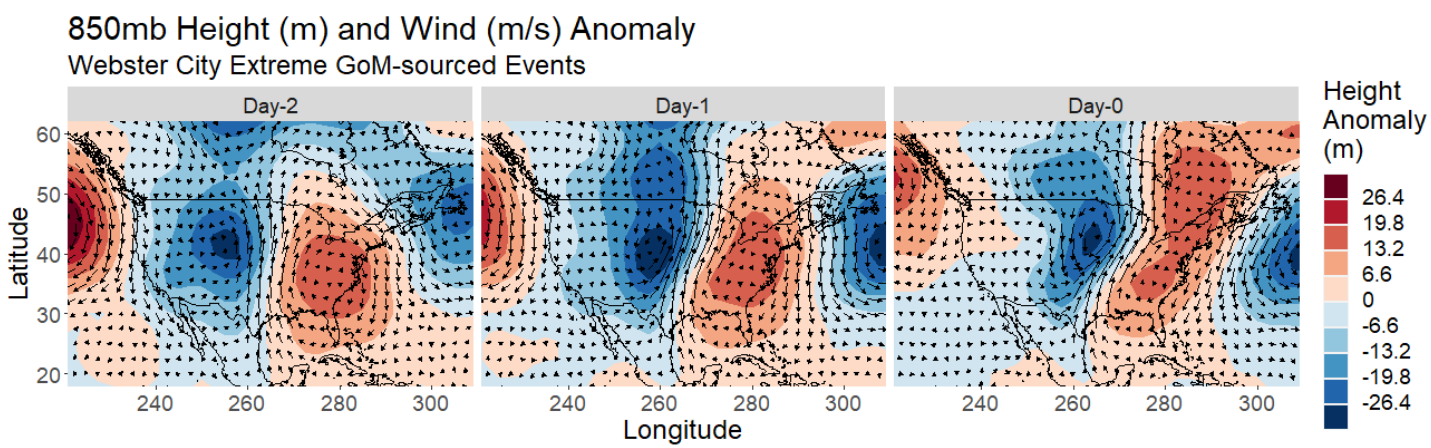


- Pathway(s) – aerial density plots of trajectories
- Rain (left) and extreme (right) for land-sourced (top) and GoM-sourced (bottom) at Webster City, IA
- **GPLLJ** influence apparent in all events
- Pacific Ocean/western pathway influence more apparent the further NW the station

Large-scale Setup – Extreme Events

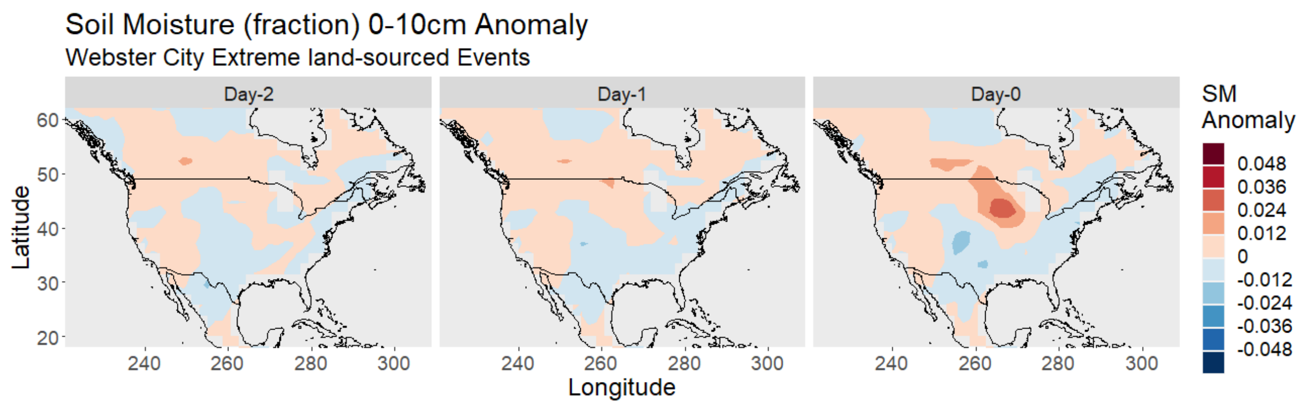
- Composite of extreme events on day of (Day-0) and two days prior
- Land- and GoM-sourced extreme events – **low-pressure system over W US**
- Strongest winds coincide with pathways seen in aerial density plots **(GPLLJ)**

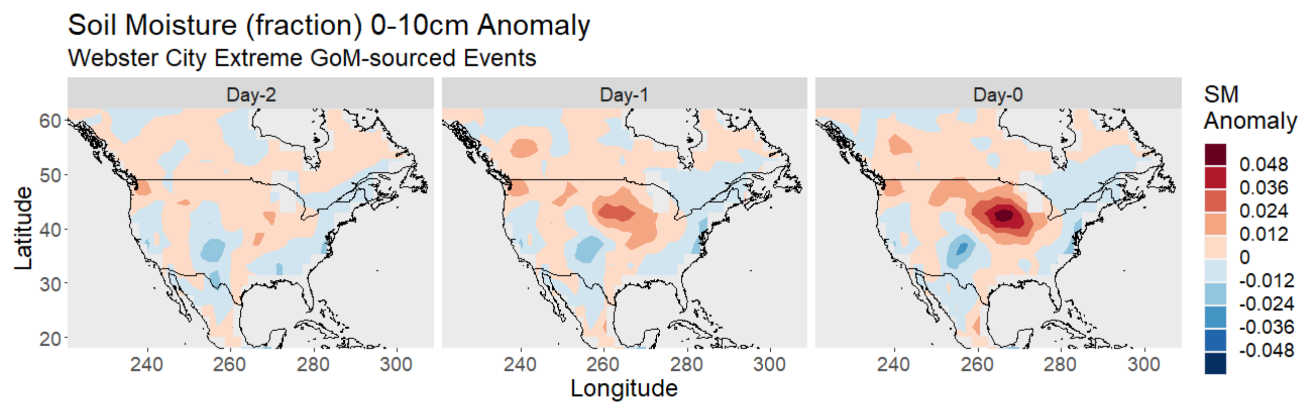




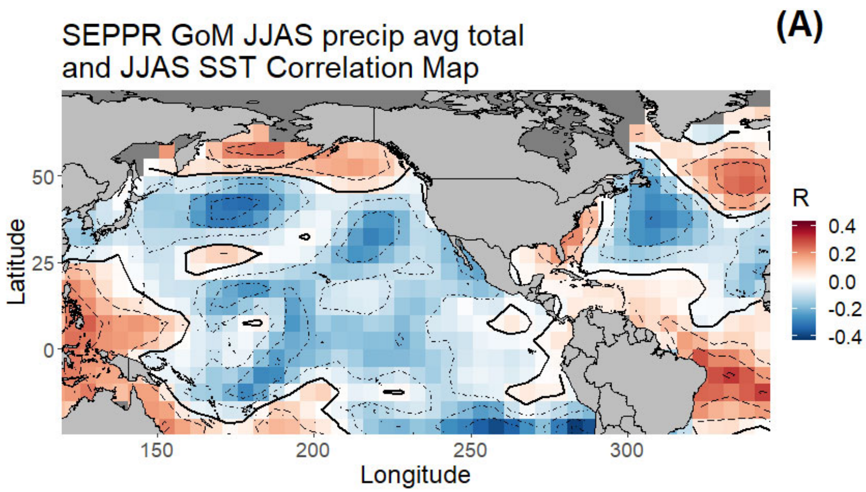
Large-scale Setup – Extreme Events

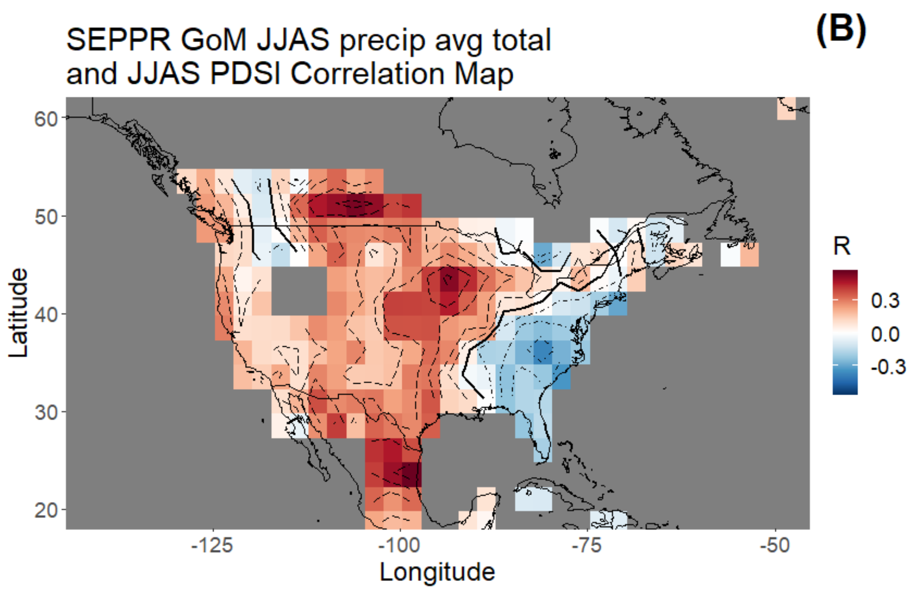
- Land- and GoM-sourced extreme events – **positive soil moisture (SM) anomalies over SEPPR**
- GoM-sourced events
  - Stronger setups (stronger variables, more widespread)
  - Setup more evident 2 days prior (Day-2)





