Terrestrial Hydrology in the Laurentian Great Lakes Watershed

Noah-MP Workshop 2024

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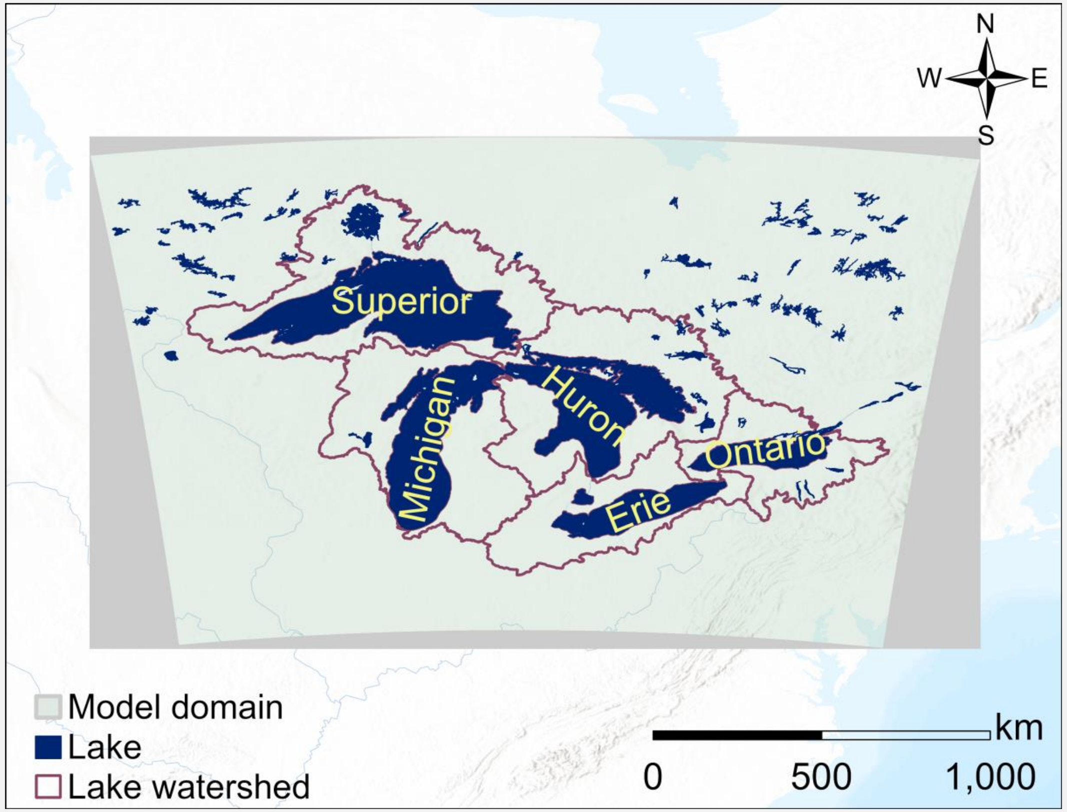
Analyze the **terrestrial water budget** in the **Great Lakes watersheds** using the **WRF-Hydro/NOAH-MP** modelling system

Understanding the modalities of the terrestrial water budget is important because:

- Land surface processes affect lake levels and water quality
- Can help improve prediction capabilities of hydrological processes



Water Resources Research®

RESEARCH ARTICLE
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Controls of Variability in the Laurentian Great Lakes Terrestrial Water Budget

Samar Minallah[1,2], Allison L. Steiner[1], Valeriy Y. Ivanov[3], and Andrew W. Wood[2,4]

Terrestrial Water Budget

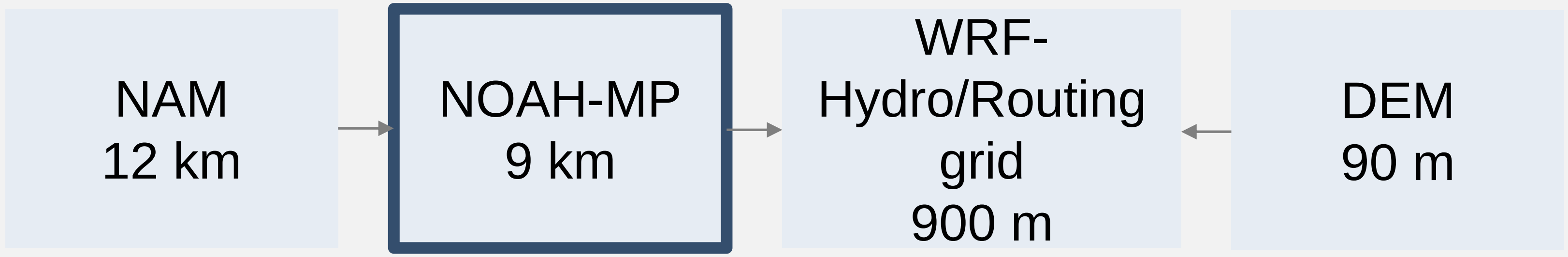
$$\underbrace{\Delta SM + \Delta SWE + \Delta Aq + \Delta Can}_{\Delta W} = P_t - ET - RO$$

P_t	Total precipitation
ET	Land evapotranspiration
RO	Surface + sub-surface runoff
ΔW	Change in terrestrial water storage
SM	Soil moisture in the top 2-meter soil layer
SWE	Snowpack water equivalent
Aq	Aquifer recharge
Can	Canopy interception

Modeling framework

- National Water Model (NWM) configuration for physics parameterizations
- Atmospheric forcing: North American Mesoscale (NAM) 12-km, 6-hourly analysis
- Oct 2016 – Sep 2020 (4 hydrological years)
- 10-year treadmill spin-up

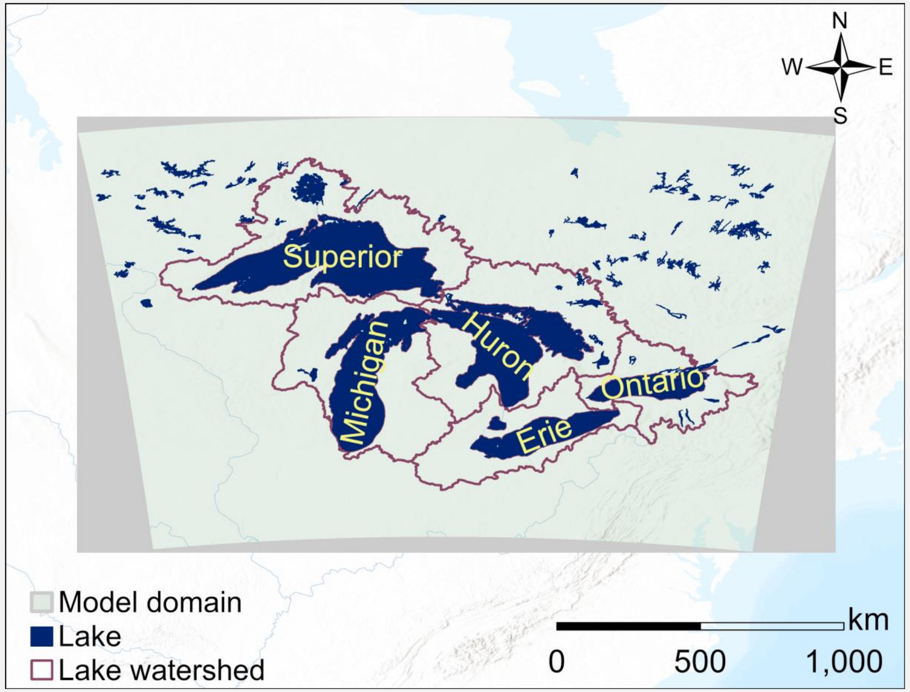
WRF-Hydro
NOAH-MP



Study objectives

1. Identify the **dominant quantities** contributing to the **variability in the land surface hydrology** at **different timescales**

