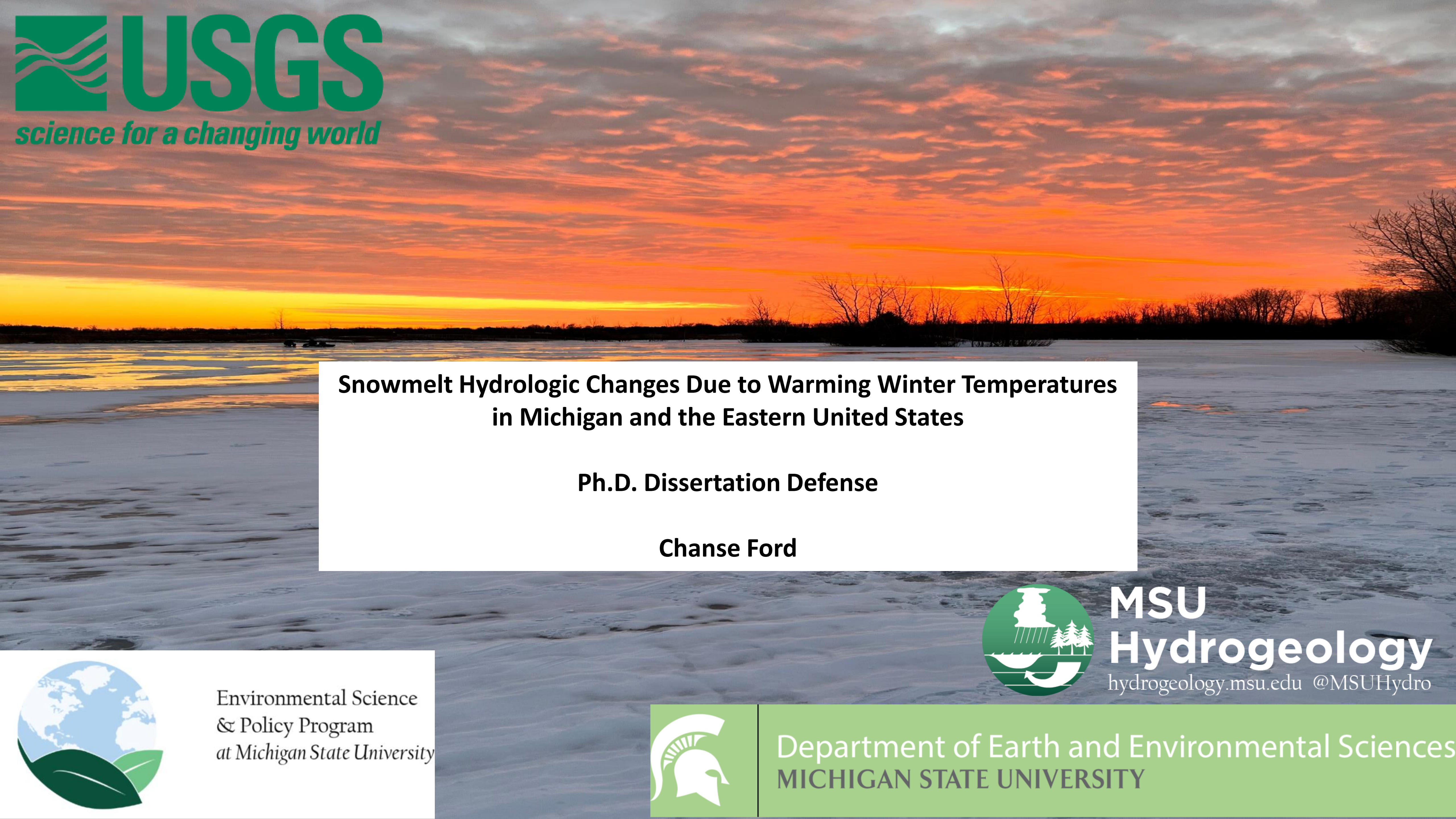

USGS
science for a changing world

Snowmelt Hydrologic Changes Due to Warming Winter Temperatures in Michigan and the Eastern United States

Ph.D. Dissertation Defense

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Motivation

Snow is a critical component of Great Lakes hydrology

Literature in snow hydrologic changes for non-alpine settings lacking

- Snow studies in non-alpine, non-arctic settings generally too big or too small
  - Continental or country scale settings too coarse for regional/local interpretations
  - Studies at local/regional scales focused on one aspect of hydrologic cycle

January 18, 2020

February 1, 2020

Significance

Changes to melt amounts and timing could affect:

- Ecosystems
  - Spring a critical spawning time for many freshwater fish species-spawning sensitive to temperature and flow changes
- Infrastructure
  - Shifts in flooding from spring to winter could have management implications
  - Great Lakes one of the largest fresh water reservoirs on the planet
- Economies
  - Snow tourism spending

Dissertation Objectives

- Identify winters warmer and cooler than the norm
- Quantify changes to snow melt
  - Timing
  - Amount
  - Frequency of coverage
- Quantify hydrologic changes
  - Surface water flow amounts and timing
  - Shallow groundwater recharge amounts

Approach

1. Lay the Foundation
    - Small temporal and spatial scales
    - Establish methodology
2. Expand the temporal and spatial scale
    - Larger areas lead to better interpretation
    - Longer temporal scales establish changes to climate
3. Fill in the data gaps through simulation
    - Empirical groundwater data not as available as surface processes
4. Examine real-world consequences
    - Makes the data tangible, leading to more informed public and decision makers

Ch. 1: Laying the Foundation

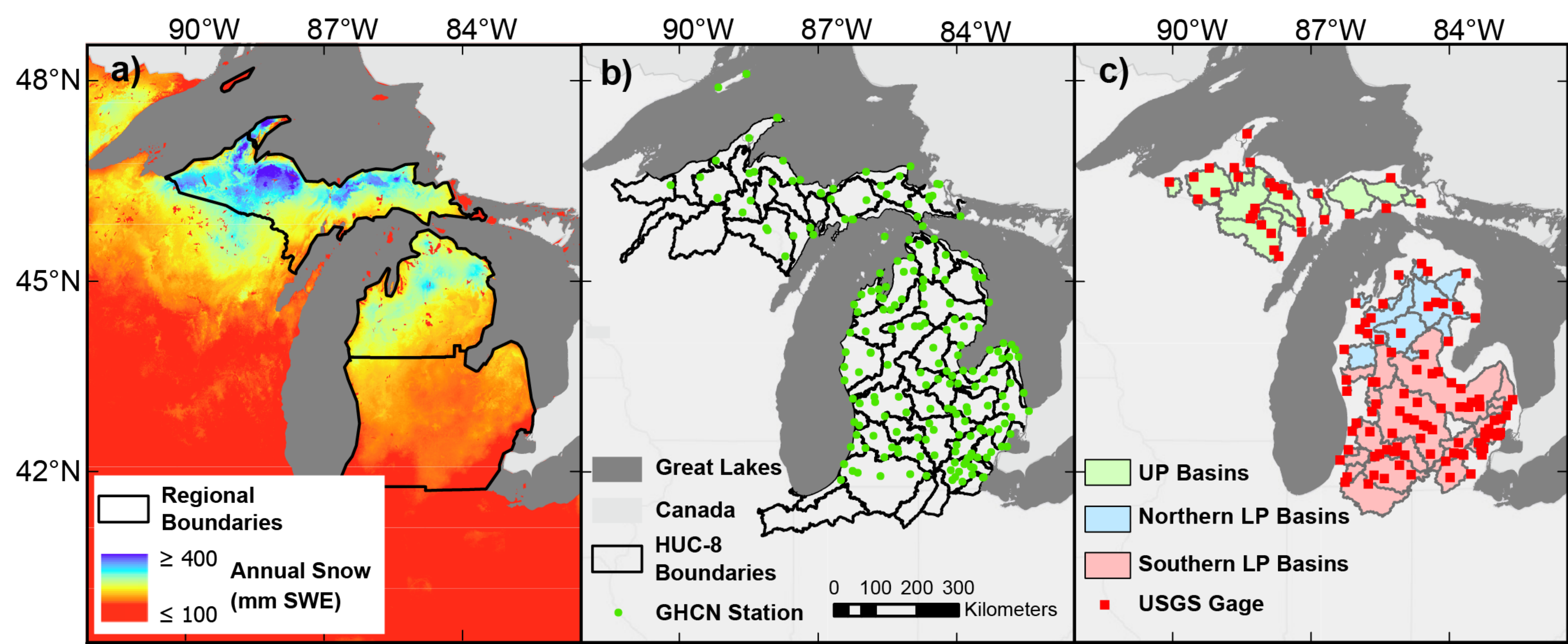
Michigan from 2003-2017

Aggregations: 3 State regions (a), HUC-8 drainage basins (b), DEM-defined drainage basins (c)