Large-scale Climate Connections





- Land- and GoM-sourced events – summer totals of daily rainfall amounts averaged spatially and correlated with SST, PDSI, and 850 mb heights
- GoM-sourced events connected to **GoM SSTs** (left, top)
- PDSI connection over SEPPR and west U.S. for both sources (GoM on left, bottom
- **Pattern resembling ENSO** in SSTs for land-sourced events (not shown)
- **850 mb low** height connection over SEPPR (land) and as a **trough** extending down from Canada (GoM) (not shown)

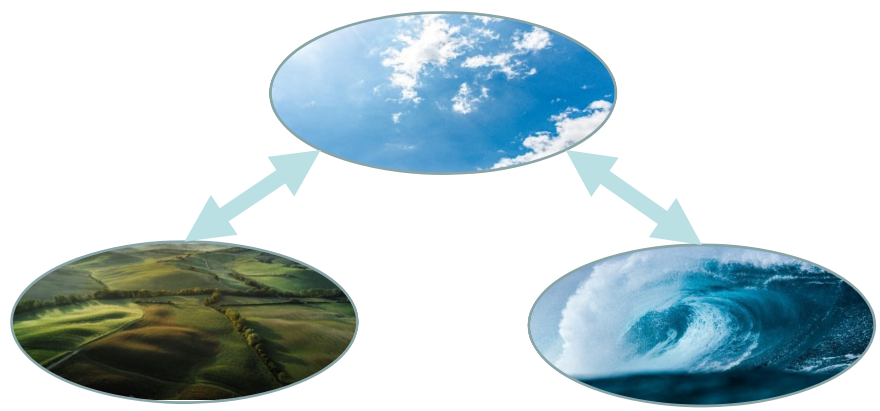
Summary and Impacts

- Land is the primary source of moisture for all summer rainfall events in the SEPPR
  - GoM secondary
- GPLLJ is the primary pathway of moisture delivery for both land- and GoM-sourced events

- Large-scale climate connections, via PDSI, 850 mb heights, and SST, convey a coupling between land, atmosphere, and ocean

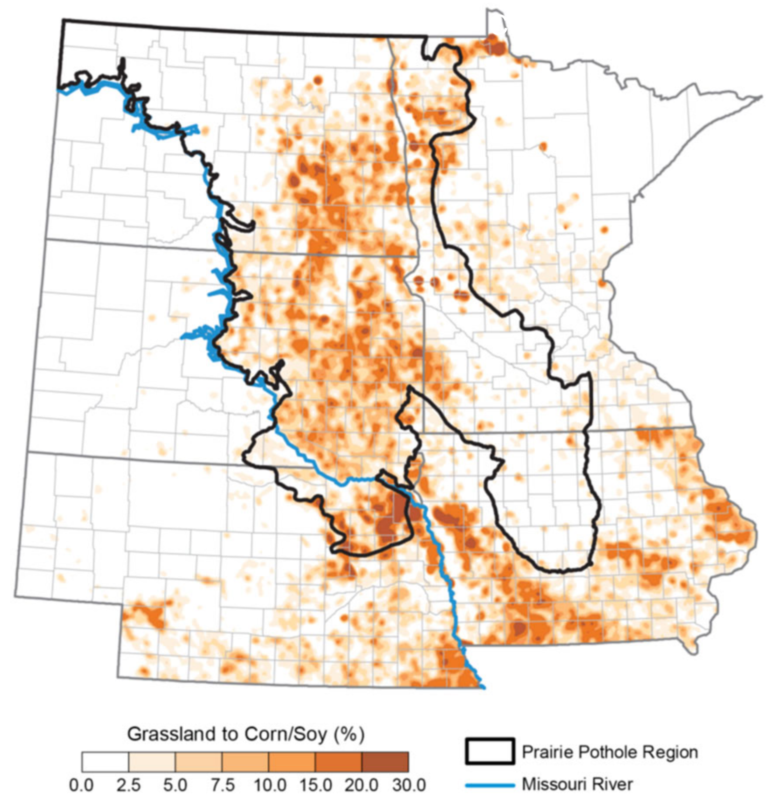
- Moisture recycling, GPLLJ

- Enhance predictability, precipitation forecasts



PPR Wildlife Management

- Habitat conservation strategies
- Major threats:
  - Agricultural land modifications
  - Climate change and variability
- Prescribed grazing, noxious weed control, haying or prescribed burns (U.S. Fish and Wildlife Service 2014)
- Target wetlands and/or surrounding grasslands



Research Question 3

How well does a predictive model for pond counts perform using large-scale climate variables as predictors?

Data

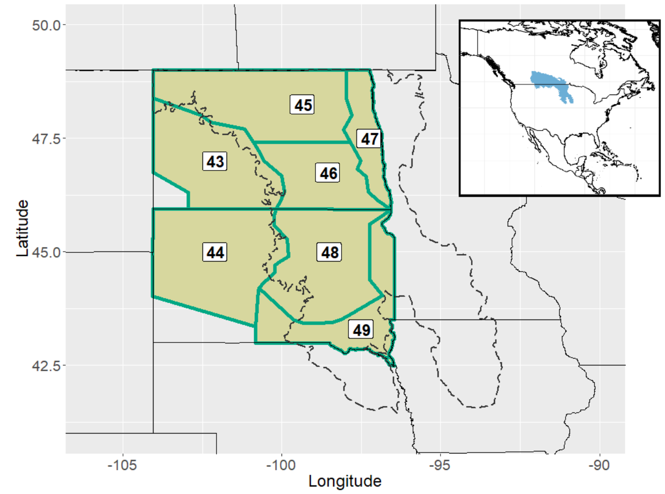
- Pond, duck counts
  - USFWS Breeding and Habitat Survey, Production and Habitat Survey
- SSTs and 500 mb heights
  - IRI Data Library
- PDSI
  - NOAA NCEI nClimDiv

Methods

- Develop predictors
  - Correlate May pond counts with space-time fields of 500 mb heights and SST
- Create multisite predictive model
  - Use canonical correlation analysis (CCA, von Storch and Zwiers 2001)
- Assess model performance
  - Use common metrics and methods

Abel, B. D., Rajagopalan, B., Ray, A. J., 2020. A predictive model for seasonal pond counts in the United States Prairie Pothole Region using large-scale climate connections. Environ. Res. Lett. 15, 044019. https://doi.org/10.1088/1748-9326/ab7465