2. Study the **relationships between the budget quantities** and the relative contributions of change in each variable from other components



Principal Component Analysis (PCA)

PCA is a multivariate dimensionality reduction method:

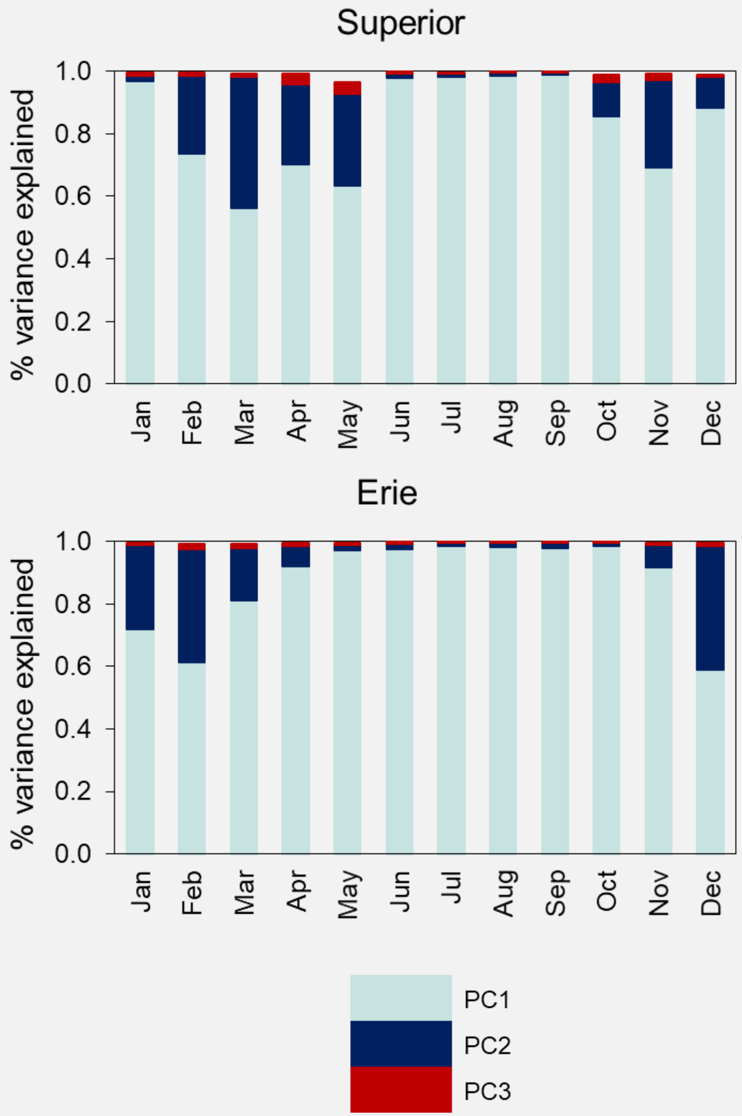
- ➢ Reduces the number of observed variables to components which account for the most variability in the system
- ➢ **Can help identify variables more important to characterize the hydrological regime**

We conducted PCA over two temporal scales for each basin:

(1) Spatially averaged, daily time series → to explain the sub-seasonal variation

(2) Spatially averaged, monthly timeseries → to explain seasonal variation

PCA results: Sub-seasonal timescale

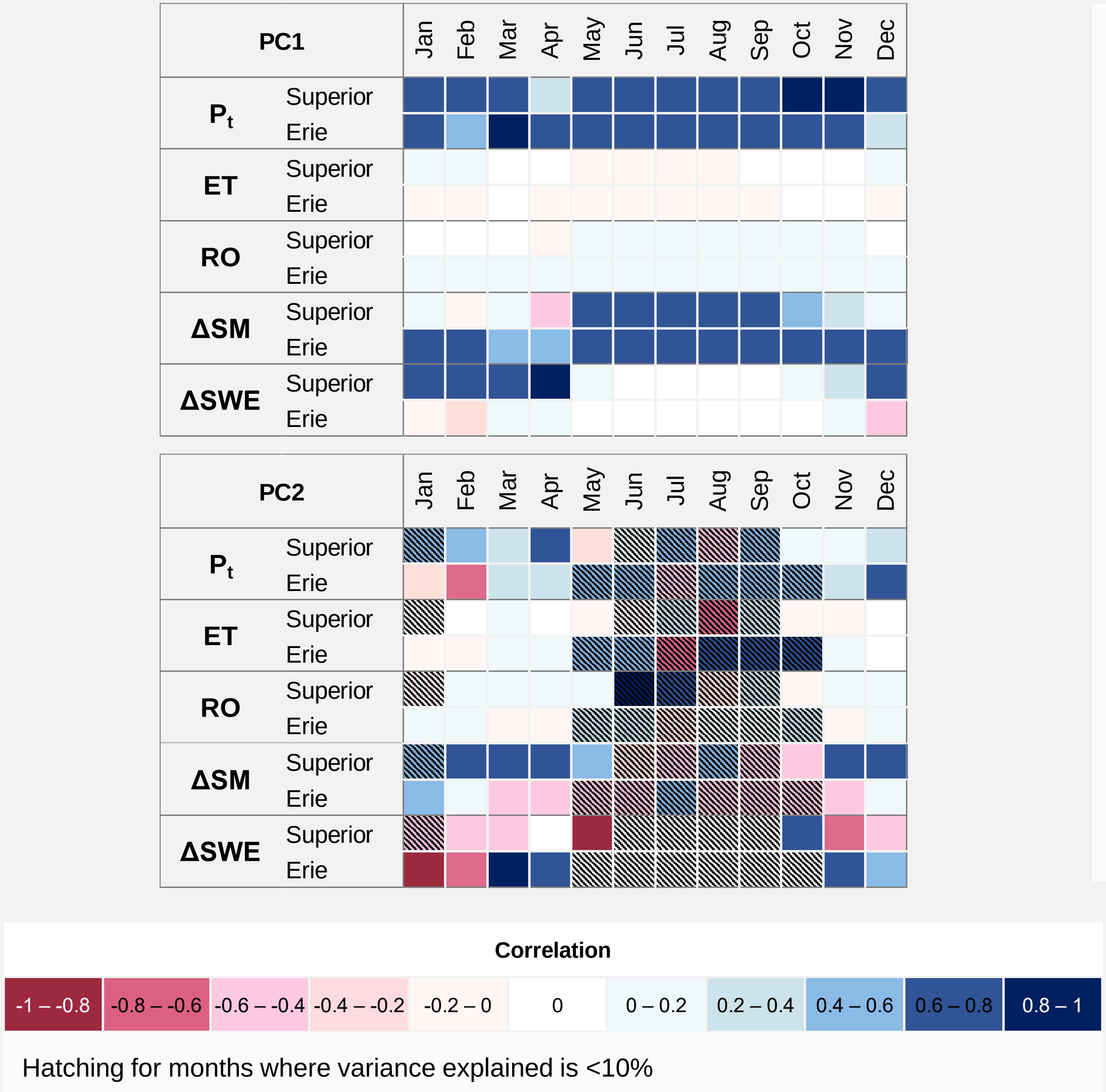


In summer (Jun – Sep), the first PC accounts for nearly all the variance (>97%) in the five basins

In the colder months (Nov – Mar), PC2 also explains a large percentage of the variability in the water budget (~ 40% for some months)

- For Superior, which is located at higher latitudes, PC2 contributes more to Feb – May (25 – 42%) variability
- In Erie, PC2 effect is larger in Dec – Feb (27 – 40%)