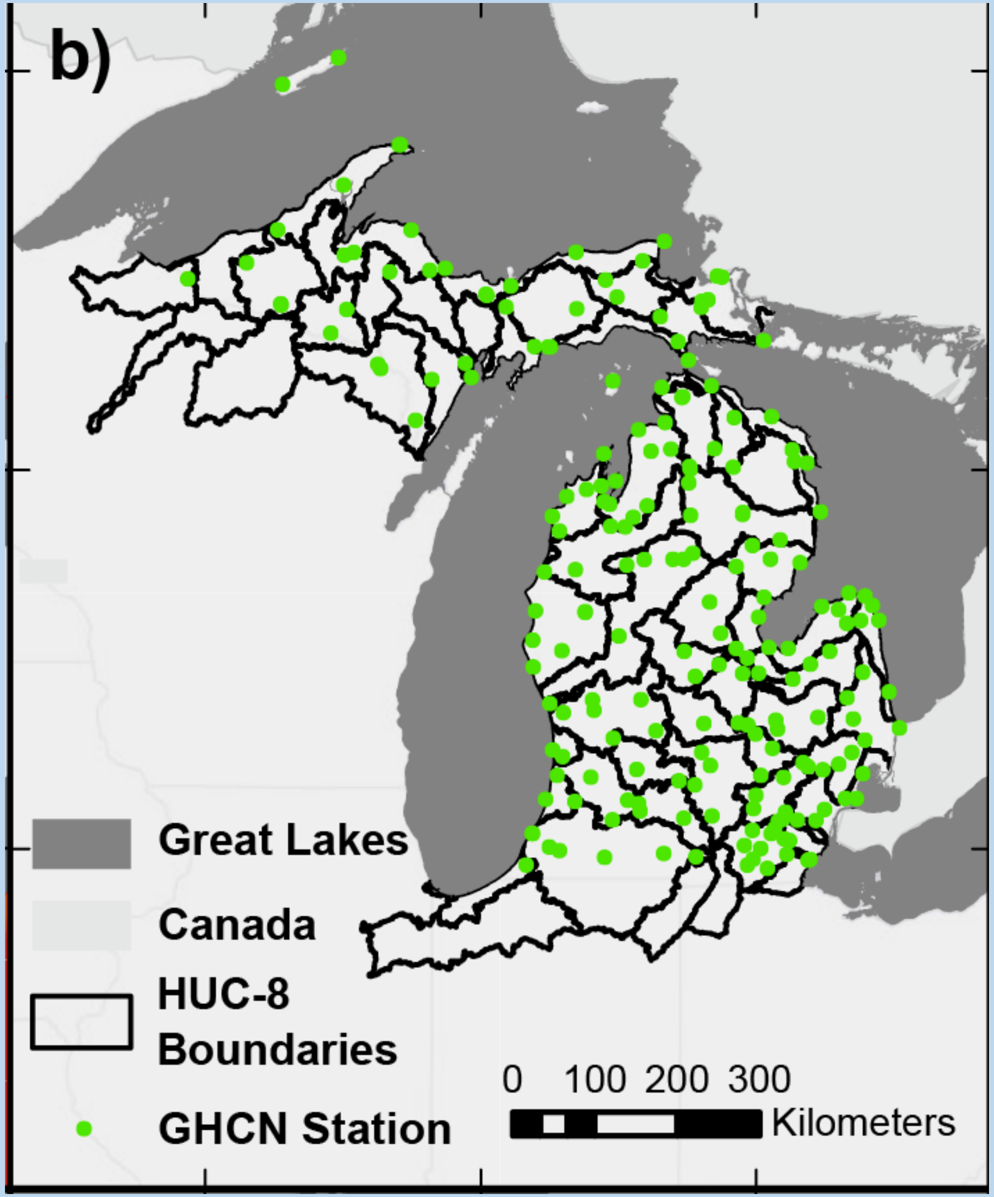
240 GHCN stations

123 USGS gages

Simulated depth and SWE from SNODAS



Multimetric Analysis

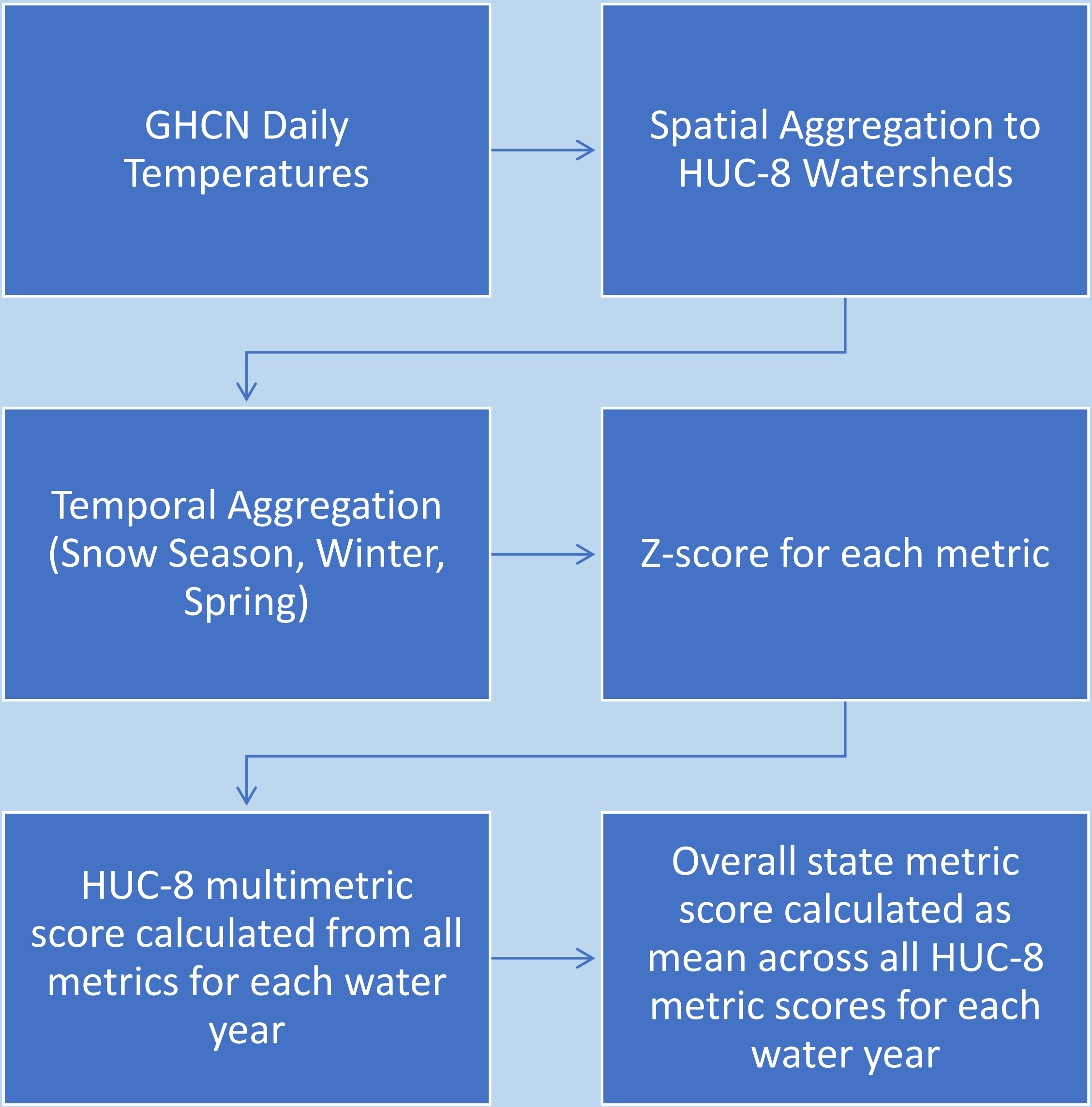


1. GHCN Daily Temperatures
2. Spatial Aggregation to HUC-8 Watersheds
3. Temporal Aggregation (Snow Season, Winter, Spring)
4. Z-score for each metric
5. HUC-8 multimetric score calculated from all metrics for each water year
6. Overall state metric score calculated as mean across all HUC-8 metric scores for each water year

Multimetric Analysis

6 metrics of mean and min temps

- Mean and min temp for snow months (Oct-May)
- Mean and min temp for winter months (DJF)
- Mean and min temp for spring months (MAM)

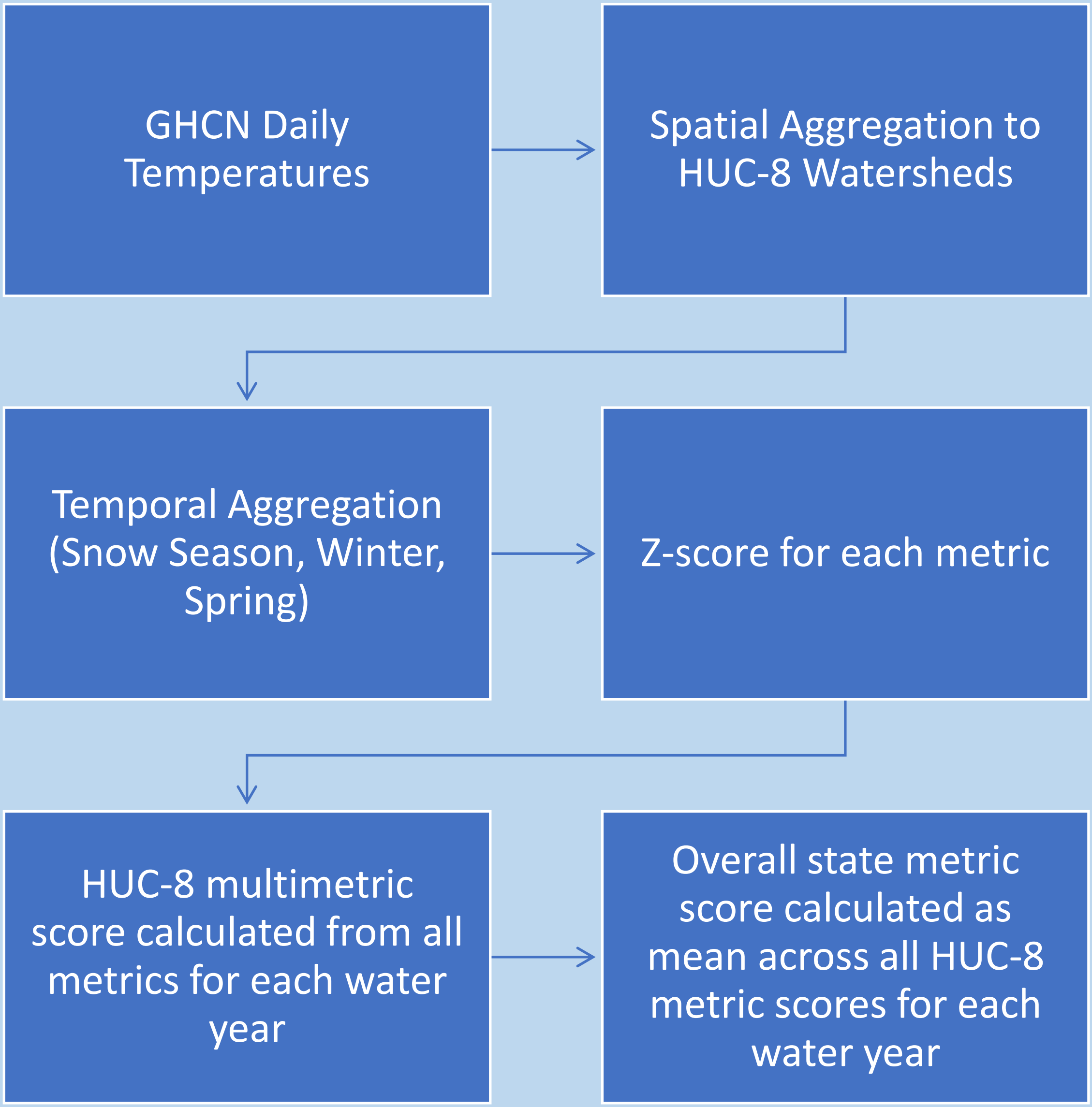


Multimetric Analysis

For each metric, z-score calculated

$$Z = \frac{x - \mu}{\sigma}$$

Z = z-score (metric score)
x = obs. Value
μ = mean of the sample
σ = standard deviation of the sample