Pond Count Models

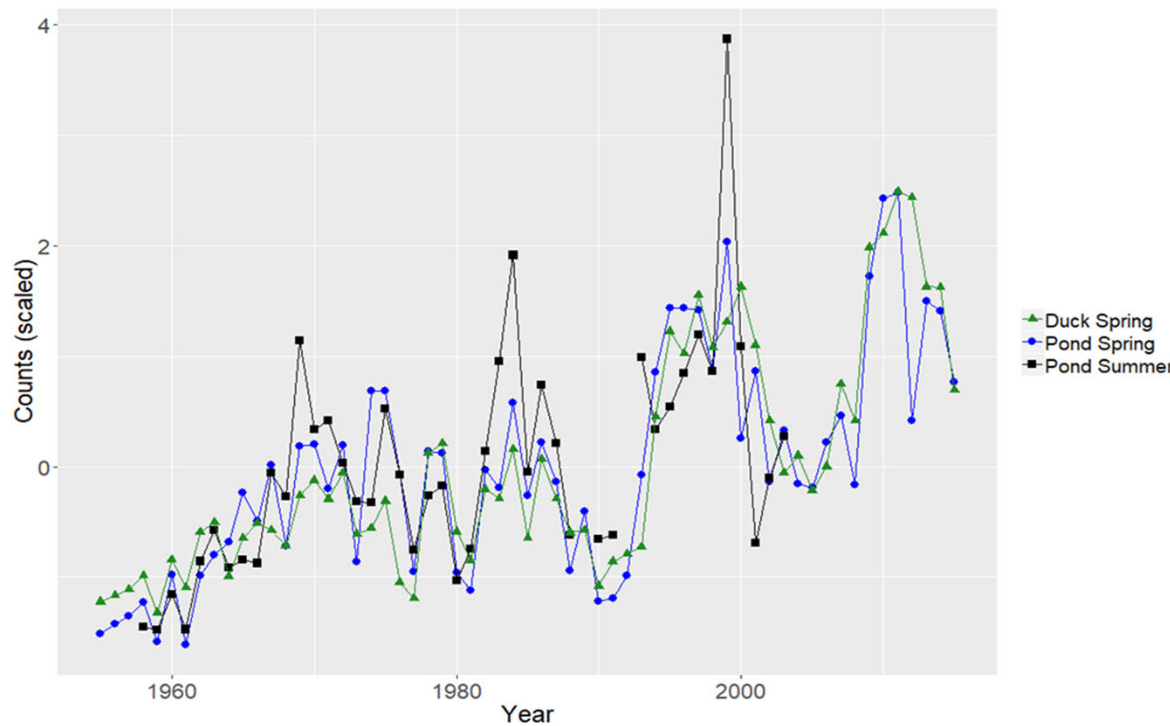


Develop models

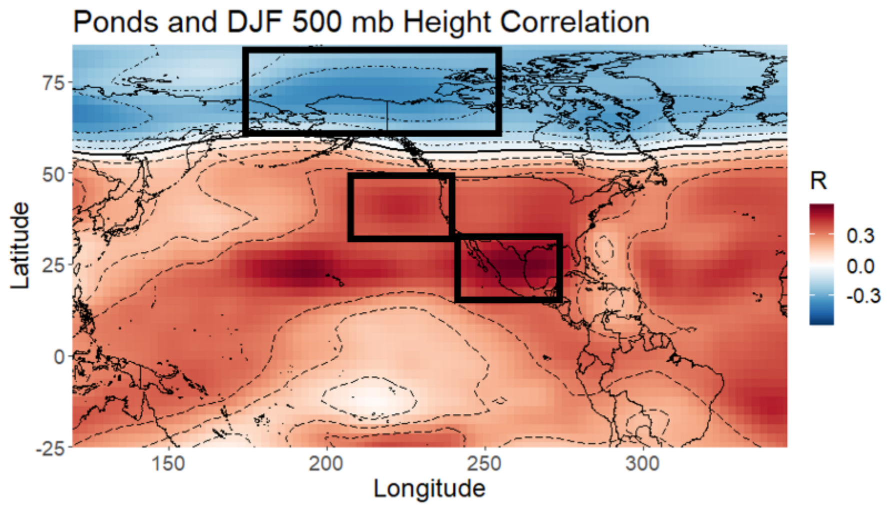
- Predict spring (May) and summer (July) pond counts in each stratum (region)
- Models for various lead times
- Use canonical correlation analysis (CCA) to relate two space-time datasets

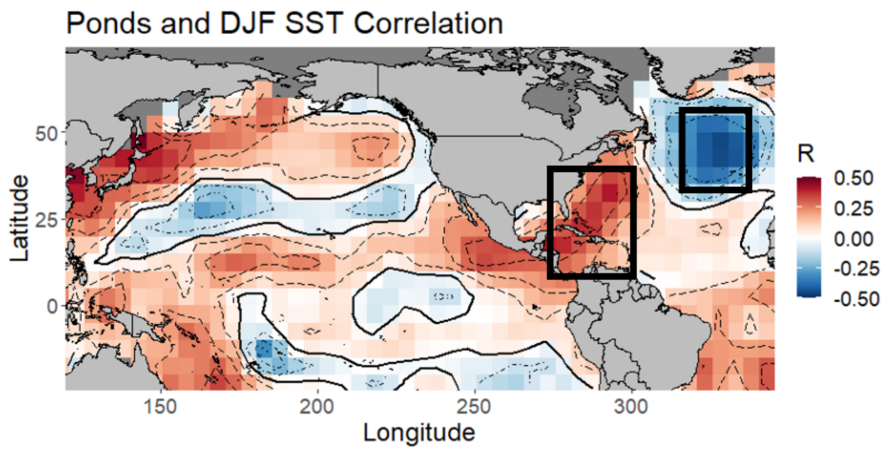
Assess performance

- Measure model fit and forecast skill using correlation coefficient (R) and root mean square error (RMSE)
- Leave-one-out cross-validation (LOOCV) to test in a predictive mode



Predictor Selection

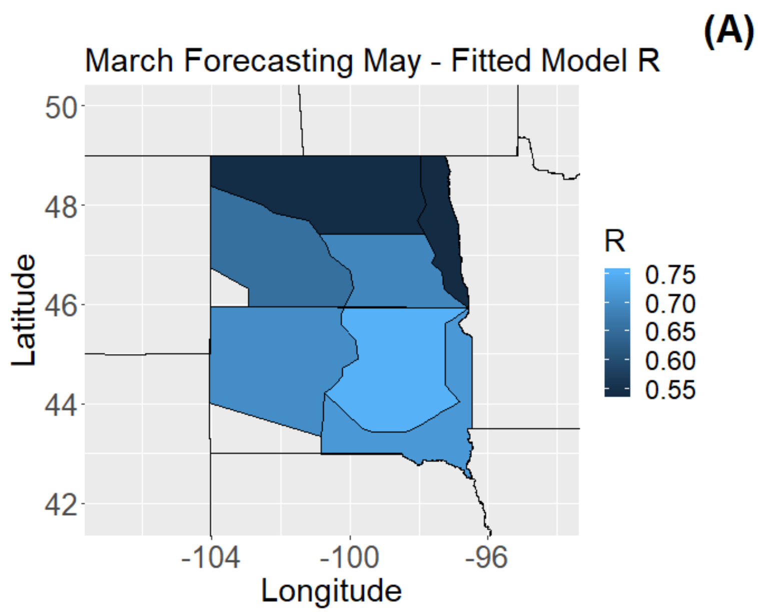


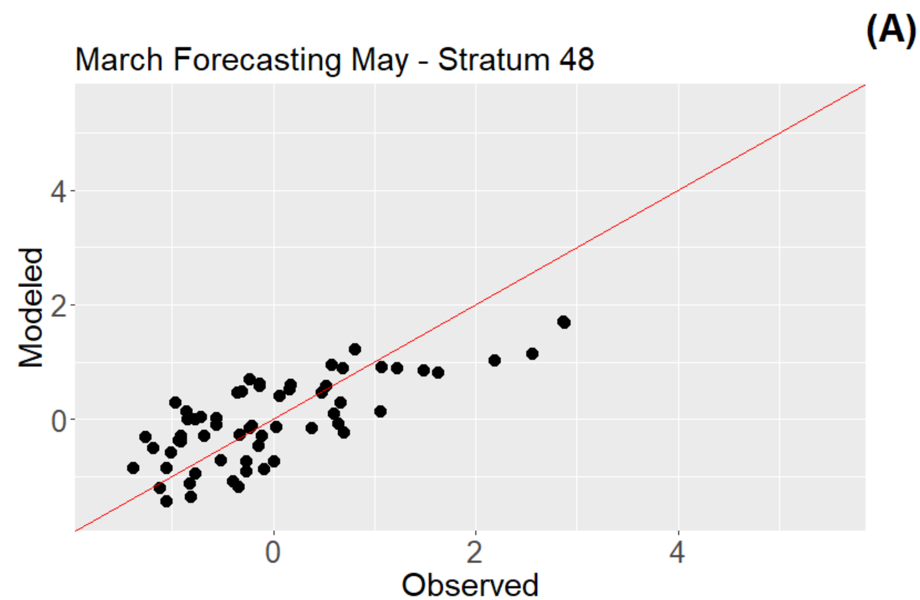


Predictors	Forecast Date			
	March 1	April 1	May 1	June 1
PDSI Winter				
PDSI March	---------------			
PDSI April	---------------	---------------		
500 mb Winter				
500 mb March	---------------			
500 mb April	---------------	---------------		
SST Winter				
SST March Atlantic	---------------			
SST March Pacific	---------------			
SST April Atlantic	---------------	---------------		
SST April Pacific	---------------	---------------		
May Pond Count	---------------	---------------	---------------	

- Uses knowledge gained from precipitation variability analysis (Question 1)
- Correlated May pond counts from the USFWS survey with large-scale variables
- Created predictors to be used at various lead times