PCA results: Sub-seasonal timescale



In summer and autumn (May – Oct), PC1 is highly correlated with only two variables in all basins:

- Precipitation (correlation coefficient varying from 0.72 – 0.76, depending on basin)
- Change in soil moisture (correlation of 0.63 – 0.69)

In the colder months (Nov – Apr), there are differences amongst the basins and the role of ground snow accumulation emerges

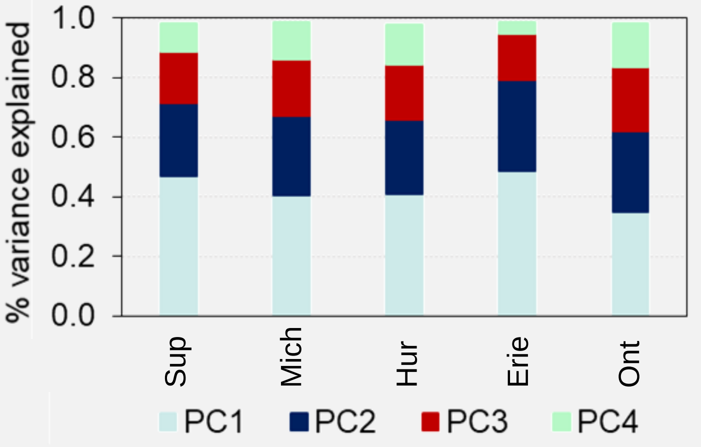
PC2 is also almost entirely correlated with these three variables

PCA results: Sub-seasonal timescale

Key findings

1) **Precipitation** is a year-round important variable in the budget for all basins, not just in terms of magnitude, but also in explaining the variability in the system.
2) **Soil moisture** is a particularly dominant variable for the entire domain in the summer months, and for the southern basins year-round.
3) **Snowpack** is important for the colder season, especially for the northern basins, and less so for Erie.
4) **ET and runoff**, which have relatively large overall magnitudes, and are important quantities in any terrestrial water budget, have no contribution in explaining the variability in the budget.

PCA results: Seasonal timescale



Superior	PC1	PC2	PC3	PC4
P_t	0.21	**-0.68**	**-0.55**	0.11
ET	0.18	-0.45	0.19	**-0.74**
RO	0.28	-0.38	0.32	**0.57**
ΔSM	0.37	0.35	**-0.67**	-0.10
ΔSWE	**-0.82**	-0.24	-0.32	0.08
ΔCan	0.00	0.00	0.00	0.00
ΔAq	0.20	0.04	-0.08	0.30

Erie	PC1	PC2	PC3	PC4
P_t	0.15	**0.87**	-0.08	
ET	**0.82**	0.06	-0.34	
RO	0.07	0.33	**0.76**	
ΔSM	-0.48	0.34	**-0.53**	
ΔSWE	-0.02	-0.01	-0.06	
ΔCan	0.00	0.00	0.00	
ΔAq	-0.26	0.15	0.09	

More components (PCs 1 – 4) are needed to explain the maximum variance

Importance of other processes emerges along with greater differences amongst the basins

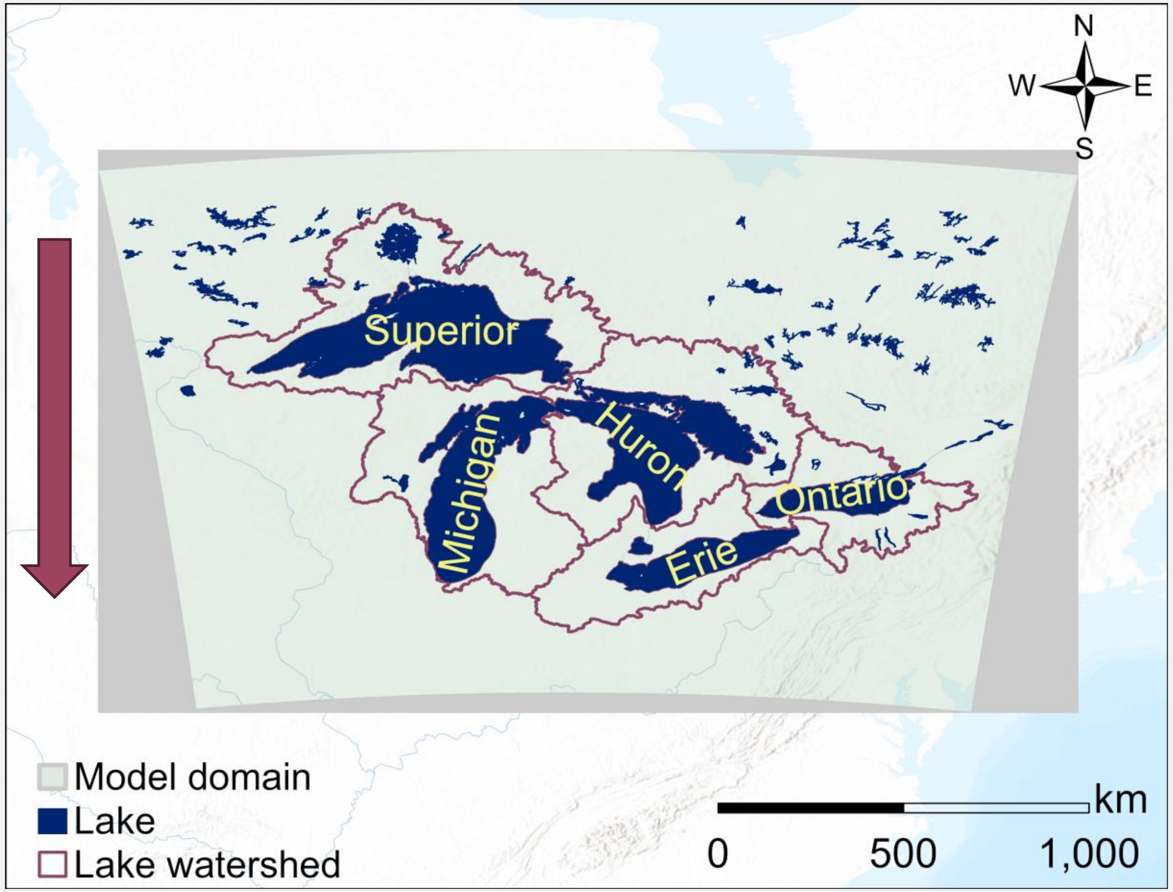
- In Superior, PC1 is strongly correlated with ΔSWE, PC2 with precipitation, and PC3 primarily with ΔSM.
- In Erie, P_t – ET – RO quantities dominate the budget variability

PCA results: Seasonal timescale

Northern region: snowpack and precipitation are the drivers of variability

Middle domain: role of evapotranspiration and soil moisture becomes evident

Southern region: precipitation-evapotranspiration-runoff nexus is the dominant source of variability