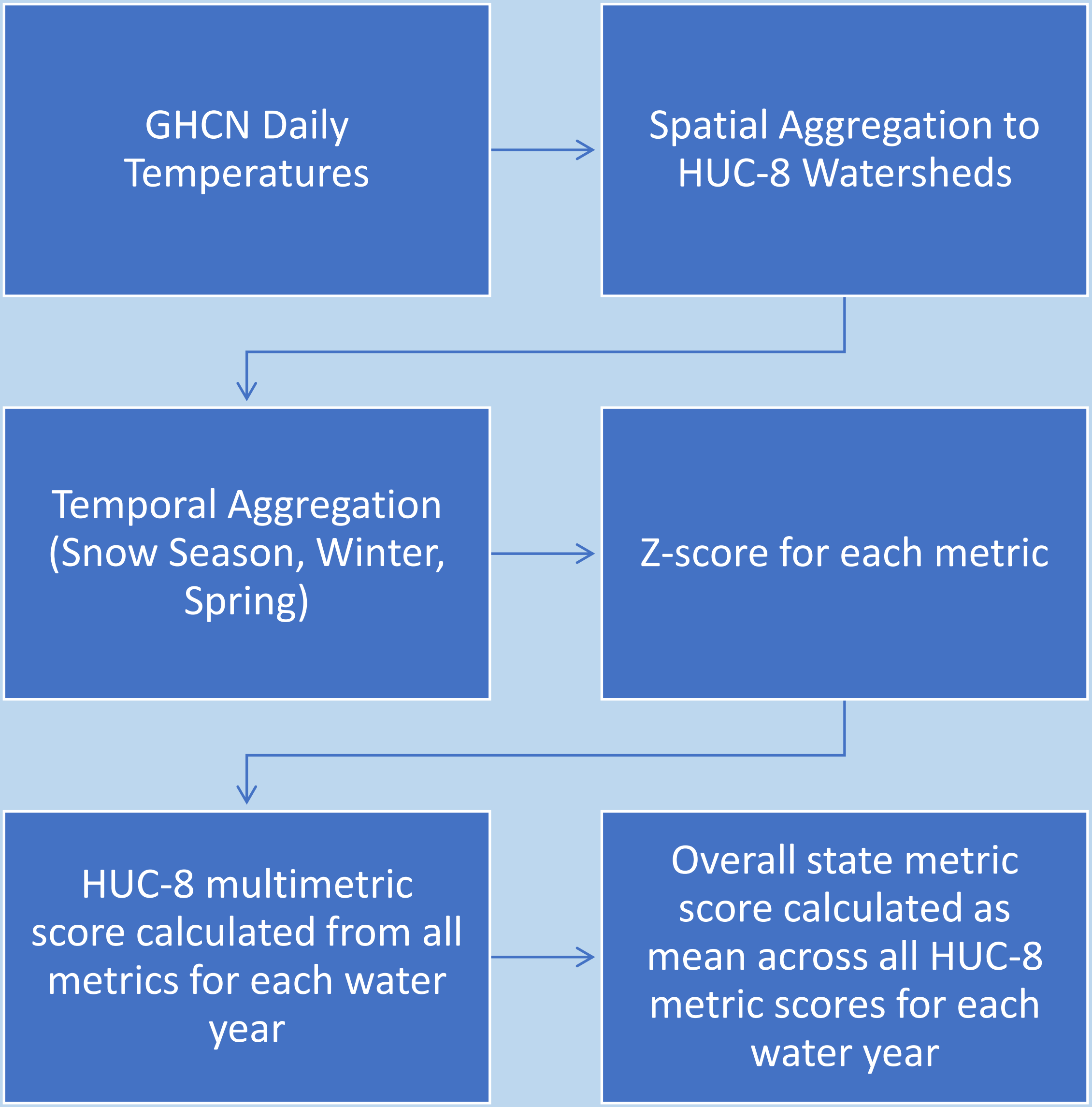


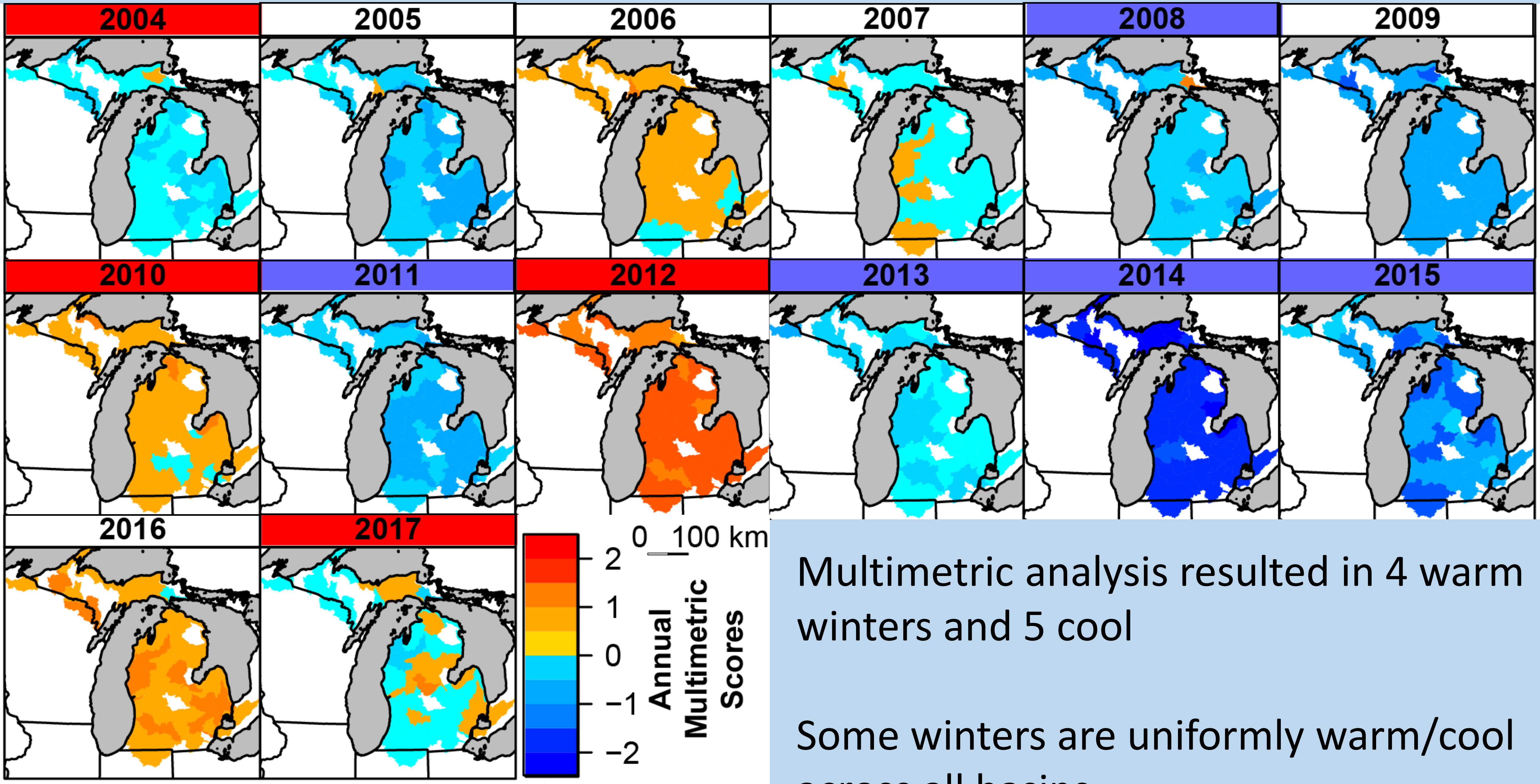
Multimetric Analysis

Mean of 6 z-scores = multimetric score for that winter for that HUC

Then averaged across all HUC’s in state for one multimetric score for that water year

Scores > 0.5 were deemed “warm” and < -0.5 deemed “cool”





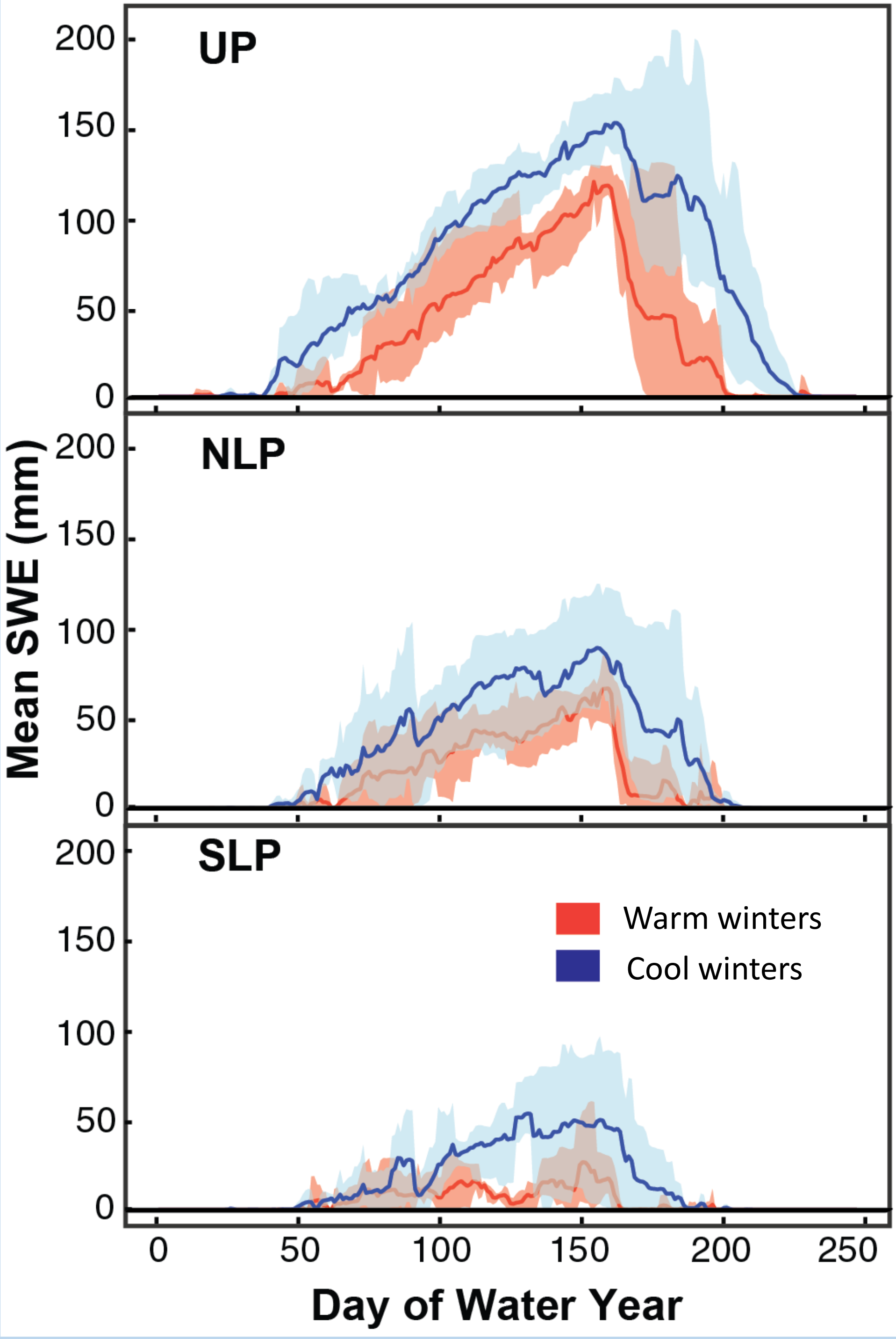
Multimetric analysis resulted in 4 warm winters and 5 cool

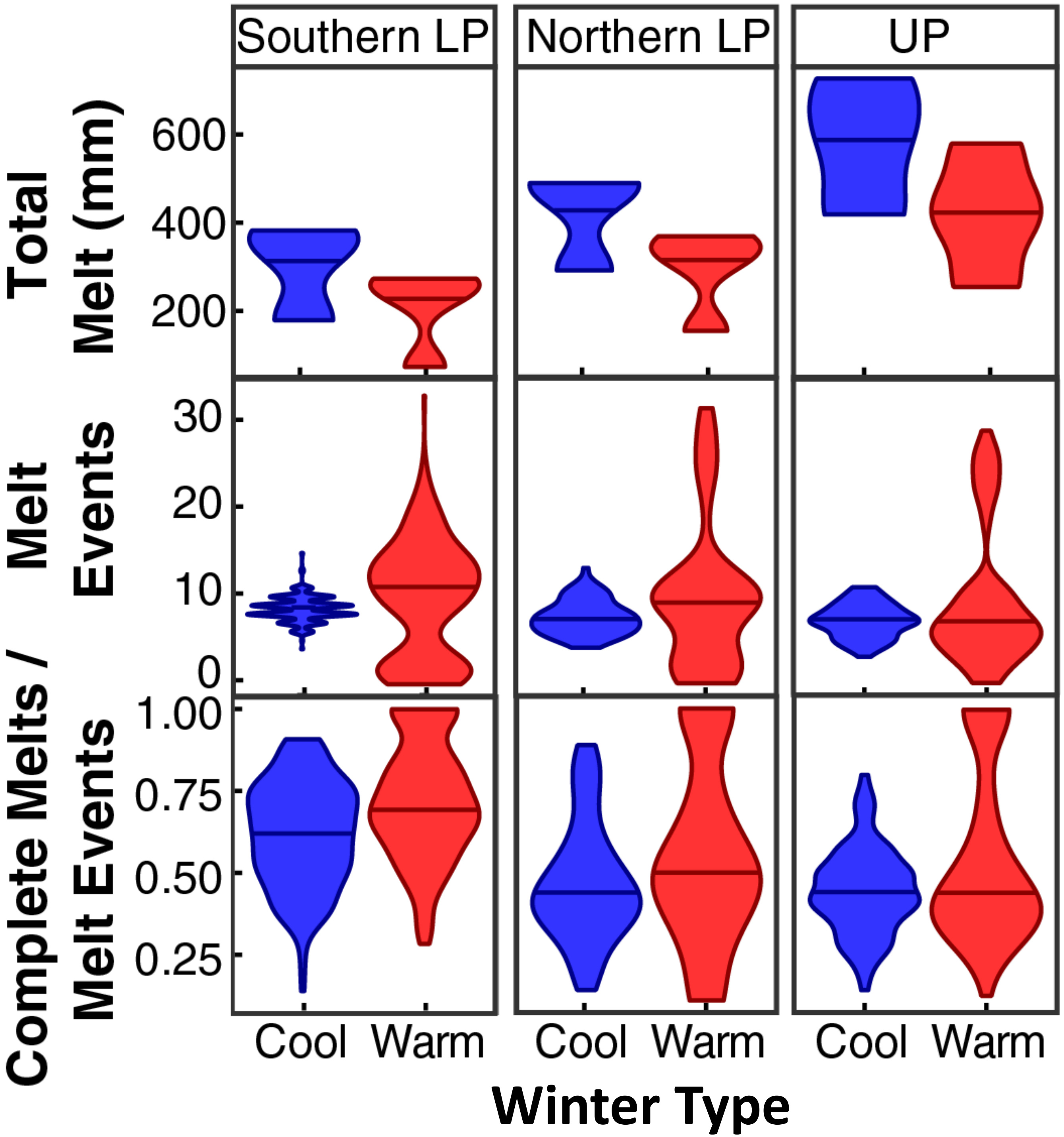
Some winters are uniformly warm/cool across all basins

Warmer winters in all regions have decreased SWE throughout most of the season and melt earlier

Differences between warm and cool winters increase northwards

Latitudinal differences evident regardless of year type





Melt event defined as periods of consecutive days with melt generated from snowpack