Model Fit

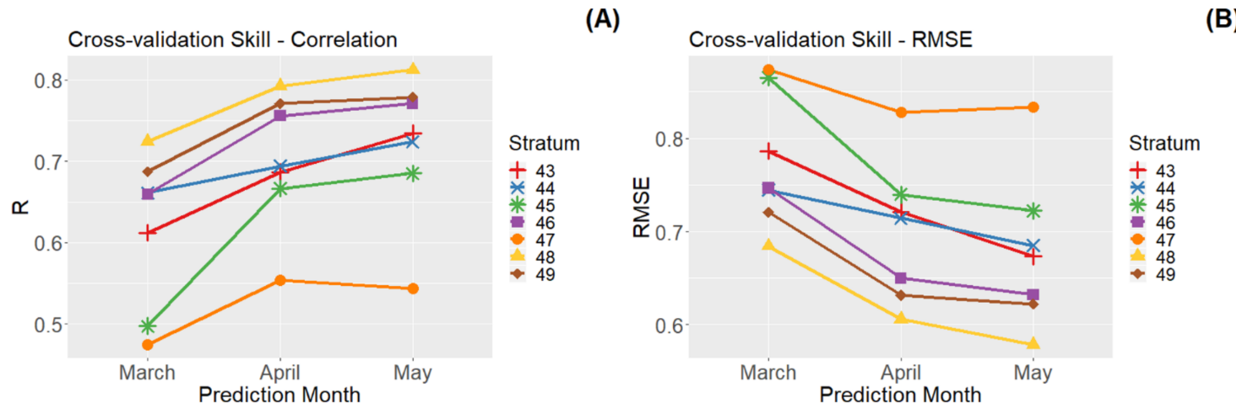


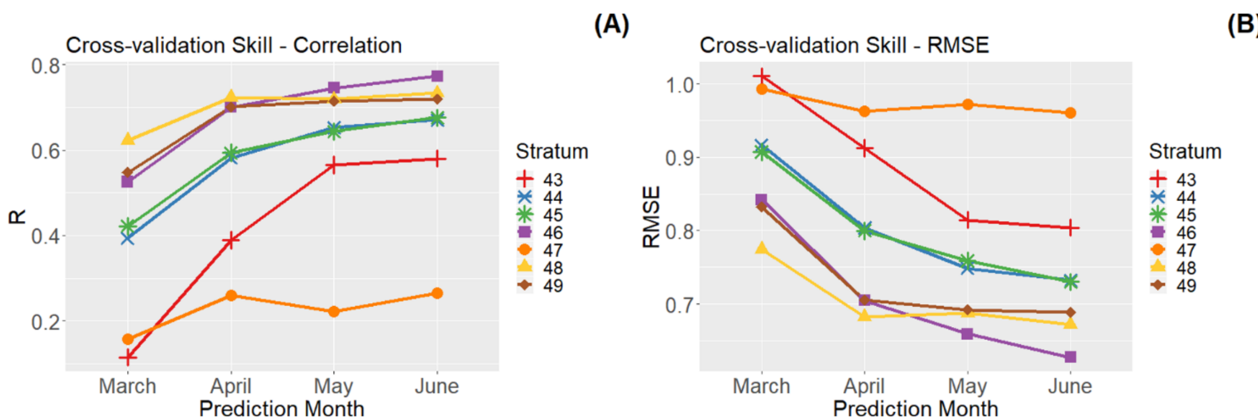


- Models fit well – R mostly **above 0.65 for May** and 0.5 for July
- Performance increased as lead time decreased

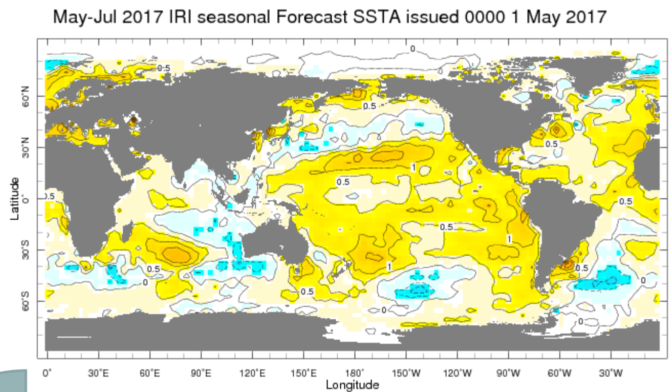
Model Skill

- May models in LOOCV
  - **R values** mostly **above 0.6**, **RMSE below 1**
- July models in LOOCV
  - R values mostly above 0.4, RMSE mostly below 1

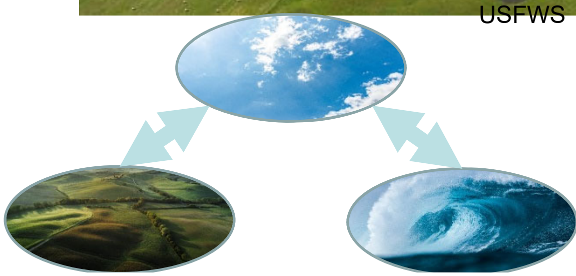




Summary and Impacts



USFWS



- Predictor suite based on precipitation variability analysis (Question 1)
- Novel modeling approach (CCA) not used before for this purpose
- Spring and summer pond count prediction models
  - High skill
  - Forecasts for multiple strata (managers familiar)
  - Large-scale variables
- Assist managers in making important management decisions
  - Longer lead times
  - Versatile
- Inspire CCA to be used elsewhere
- Demonstrate large-scale variables' predictability

Research Question 4

Can wetland vegetation be adequately modeled using a point-based, physical numerical model coupled with climate information?

Data

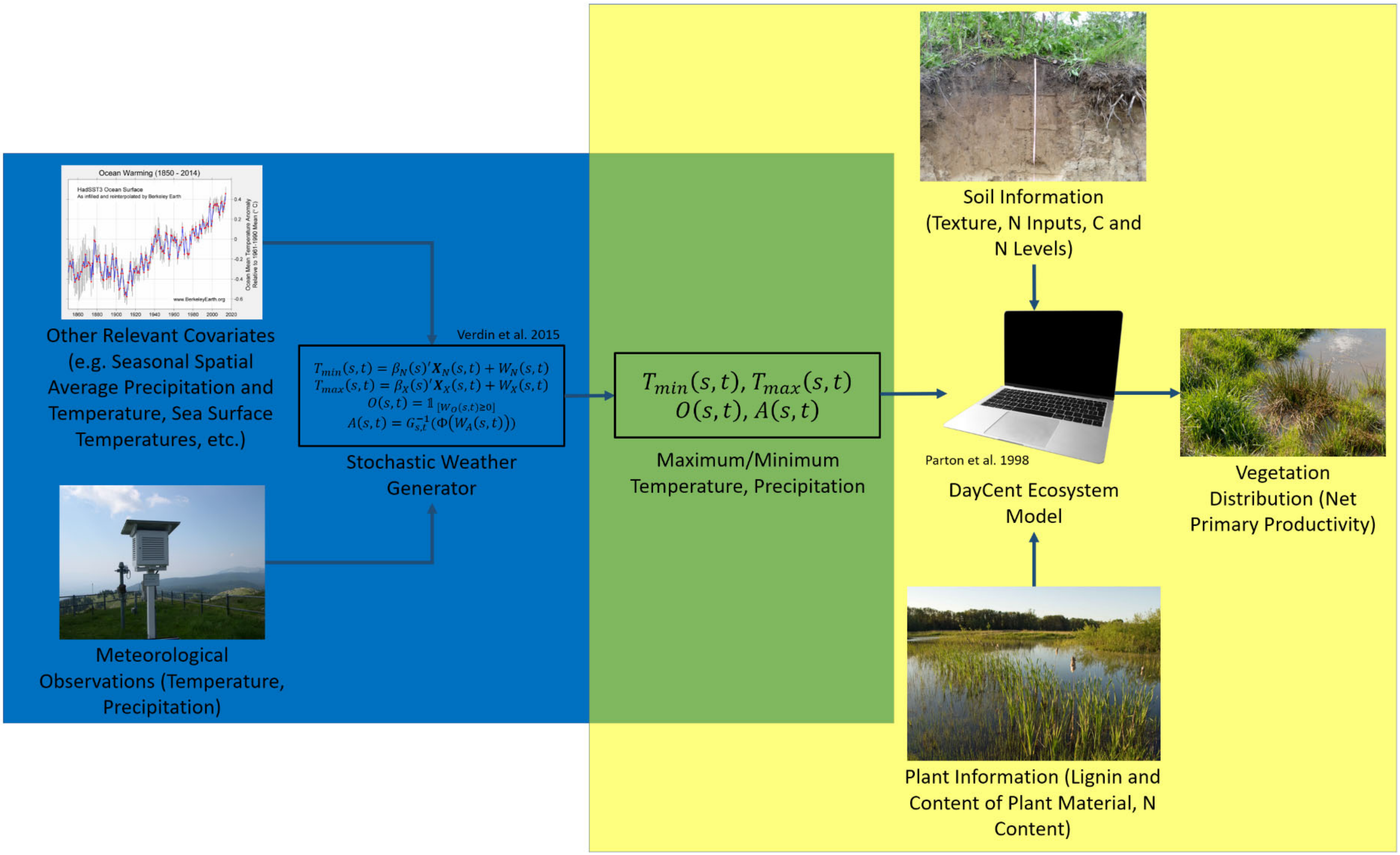
- Meteorological data
  - Global Historical Climatology Network (GHCN)
- Soil data
  - Soil Survey Geographic (SSURGO) database (NRCS 2020)
- Net primary productivity (NPP), Normalized Difference Vegetation Index (NDVI)
  - NASA
- Seasonal climate forecast
  - IRI Data Library