Study objectives

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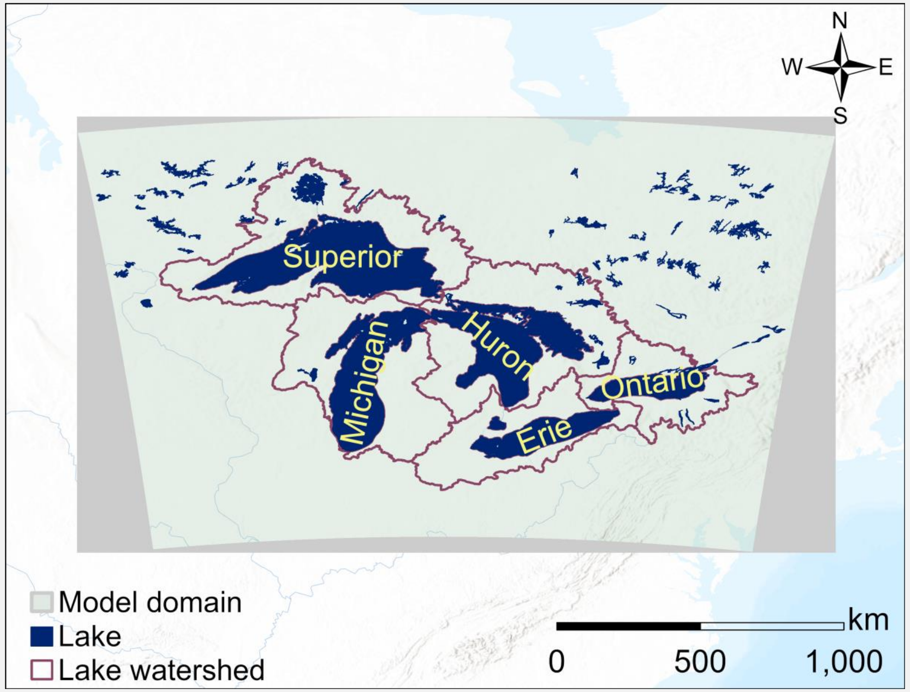


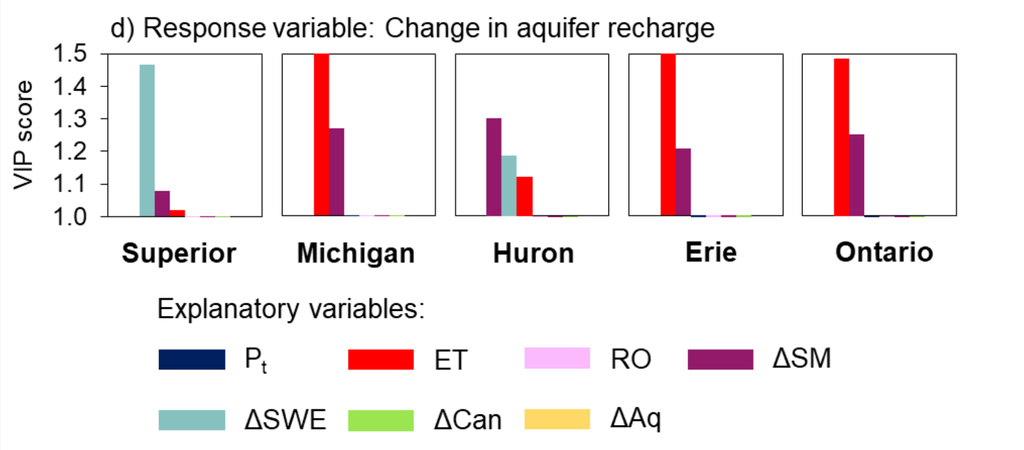
Partial Least Squares Regression (PLSR)

PLSR is another multivariate statistical approach which projects data to a new component space:

- Key distinction from PCA:
    - It establishes a relationship between a dependent variable (response variable) and a set of independent variables (explanatory variables)
    - VIP score (variable influence on projection) measures the importance of each explanatory variable for the response variable.

We use the PLSR approach to establish the most important predictor variables that drive change in each budget quantity at seasonal timescales

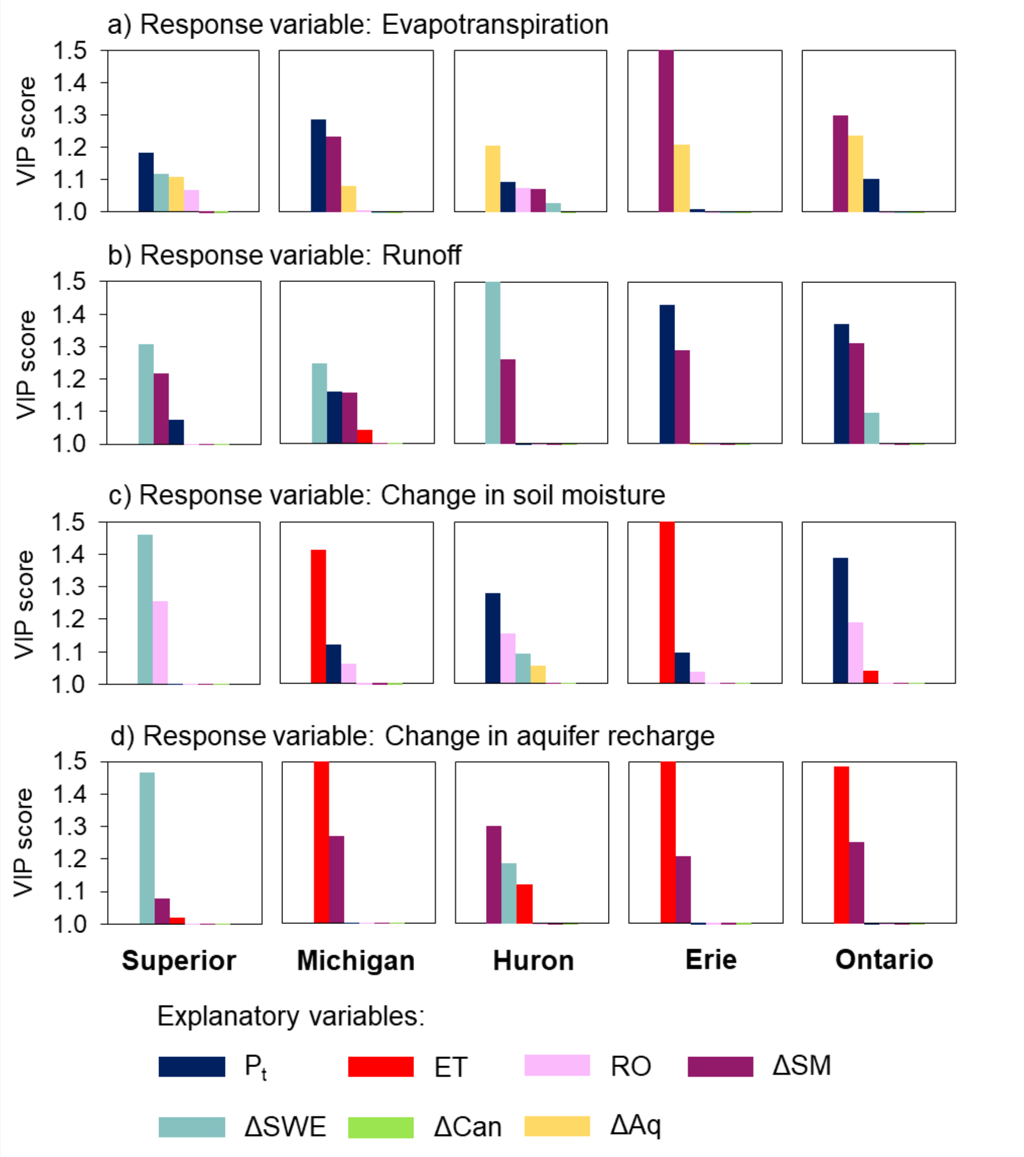
PLSR results: Relationship among the terrestrial budget quantities



ΔAq changes are driven by ΔSWE in Superior, and ET and ΔSM in the other watersheds

A VIP score >1 is considered important for the projection

PLSR results: Relationship among the terrestrial budget quantities



Runoff dependence is primarily on ΔSWE for Superior, Michigan, and Huron. In the southern basins, precipitation is the main driver of variability in runoff

Bidirectionality in some links, for example, the ΔSM – ET dependence in Erie

Change in one quantity can be a predictor of fluctuations in another – these “predictors” of each quantity vary for the five watersheds