- Complete melts are melt events that end with no remaining snowpack

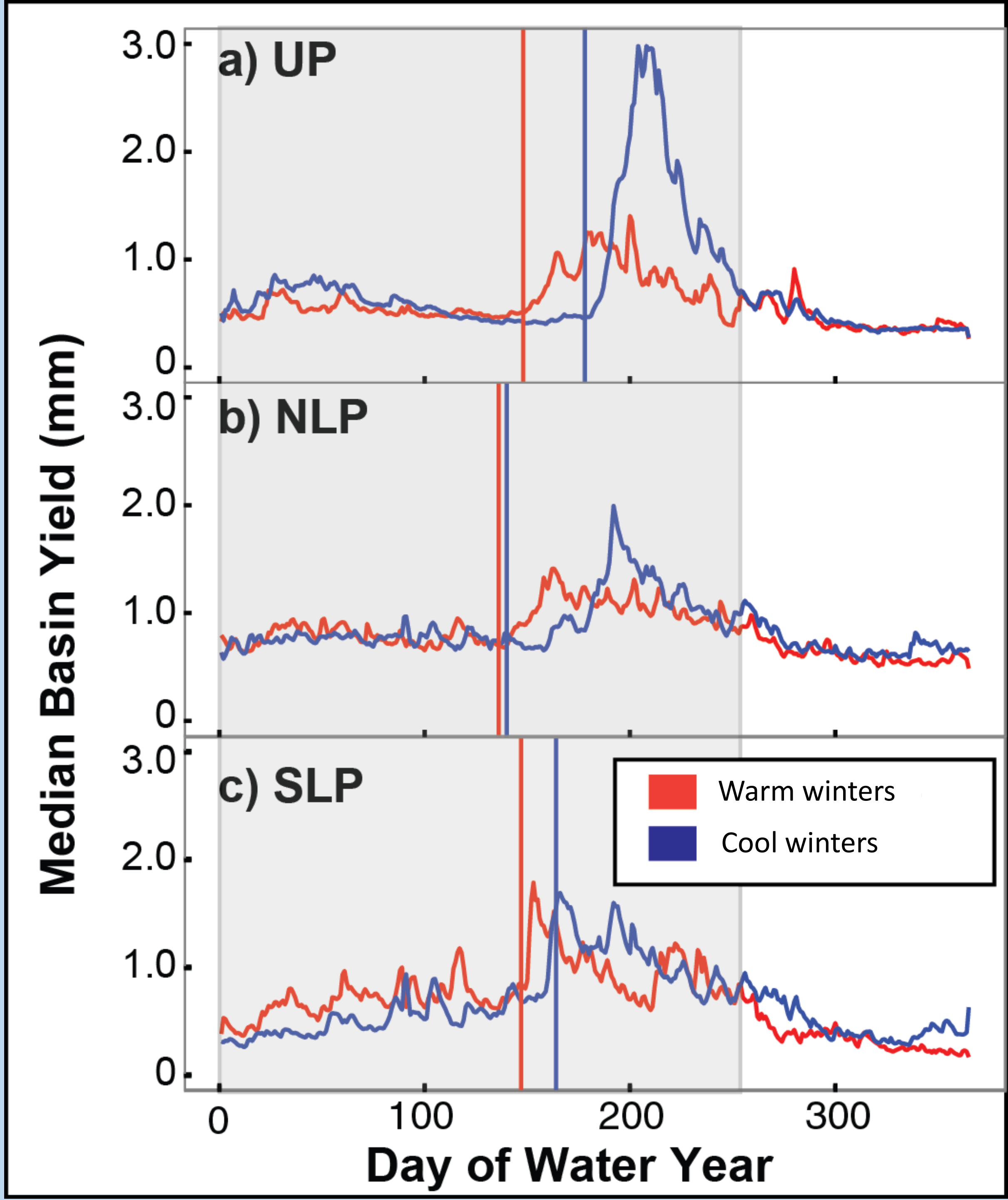
More melt in the north regardless of winter type, but more melt events in the south

Basin yield defined as stream discharge/basin area

- Vertical lines represent center of discharge volume (CDV) for Oct-May (gray box), or the day when 50% of that period's flow has occurred

Warm years have earlier and reduced peak flows, especially in the northern two regions

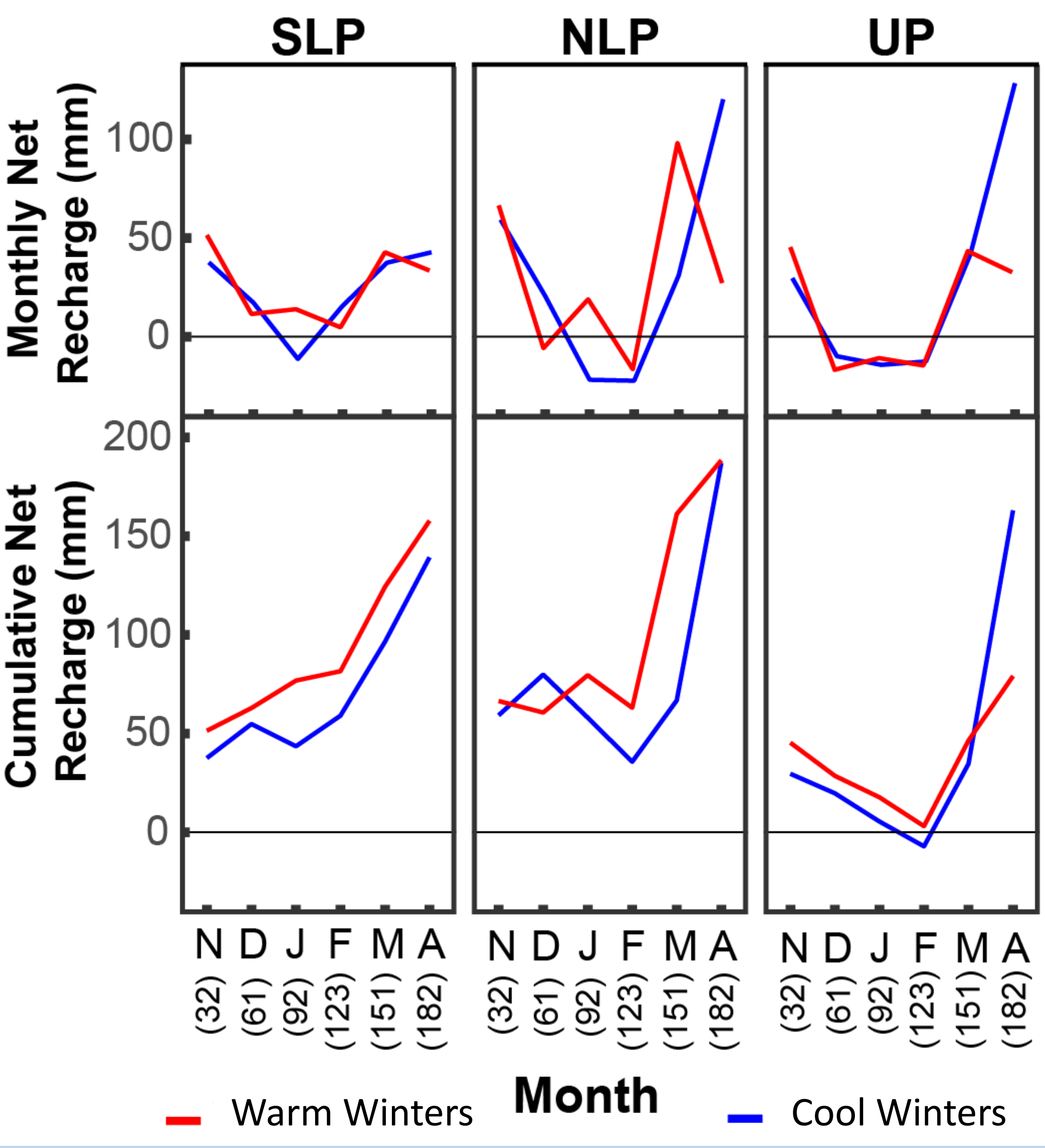
Warm years also have earlier CDV for snow period

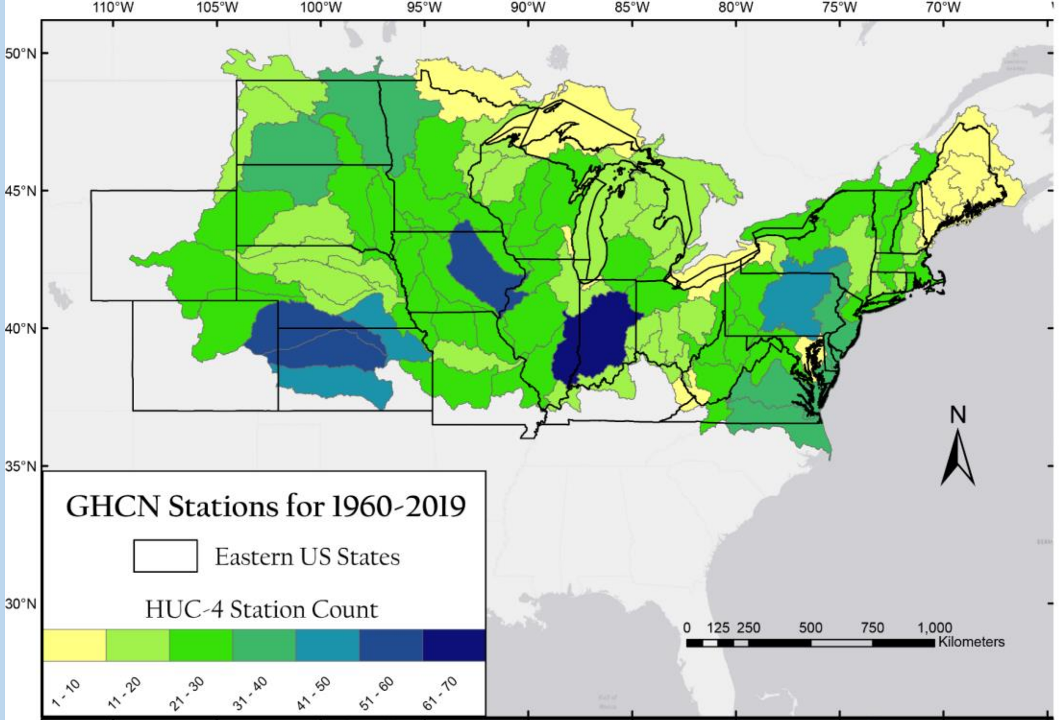


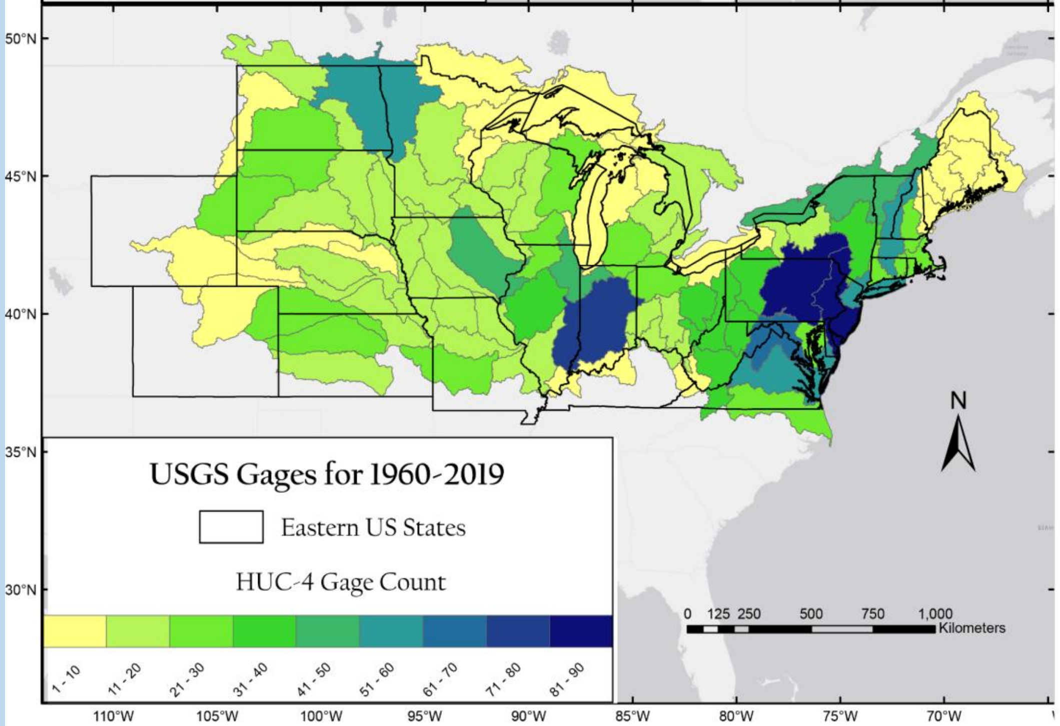
Estimate monthly net recharge to shallow groundwater using the water balance equation:

$$\Delta S = P + M - Q$$

ΔS: change in groundwater storage (i.e., net recharge)
P: Rain
M: Melt
Q: stream discharge expressed as basin yield







Ch. 2: Expanding Scales

October 1959 – May 2019

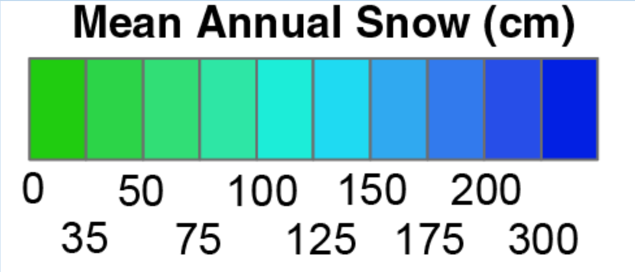
- Climate data from Global Historical Climatology Network (GHCN)
  - 1,369 temperatures stations
  - 1,725 snow stations