Methods

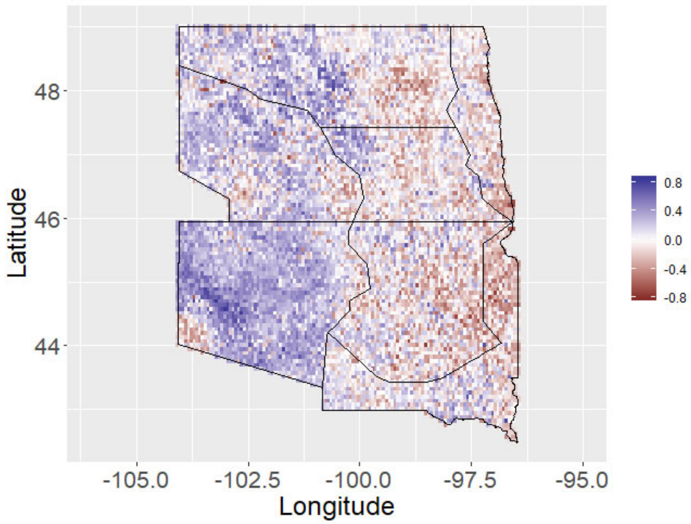
- Calibrate and validate stochastic weather generator (SWG) and DayCent
  - Develop new vegetation type – emergent
- Develop Integrated Climate-Ecological Modeling Framework (ICEMF)
  - Examine ICEMF performance
  - Demonstrate ICEMF capability

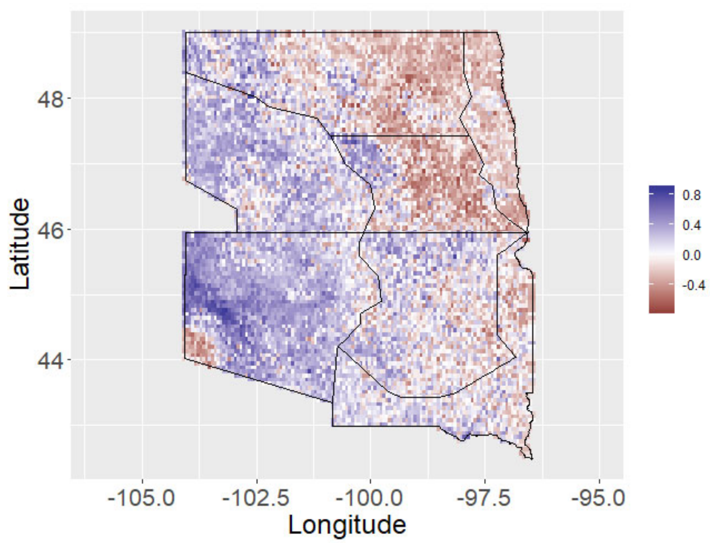
Abel, B. D., Hartman, M. D., Rajagopalan, B., 2021. A novel ecological modeling framework for the prediction of ecology in the United States Prairie Pothole Region *(Environmental Modeling and Software, In review*)

Integrated Climate-Ecological Modeling Framework (ICEMF)



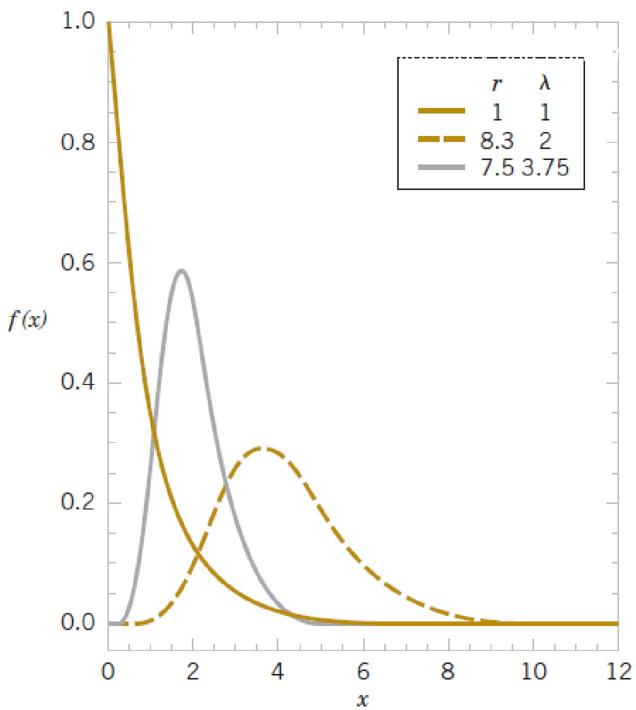
Vegetation Connection





- Ducks prefer cover ratio (open water : emergent vegetation) of near unity
- Connection between vegetation and duck/pond numbers
- NDVI correlates with duck and pond counts (region average)

Stochastic Weather Generator (SWG)



- Maximum and minimum temperature, precipitation occurrence and amount at selected stations
- Minimum and maximum temperature

$$T_{min}(s,t) = \underbrace{\beta_{min}(s)'\boldsymbol{X}_{min}(s,t)}_{\text{climate}} + \underbrace{W_{min}(s,t)}_{\text{weather}}$$
$$T_{max}(s,t) = \beta_{max}(s)'\boldsymbol{X}_{max}(s,t) + W_{max}(s,t)$$

- Precipitation occurrence

$$O(s,t) = \mathbb{1}_{[W_O(\boldsymbol{s},\boldsymbol{t}) \geq 0]}$$

- Precipitation amount

$$A(s,t) = G_{s,t}^{-1}\left(\Phi\left(W_A(s,t)\right)\right)$$

- Covariate vector

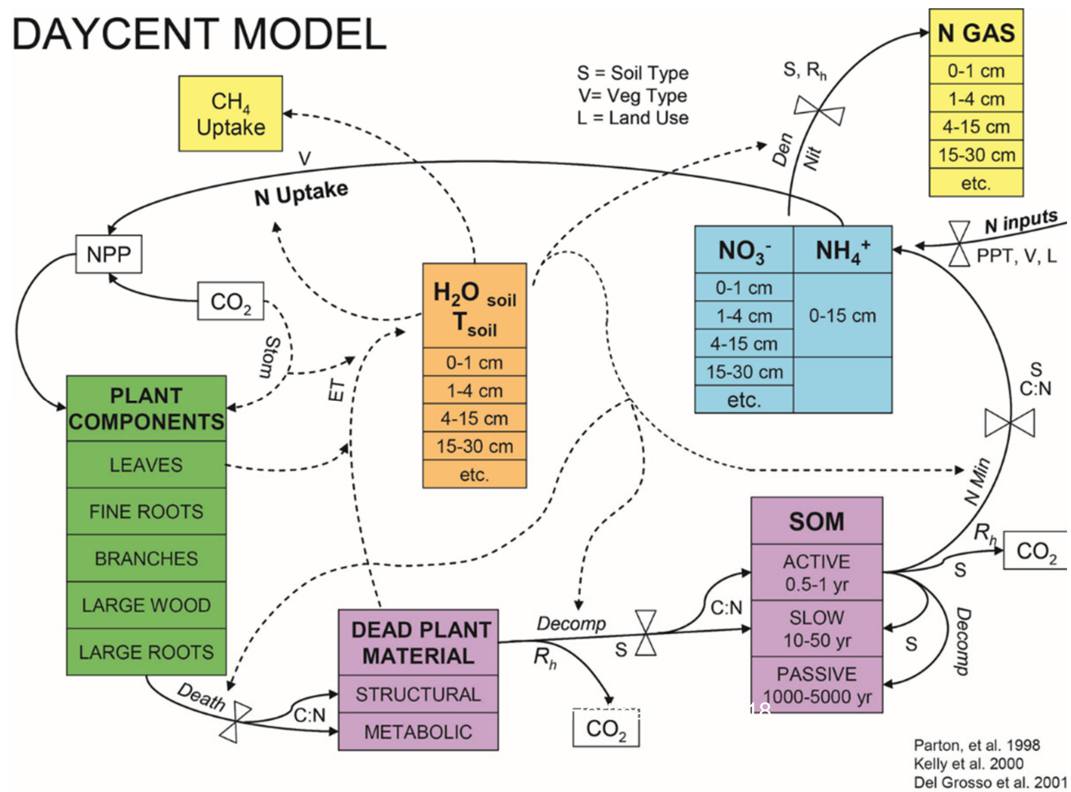
$$\boldsymbol{X}_{max}(s,t) = \left(1, \cos\left(\frac{2\pi t}{365}\right), sin\left(\frac{2\pi t}{365}\right), r(t), T_{min}(s,t-1), T_{max}(s,t-1), O(s,t), SMN(t), SMX(t), \dots\right)$$