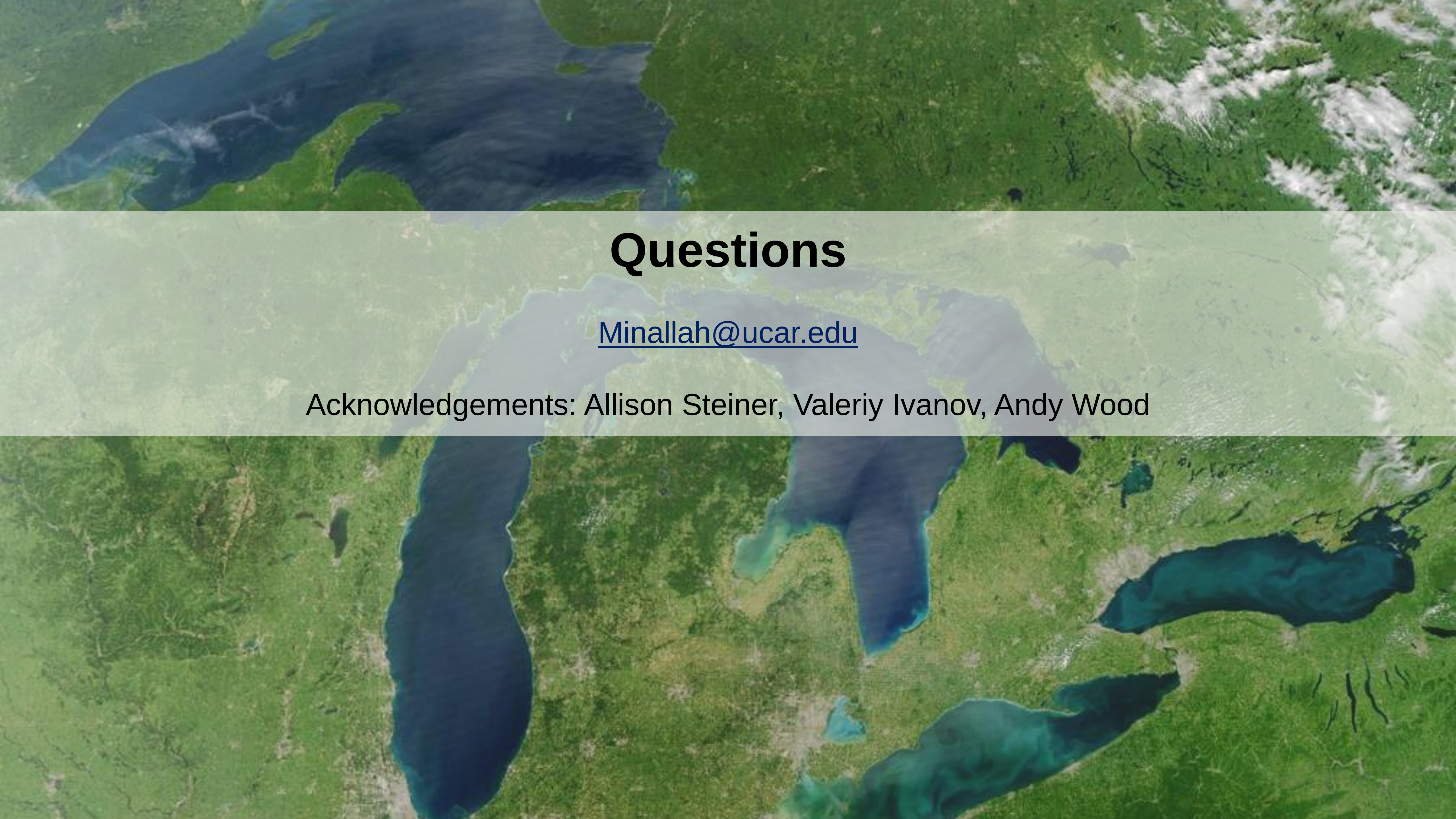
Conclusions

Key points

- ❖ The Great Lakes domain is not a hydrologically uniform regime, and the basins have differences in the dominant regulators of water budget.
- ❖ Dominant quantities characterizing the subregional terrestrial hydrology vary for daily, monthly, and annual timescales.
- ❖ Climate change impact studies on regional hydrology need to account for basin-scale differences in the terrestrial hydroclimatic dynamics

Future work

- ❖ Provides baseline to assess modifications in the budget due to changes in the atmospheric forcing
    - **Next step:** Quantify the effects of changes in atmospheric forcing e.g., temperature (warming/cooling) and precipitation (magnitude and phase) on the terrestrial water budget



Questions

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Acknowledgements: Allison Steiner, Valeriy Ivanov, Andy Wood