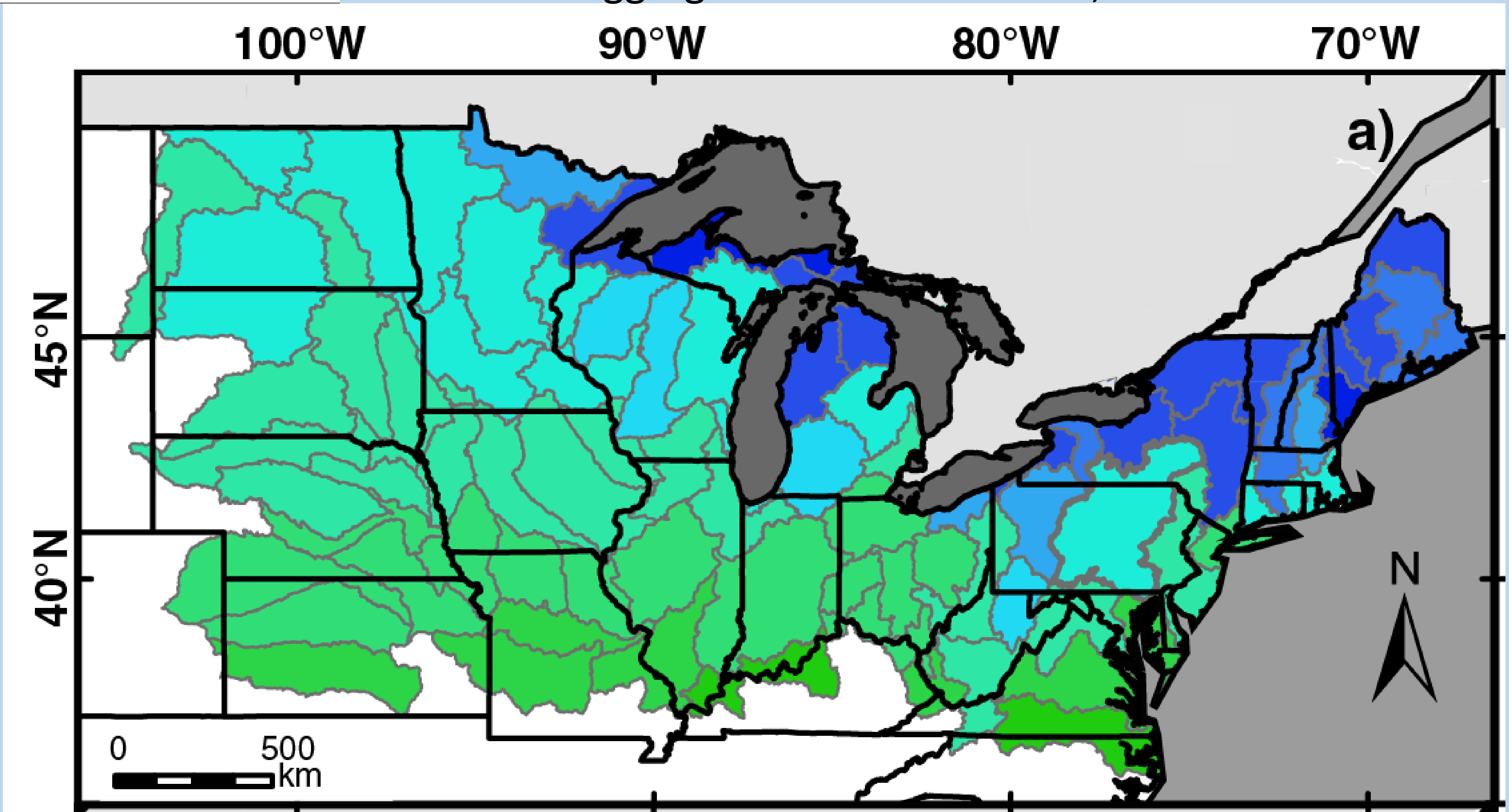
Stream data from US Geological Survey (USGS) stream gage network

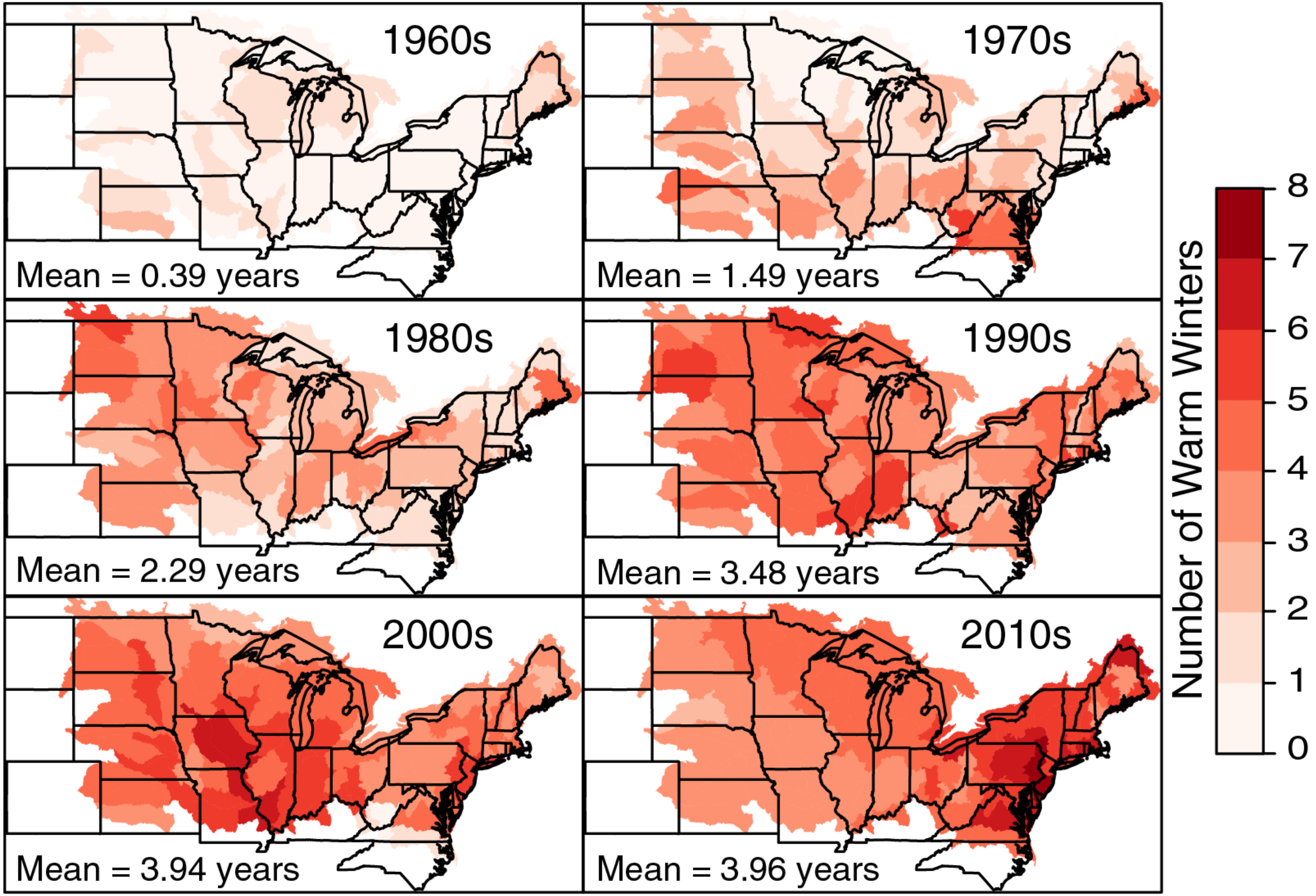
- 1,751 stream gages

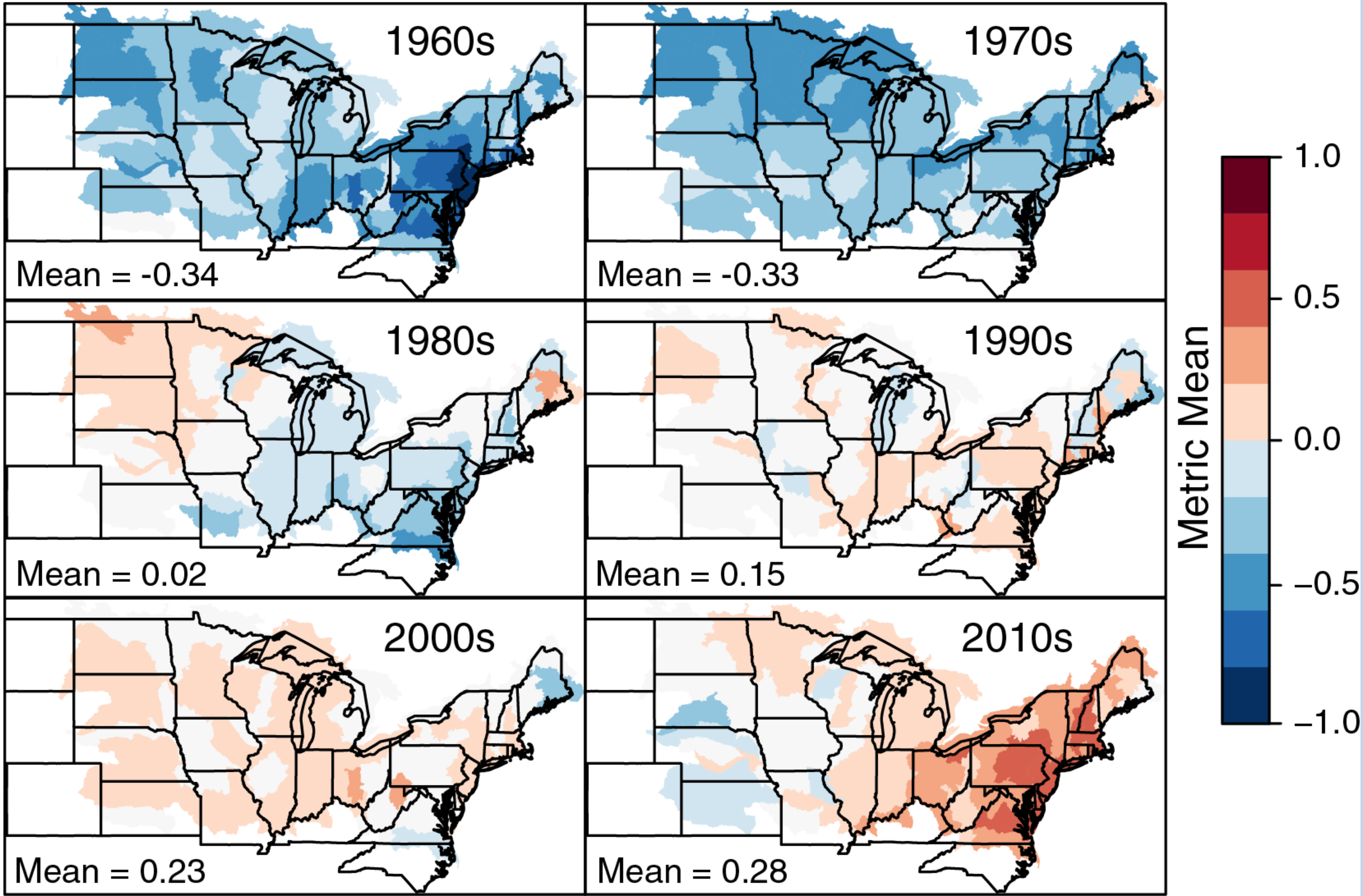
Tried to capture all non-alpine areas in US with quantifiable snow amounts