Furer and Katz, 2006
Verdin et al. (2015, 2018)

DayCent

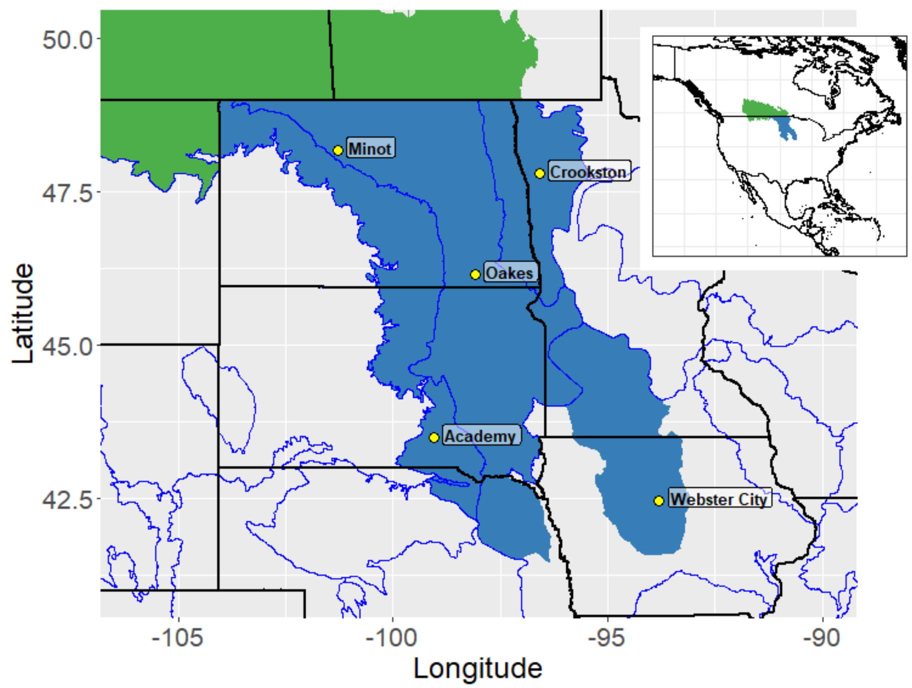
- Simulates vegetation dynamics
  - determine exchanges of carbon, nutrients, and trace gases among atmosphere, soil, and plants
- Multiple submodels
  - Water flow/soil water
  - Soil temperature
  - Soil organic matter (SOM)

  - Nitrogen
  - Methane
  - Plant growth
- Inputs – soil information, plant information, **daily maximum and minimum temperature, daily precipitation**
- Output – net primary productivity (NPP)



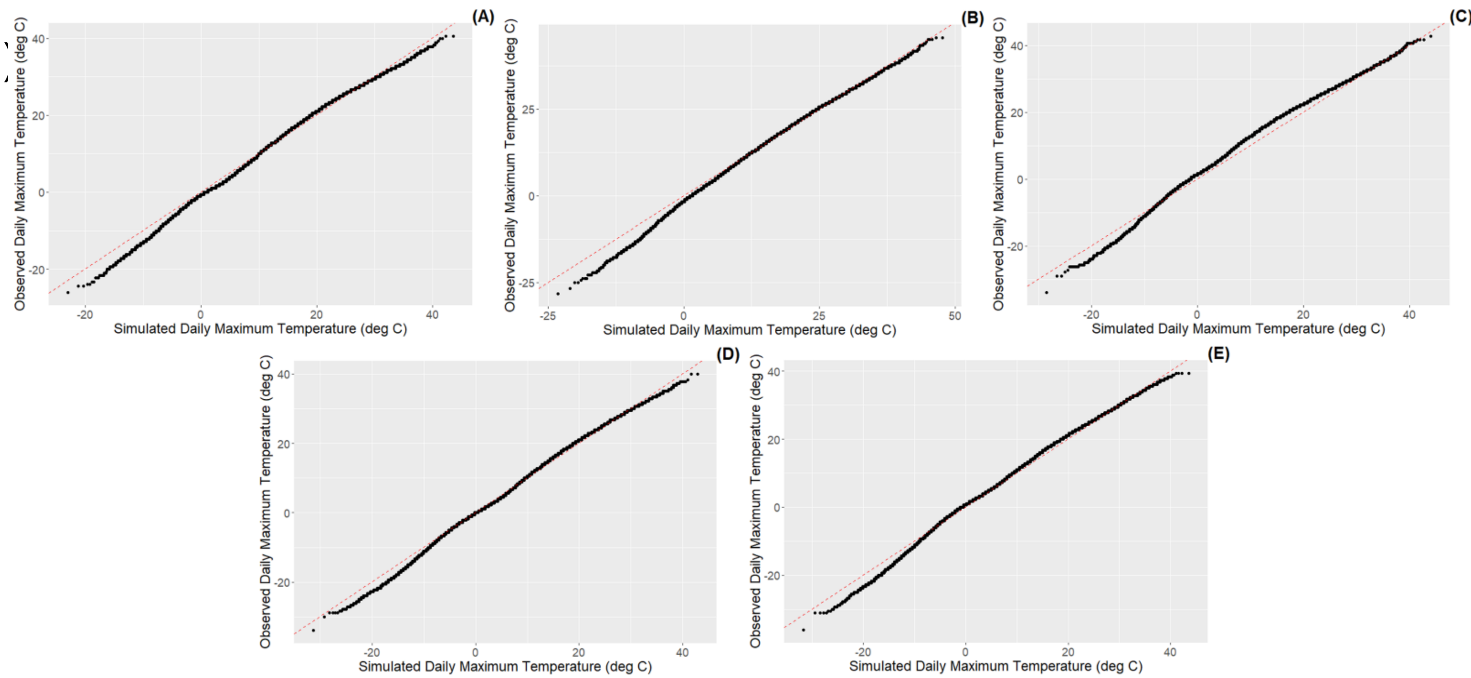
Calibration and Validation

- SWG – use historical data at five stations
  - "Calibrate" using historical data
  - Validate at five chosen stations in SEPPR
- DayCent – use historical NDVI, NPP data
  - Use DayCent's calibrated perennial grass (Hartman et al 2011, Hartman et al 2020
  - New vegetation type – emergent
    - Calibrated by adjusting soil moisture curves and adjusting to measured productivity
  - Validate using NDVI and ANPP