Surface runoff schemes

```
RUNOFF_OPTION                   = 1                     ! options for runoff and groundwater      [default = none]

                                                        !   1 -> TOPMODEL with groundwater (Niu et al. 2007 JGR) ;
                                                        !   2 -> TOPMODEL with an equilibrium water table (Niu et al. 2005 JGR) ;
                                                        ! **3 -> original surface and subsurface runoff (free drainage)
                                                        !   4 -> BATS surface and subsurface runoff (free drainage)
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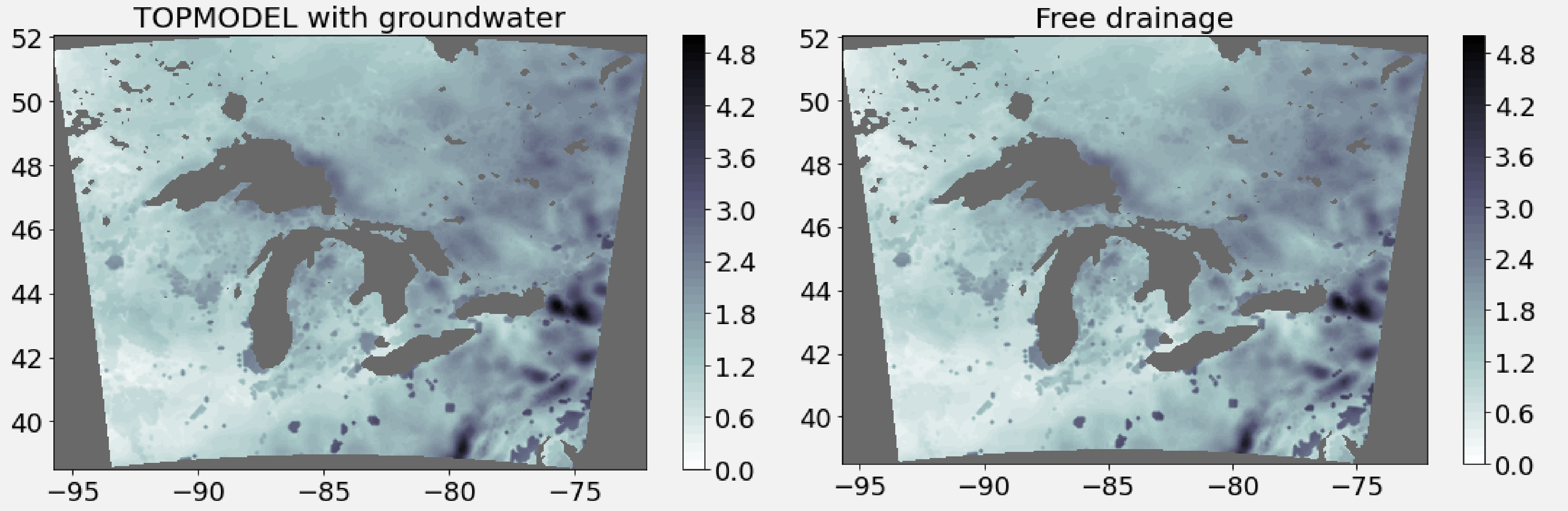
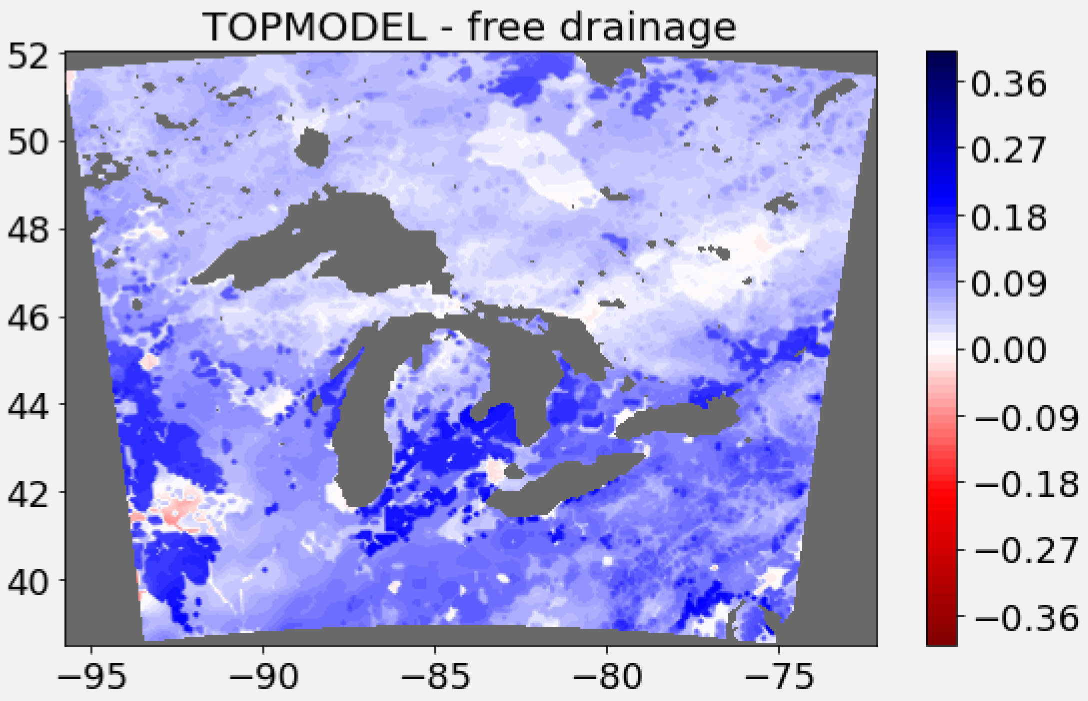
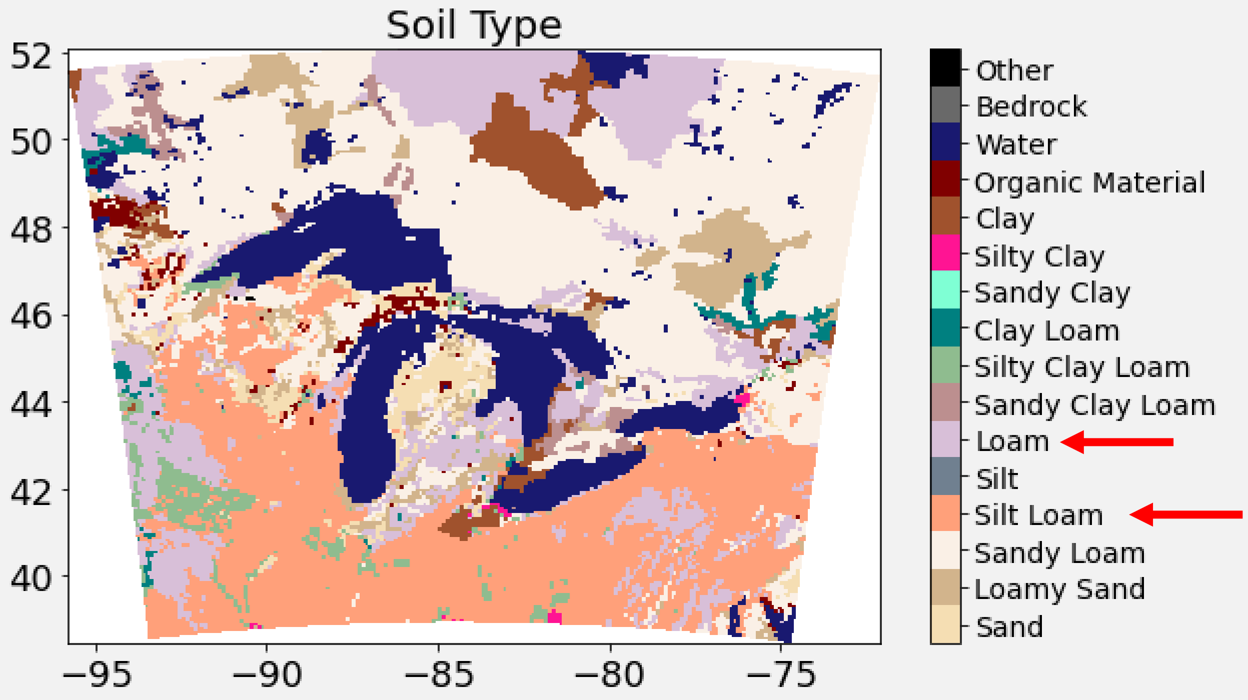


Surface runoff schemes