Data aggregated to HUC-4 basins, visualized in HUC-2 basins

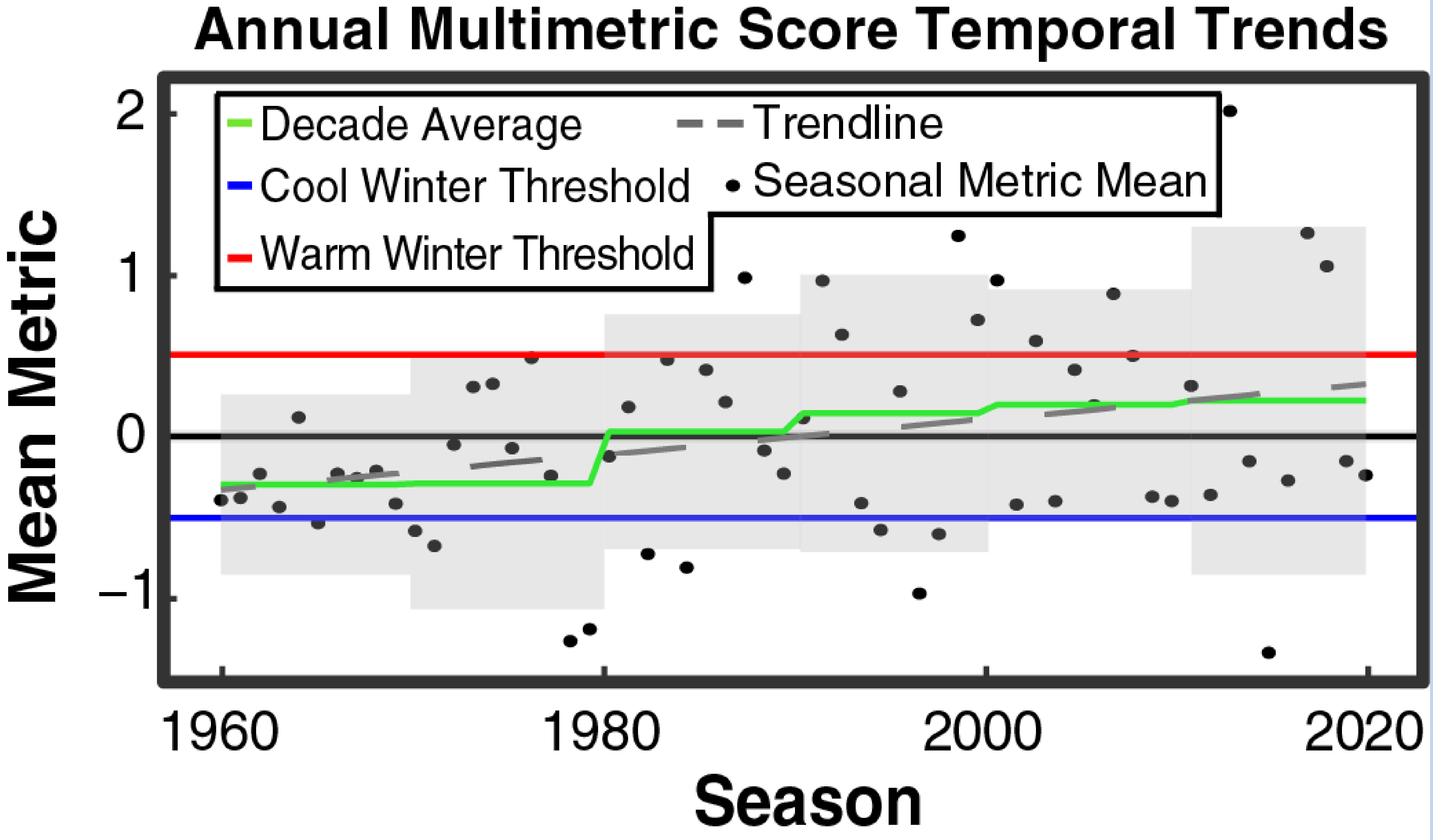




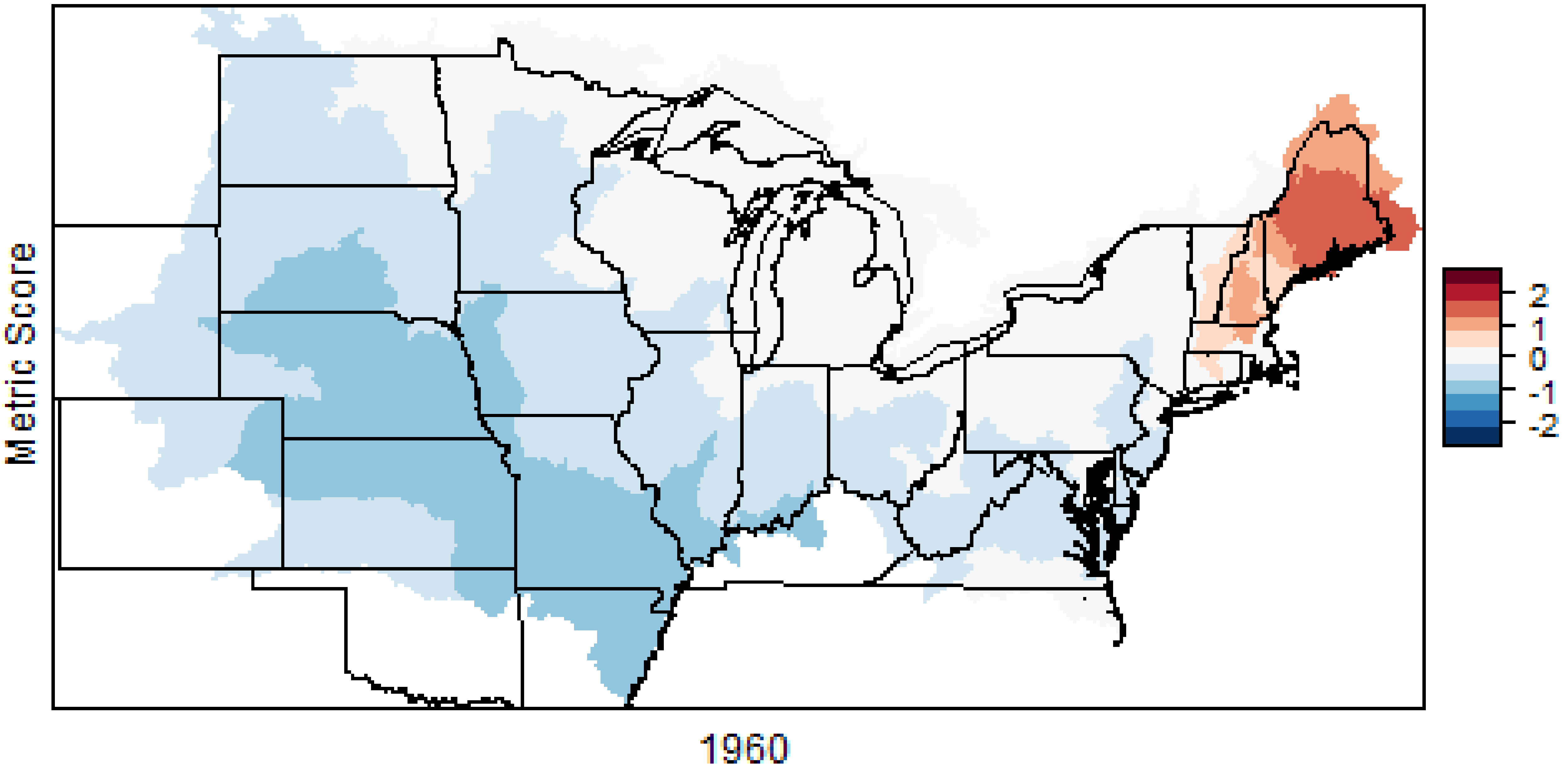

1960s
Mean = 0.39 years
1970s
Mean = 1.49 years
1980s
Mean = 2.29 years
1990s
Mean = 3.48 years
2000s
Mean = 3.94 years
2010s
Mean = 3.96 years
Number of Warm Winters
0
1
2
3
4
5
6
7
8



1960s
Mean = -0.34
1970s
Mean = -0.33
1980s
Mean = 0.02
1990s
Mean = 0.15
2000s
Mean = 0.23
2010s
Mean = 0.28
Metric Mean
1.0
0.5
0.0
−0.5
−1.0



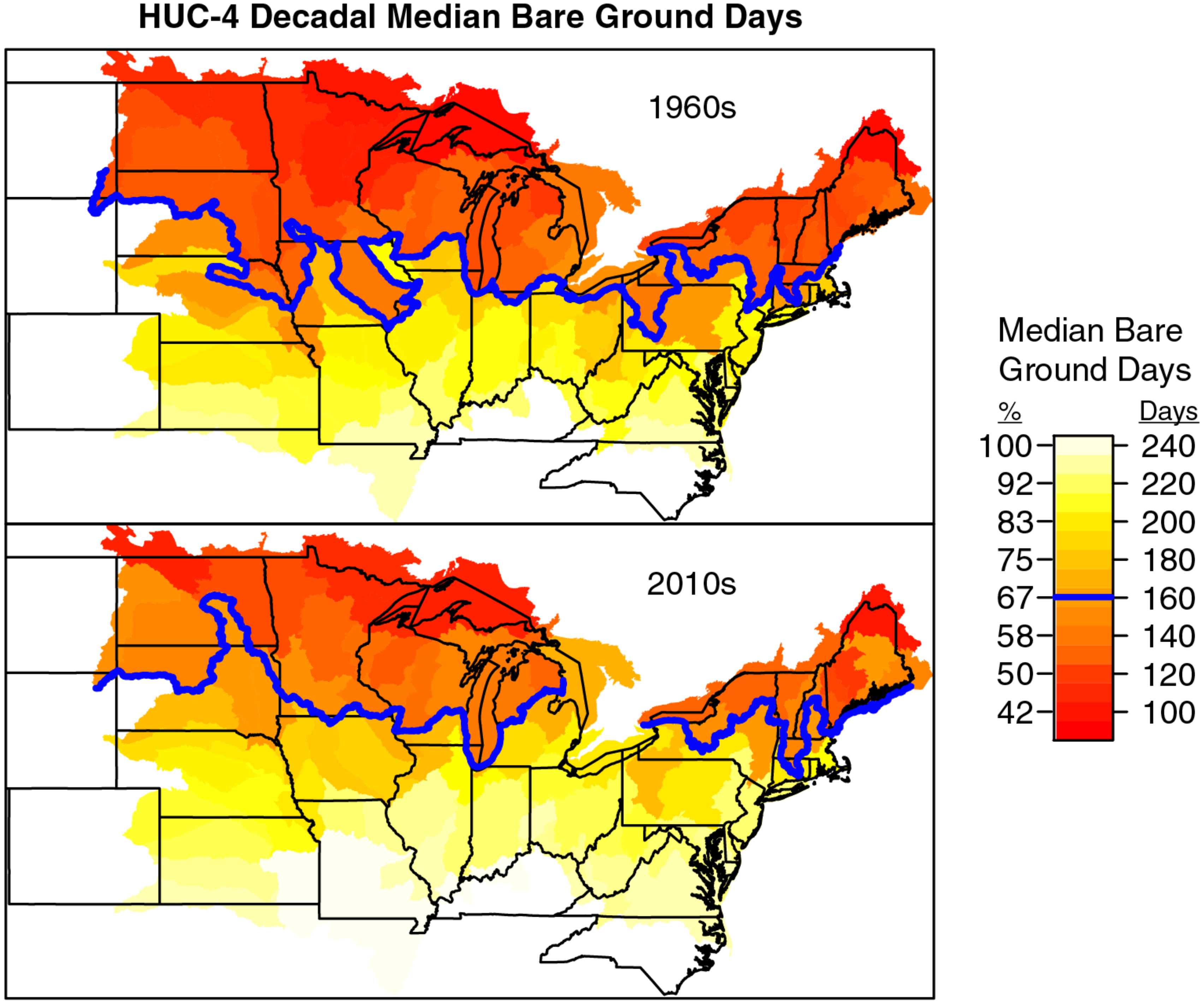
Annual Multimetric Score Temporal Trends
Decade Average
Trendline
Cool Winter Threshold
Seasonal Metric Mean
Warm Winter Threshold
Mean Metric
2
1
0
−1
1960
1980
2000
2020
Season