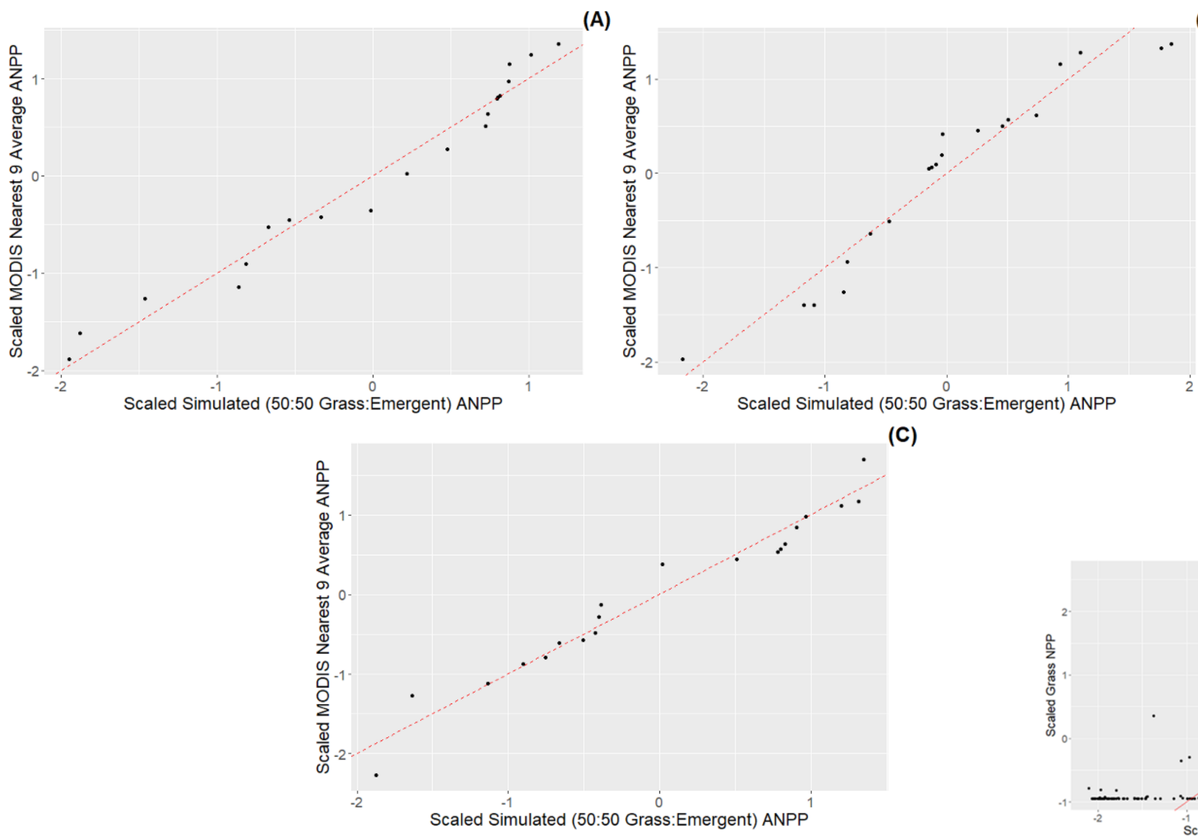
Calibration and Validation (SWG)

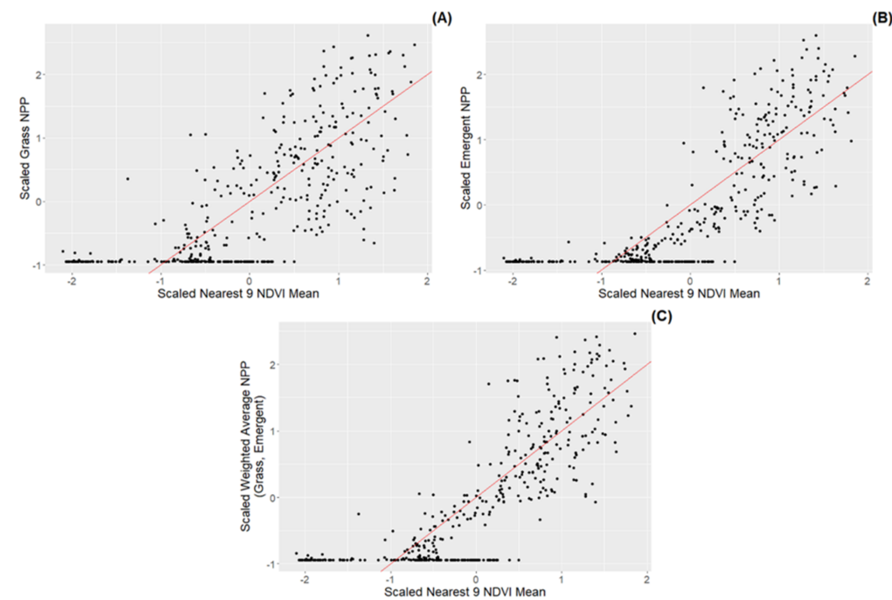
- Simulate period of record (1980-2018)
  - QQ plots of observed and simulated variables
- Temperature – **captured well** at all stations (T_{max}, right)
- Precipitation – **captured well in lower amounts**; tails off at more extreme values (not shown)



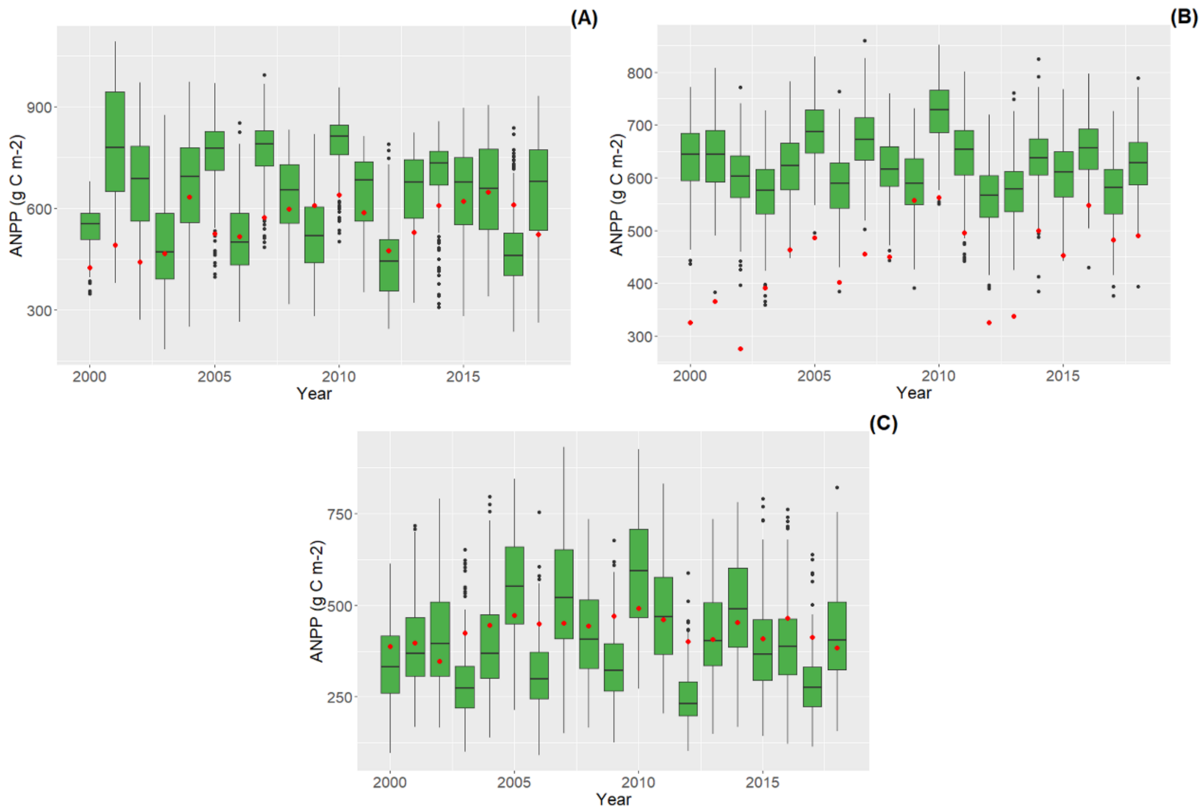
Calibration and Validation (DayCent)

- Simulated NPP with observed NDVI correlations strongest at three stations (Webster City, IA; Academy, SD; Crookston, MN)
- Simulate period of record (2000-2018) – QQ plots of scaled observed ANPP and simulated ANPP
  - Obs - remotely sensed, nearest 9 grid point average
  - Sim - 50:50 grass:emergent
- **Distribution captured well**