- Magnitude differences between the two schemes are small
- TOPMODEL has slightly higher magnitudes - especially in regions where soils are Loam/Silty Loam (i.e., southern regions of the domain)

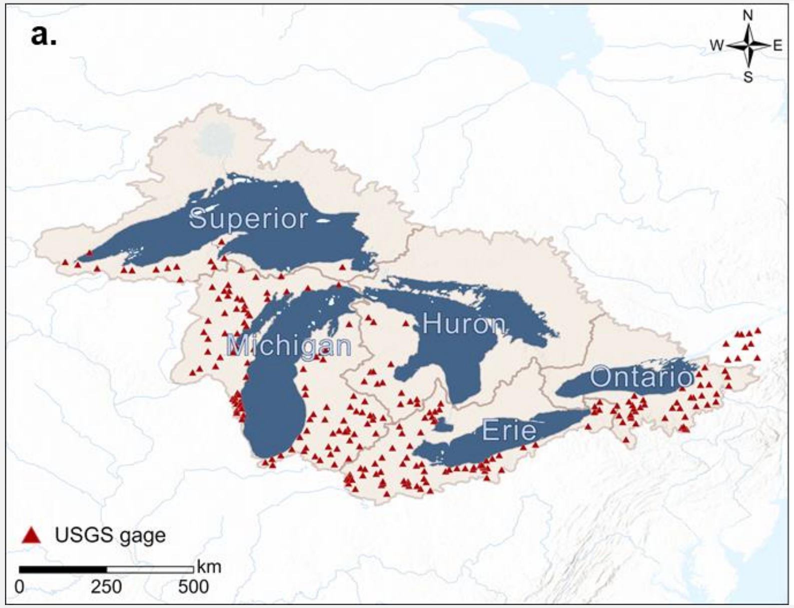


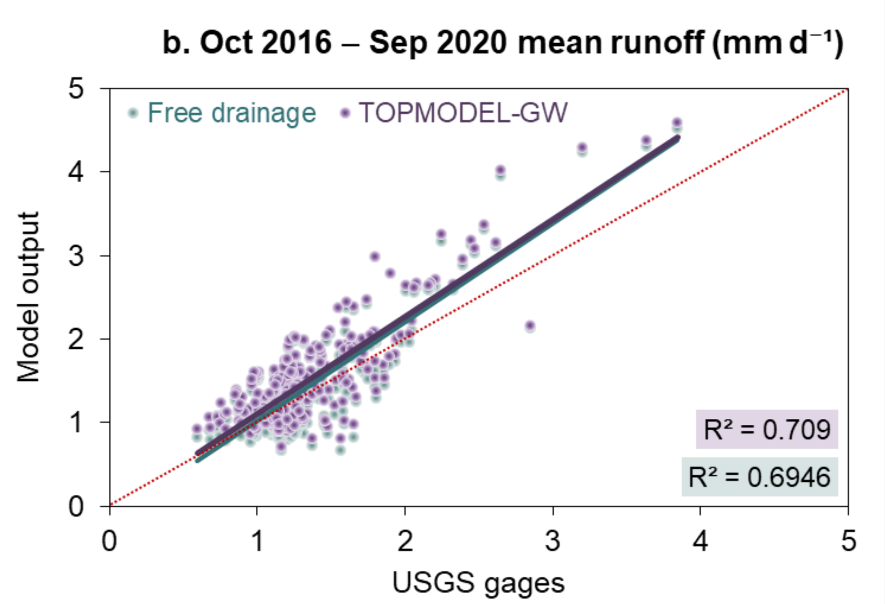


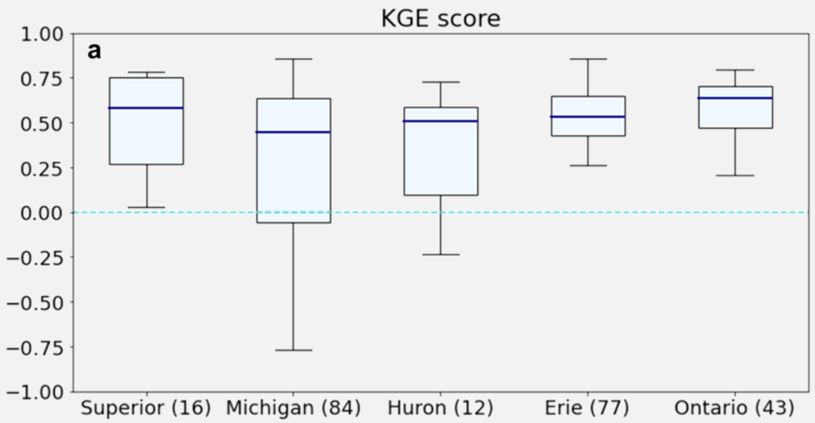
Output evaluation and validation

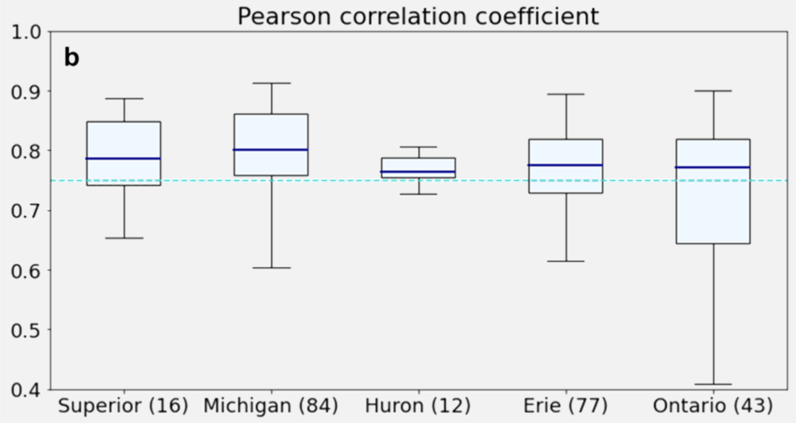
Variable	In-situ	Observation-based	Satellite-derived	Reanalysis
Precipitation		CRUv4.05		ERA5, MERRA2
Evapotranspiration			GLEAM v3.5b	ERA5, MERRA2
Runoff	USGS gauges			ERA5, MERRA2
Soil moisture			SMAP-HB	ERA5, MERRA2
SWE				ERA5, MERRA2
Canopy interception				ERA5

Runoff validation (USGS gauges)

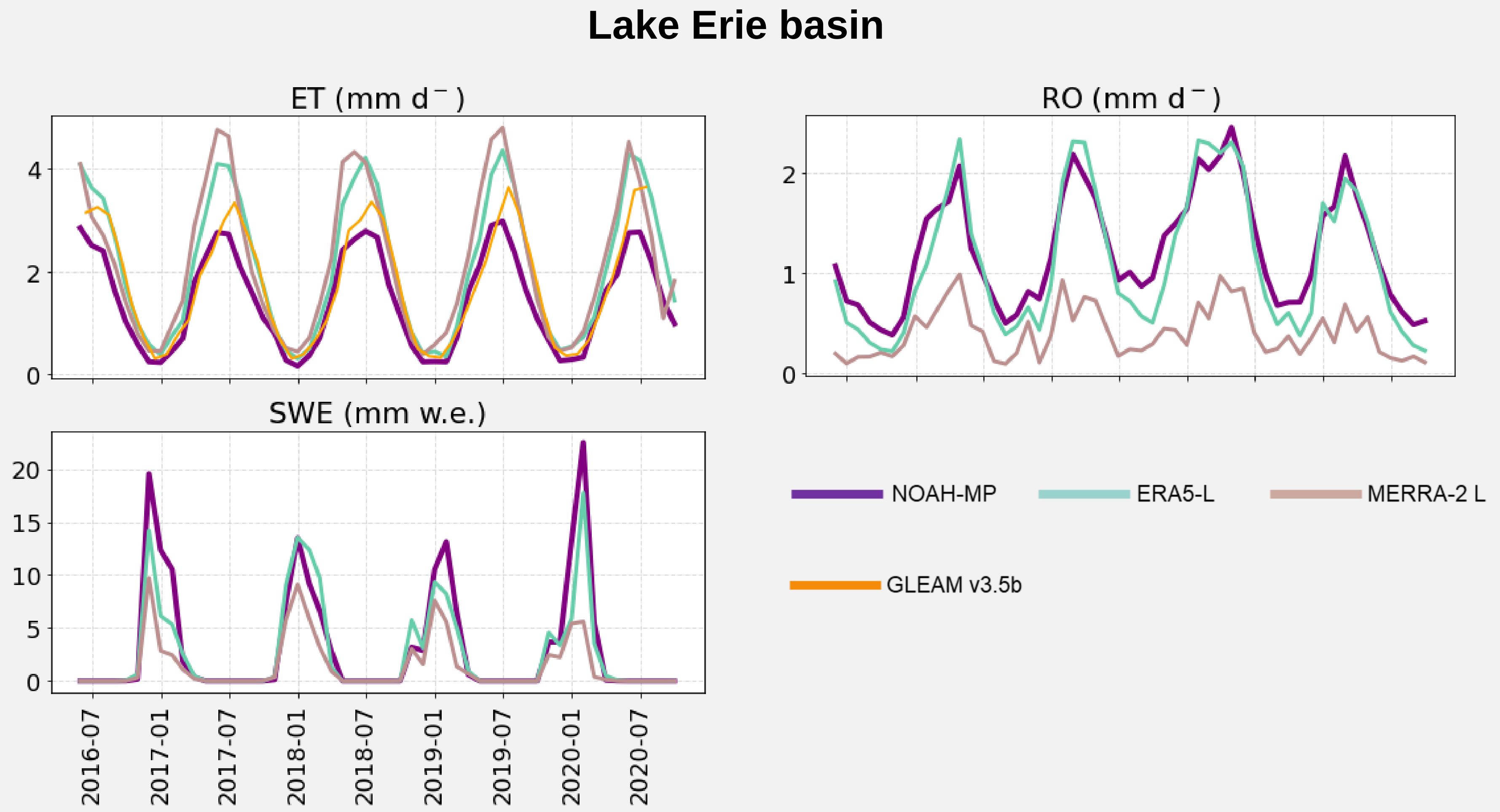




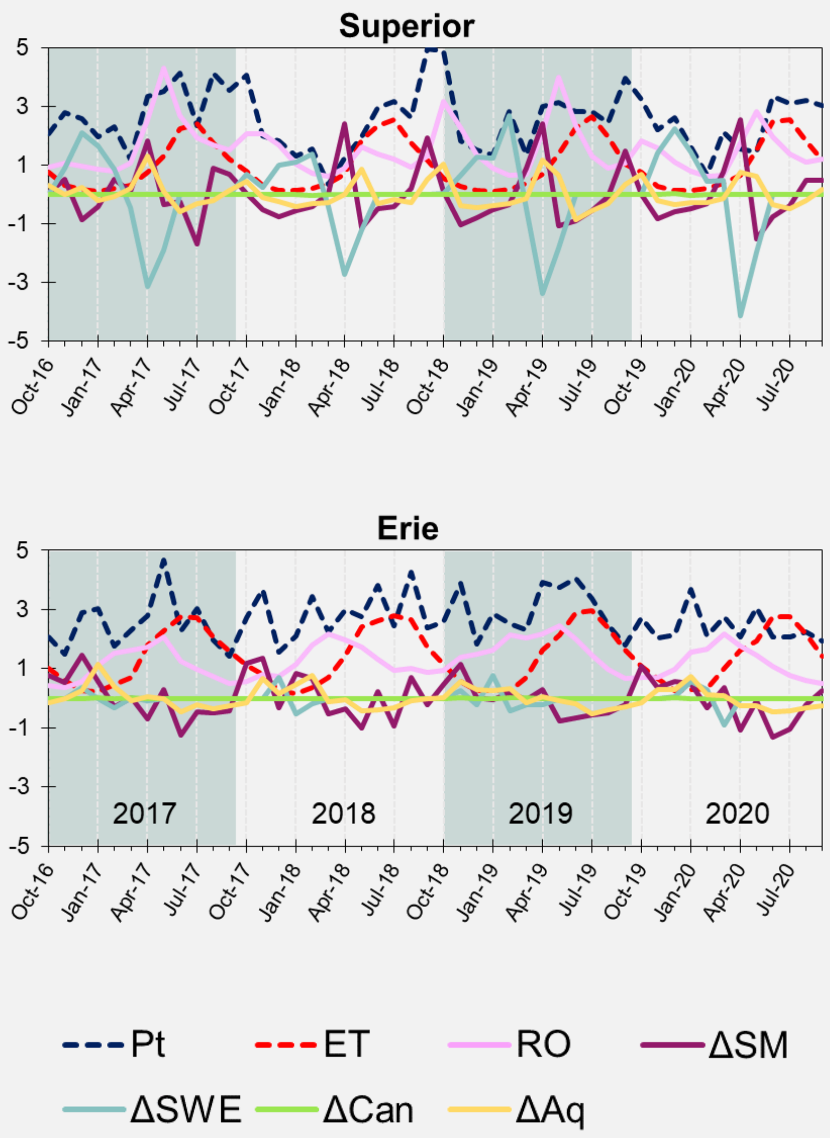




Output evaluation (Reanalysis and gridded products)