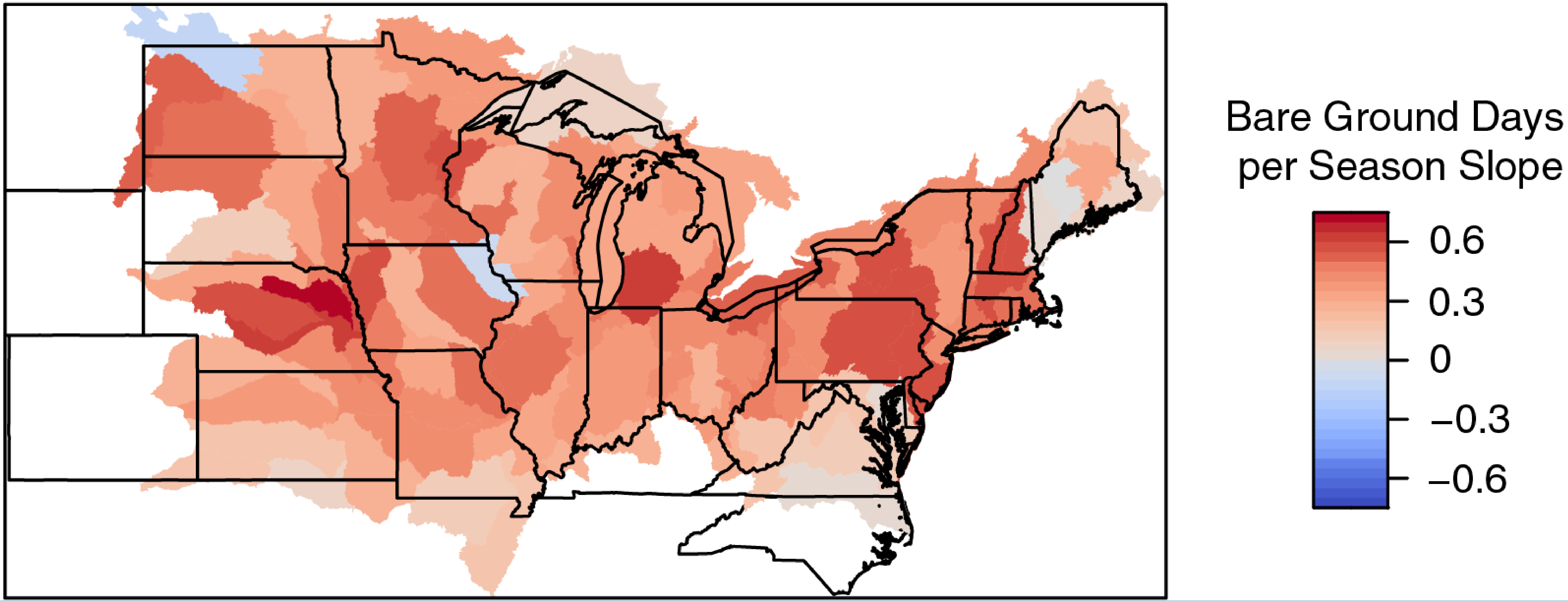
Metric Score
2
1
0
-1
-2
1960

The increasingly warmer winters correlates with less snow on the ground

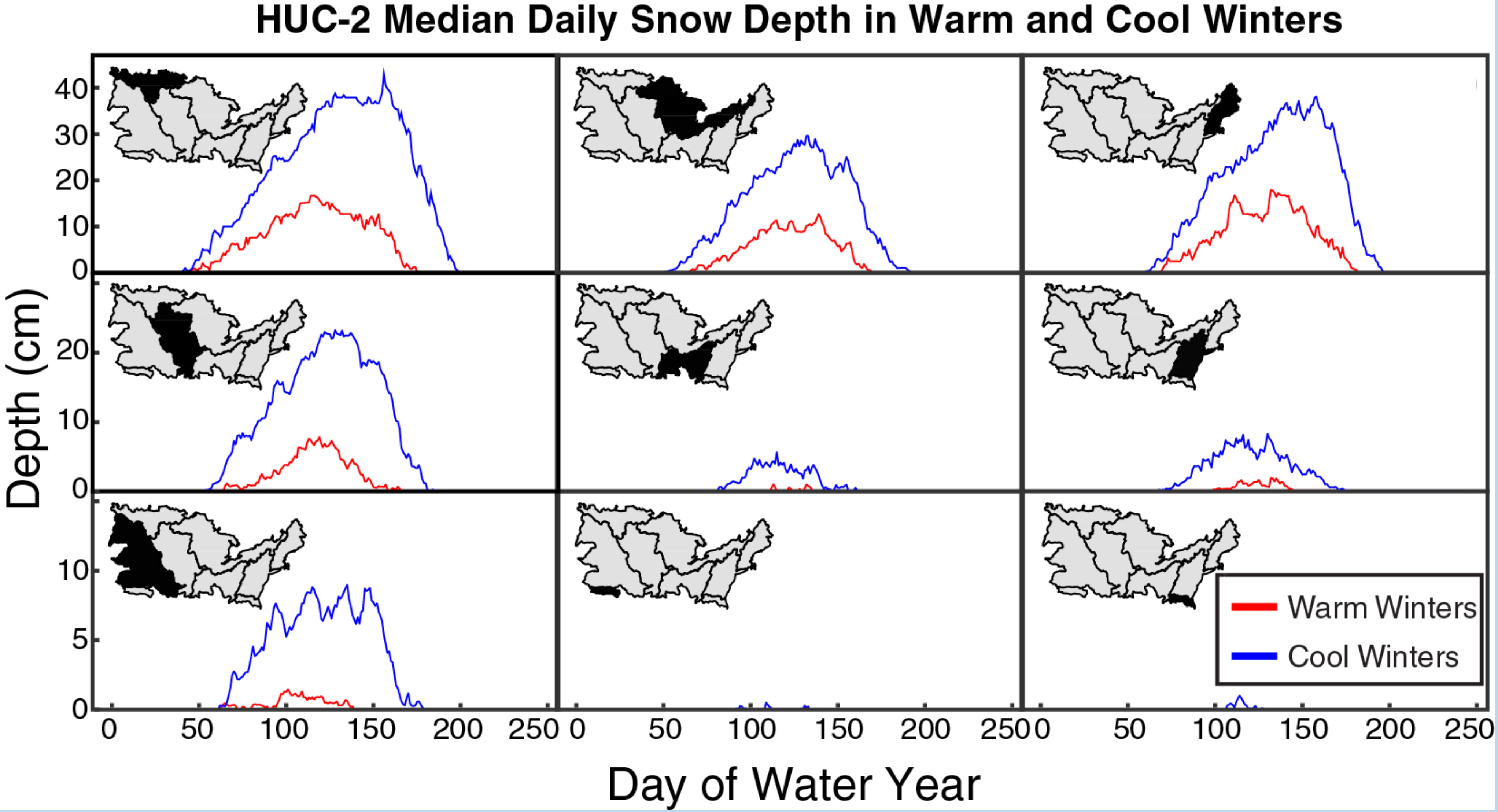
- There is a northward shift of increasing bare ground days (blue line)



HUC-4 Bare Ground Days Temporal Trends



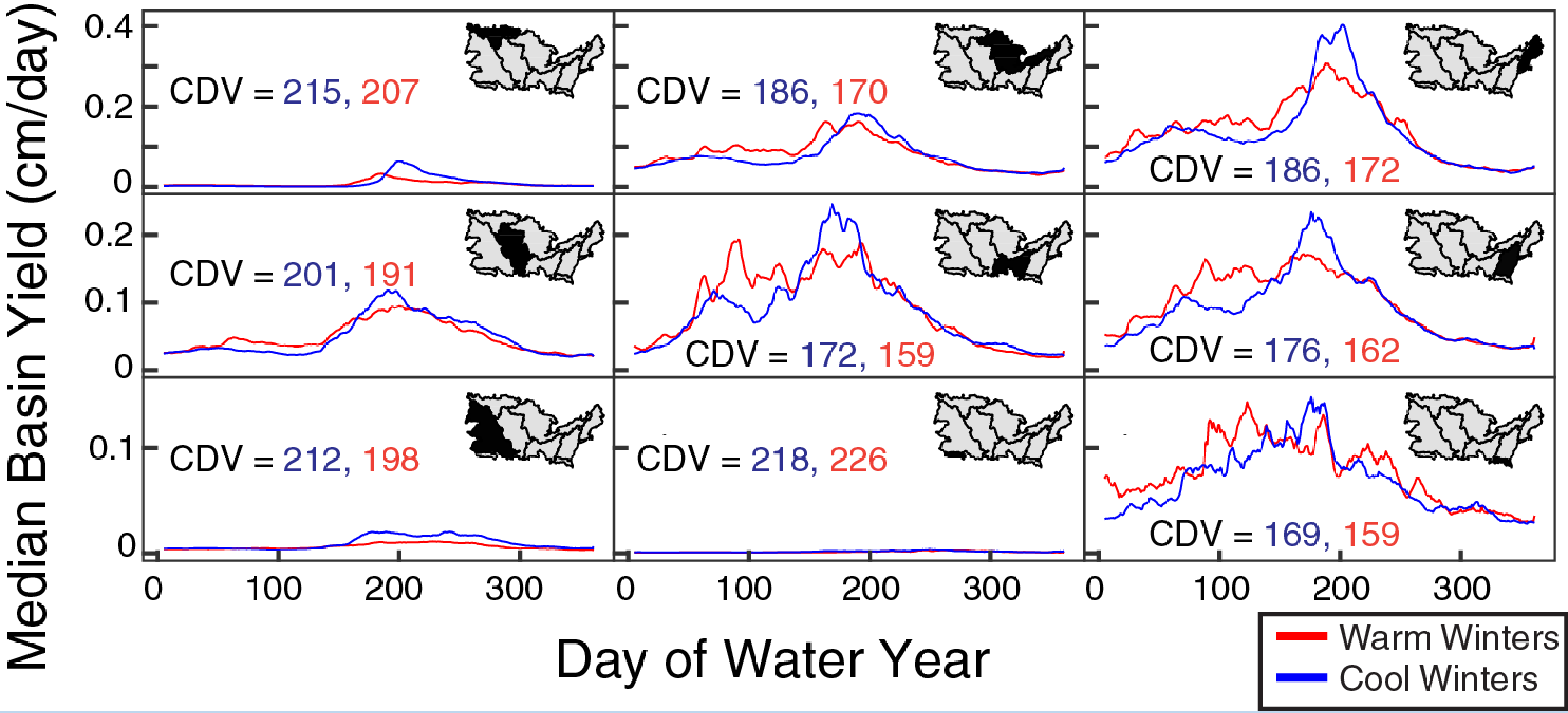
Almost all basins show increasing trend of bare ground days per season, with only two basins showing decreasing trend for entire 60-year period



In all but the southernmost basins snow depth is lower in warm winters for the entire snow season

- Bulk snowpack melts earlier

HUC-2 Median Daily Basin Yield in Warm and Cool Winter Years



Ch. 3: Filling in the Gaps

Previous chapter showed warmer winters becoming warmer and more frequent

- Leads to thinner snowpacks which melt earlier and more frequently
- Higher winter streamflow, reduced spring flow, earlier and reduced peak flow
- With larger temporal and spatial scales can link to anthropogenic climate change more confidently

But left one unexamined component of the hydrologic cycle: groundwater

Landscape Hydrology Model (LHM)