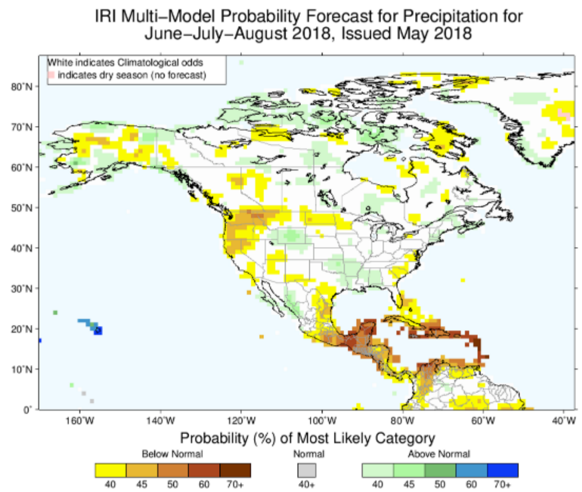


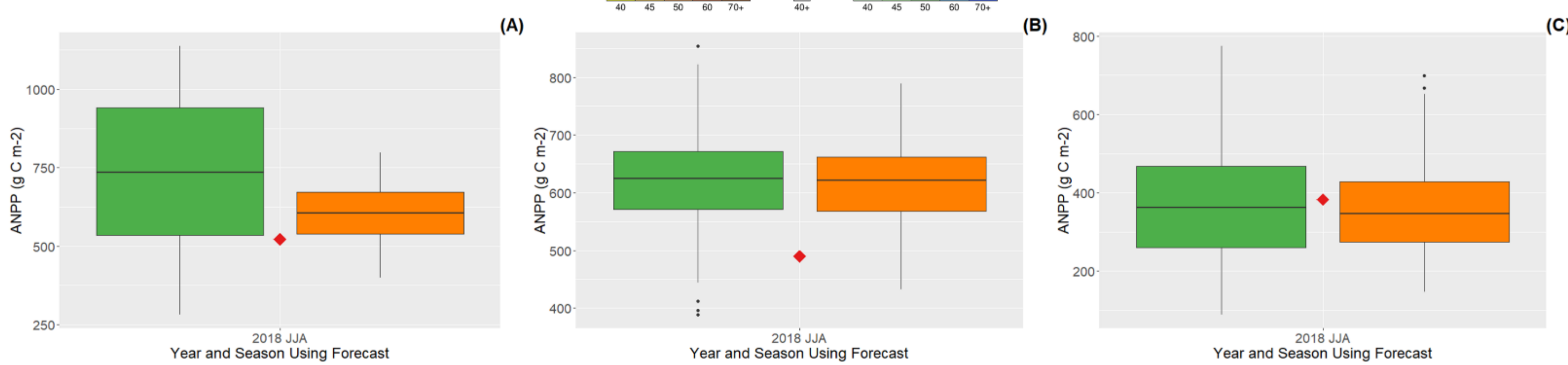
Calibration and Validation (ICEMF)



- Simulated ANPP for period of record for NASA ANPP (2000-2018) – compare sims to observed
  - 50:50 grass:emergent
- Two stations perform well – Webster City and Crookston (A and C)
- Academy (B) overpredicts ANPP

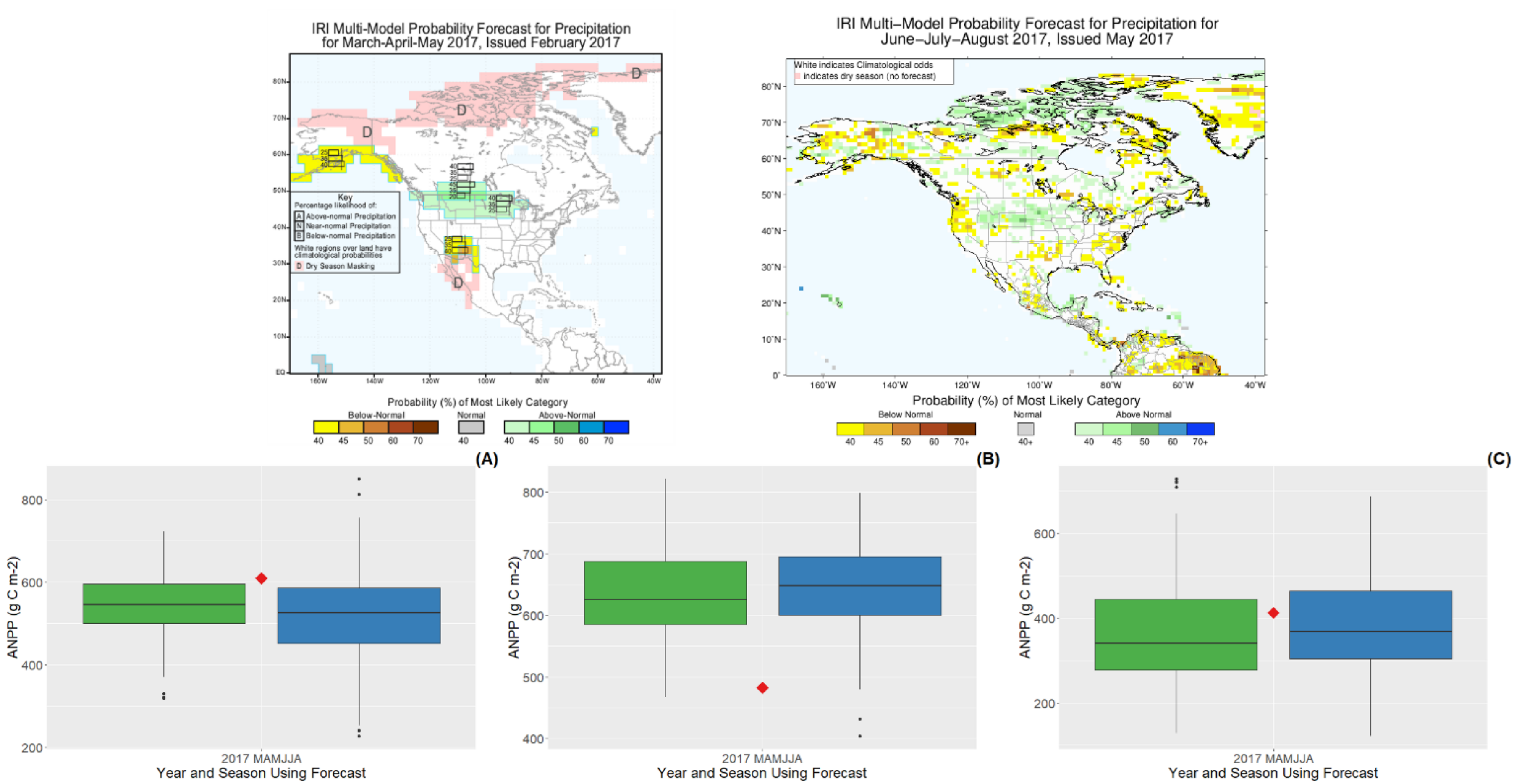
Seasonal Projection



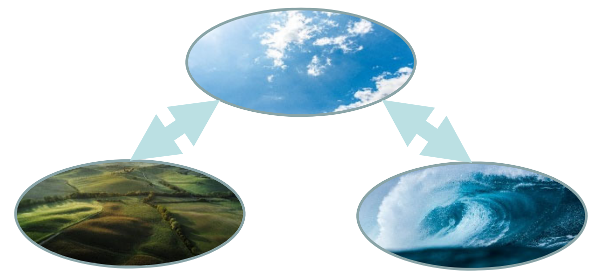


- Use IRI Probability Forecasts to drive ICEMF (SWG)
- Forecasted dry summer within otherwise normal year
- Simulations at two stations are improved with IRI probabilities
  - **Median moves toward historical value**
- **Vegetation sensitive to stochasticity**
  - Difference in variability

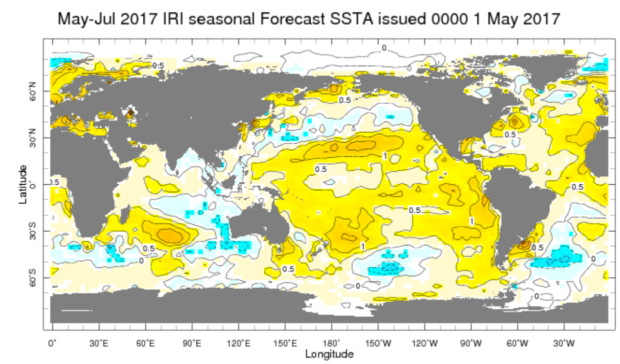
PPR Vegetation Model



Summary and Impacts

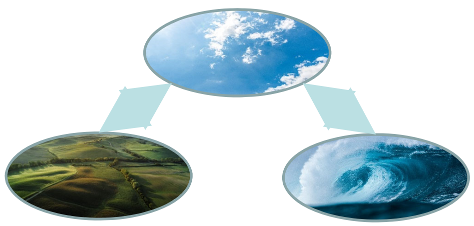


- Integrated Climate-Ecological Modeling Framework (ICEMF)
  - Coupled SWG and DayCent
  - Adaptable to numerous sites
  - Produces numerous vegetation realizations using historical climate and weather information



- Seasonal vegetation forecasting
  - Tool for resource managers
- Information on dangers of climate change on vegetation in the SEPPR

Summary and Future Extensions



Contact:
balajir@Colorado.edu

- Knowledge
  - Large-scale mechanisms and teleconnections, moisture sources and pathways for summer precipitation
    - ENSO, GoM, GPLLJ
- Tools
  - Pond count prediction models
  - Integrated Climate-Ecological Modeling Framework

- Better understanding of space-time variability, moisture delivery
- Establishing important connection
  - Atmosphere, land, and ocean
- Predictive tools for managers
  - Seasonal forecasting, climate change/variability

Hydroclimate, moisture analysis

- Analysis of other seasons
  - Spring, winter

Predictive models

- Add more variables to CCA
  - Adapt even further to managers' needs and wants
- Translating to duck populations
- Incorporate Bayesian framework
- Incorporate more weather stations into ICEMF
- Incorporate spatial SWG
- Add more vegetation types as appropriate