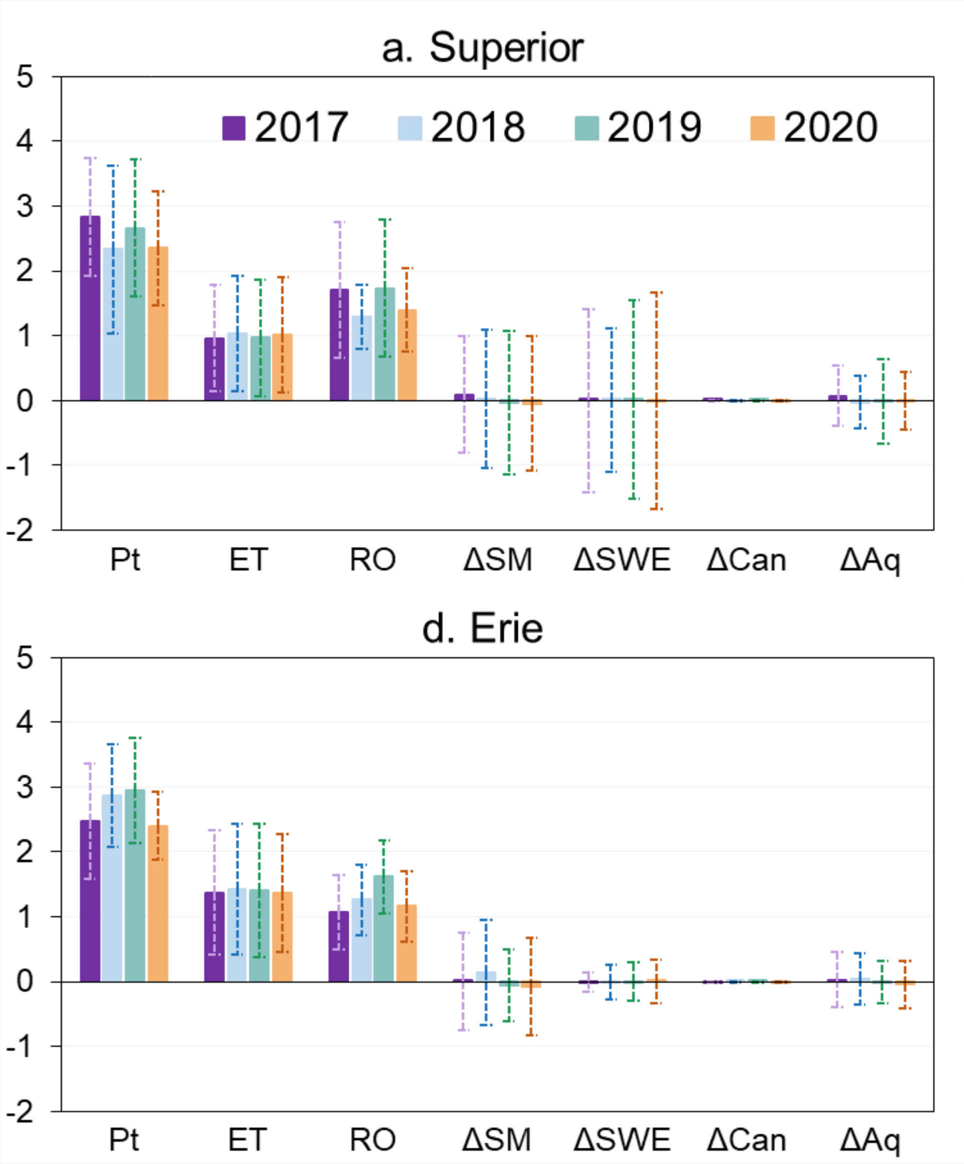


Seasonal cycles



- ET has a distinct seasonal cycle with the maxima in July for all basins
- All other variables have inter- and intra-annual and basin-wide differences
- Runoff generally peaks in spring (March – May): southern regions peak earlier, and Superior runoff maximum is in May
- The absolute magnitude of ΔSWE for Erie is small and highest for Superior
- Change in canopy interception is orders of magnitude smaller and can be ignored

Annual magnitudes



For the annual budget magnitudes:

- The water budget is controlled by the Pt–ET–RO nexus
- Change in terrestrial water storage (ΔW) is negligible
- But high standard deviation in the snowpack (ΔSWE) and soil moisture (ΔSM) → **importance of terrestrial water storage at sub-annual timescales**