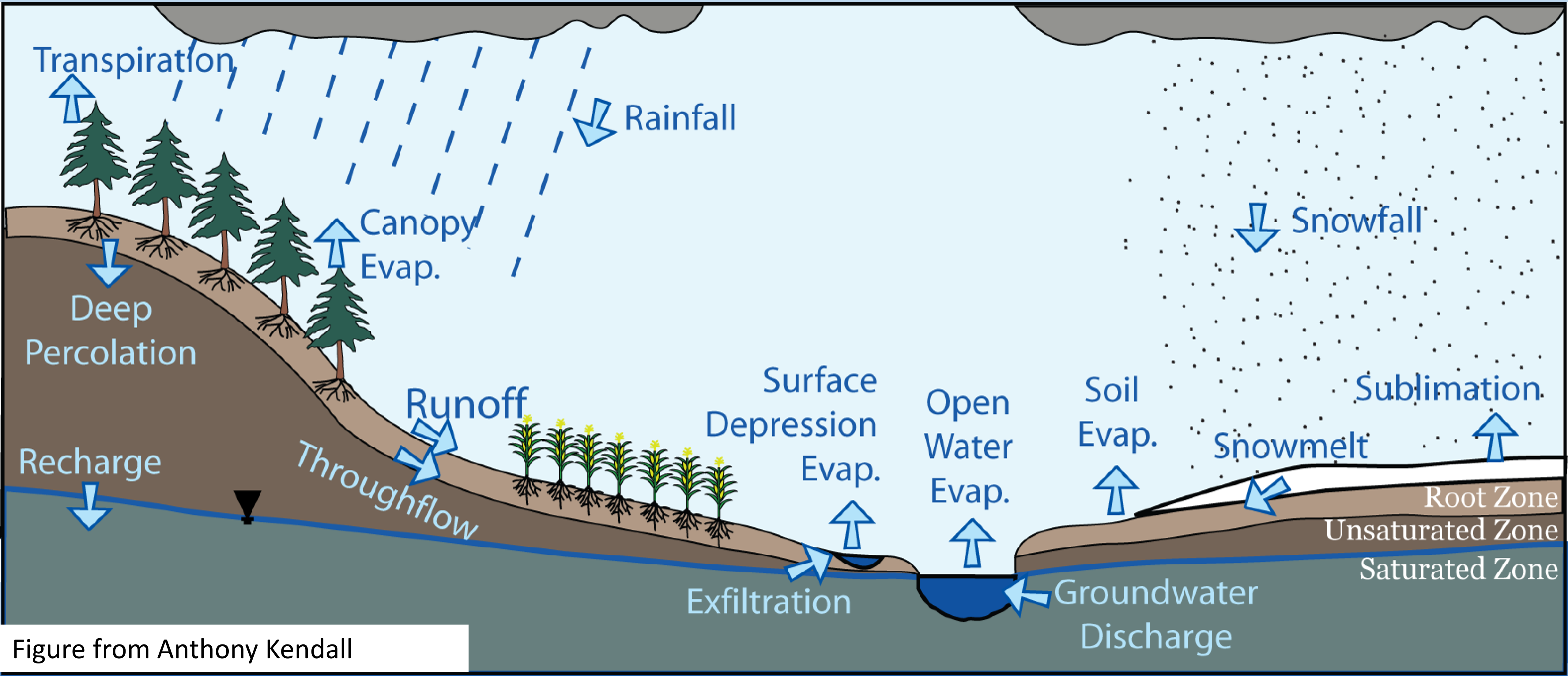
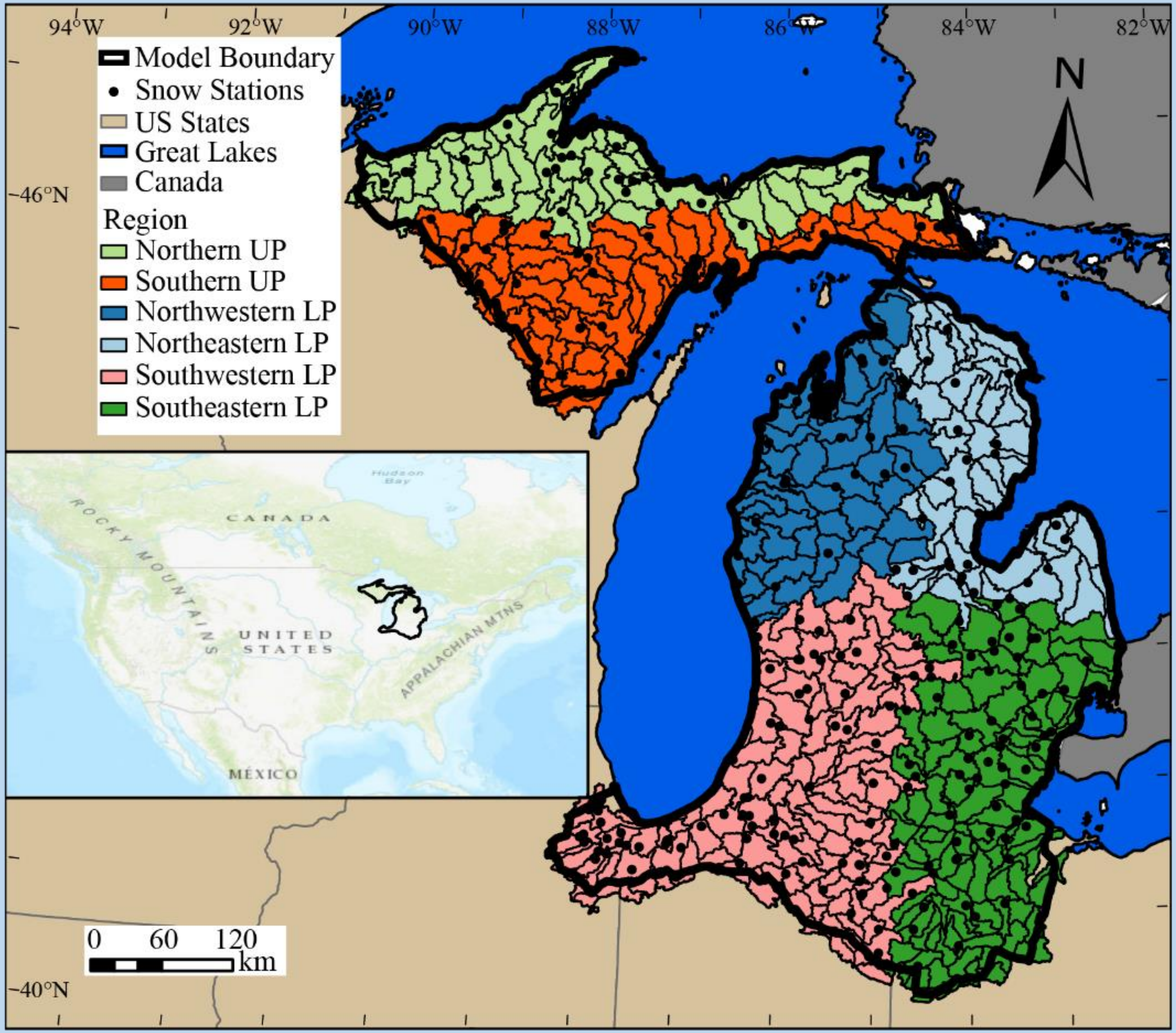


Figure from Anthony Kendall



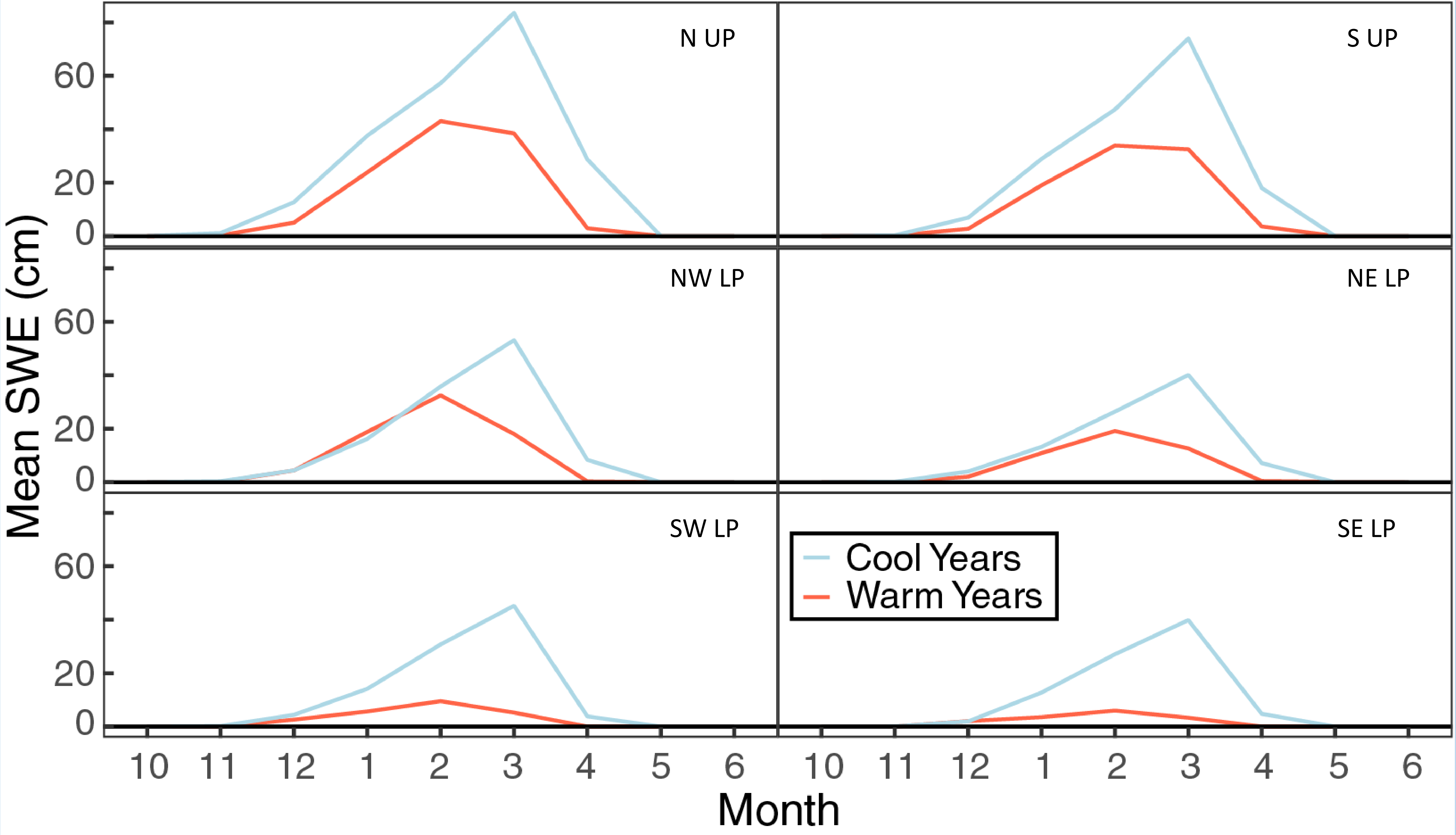
Simulation run across MI

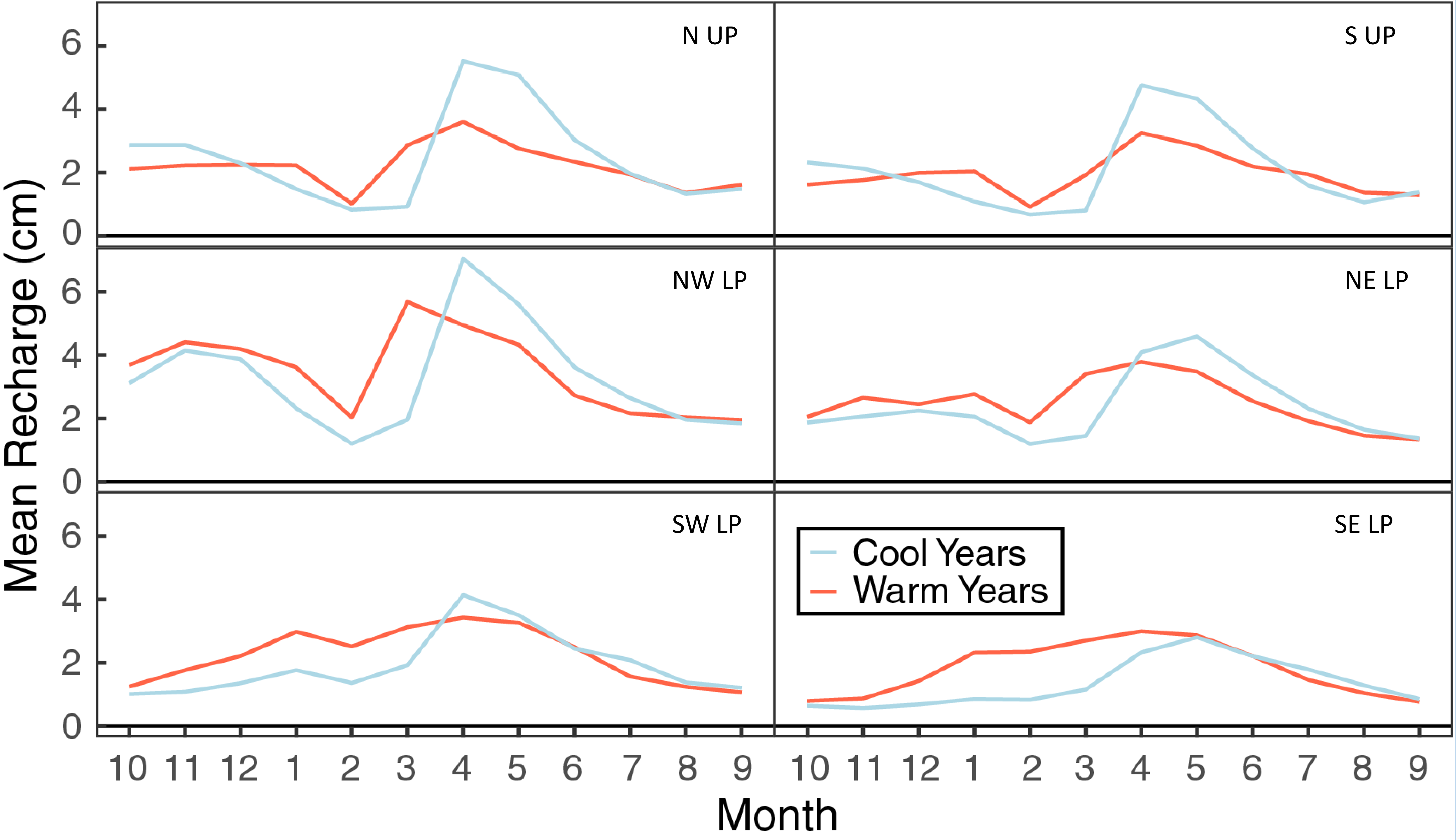
Analyses at 3 different spatial scales:

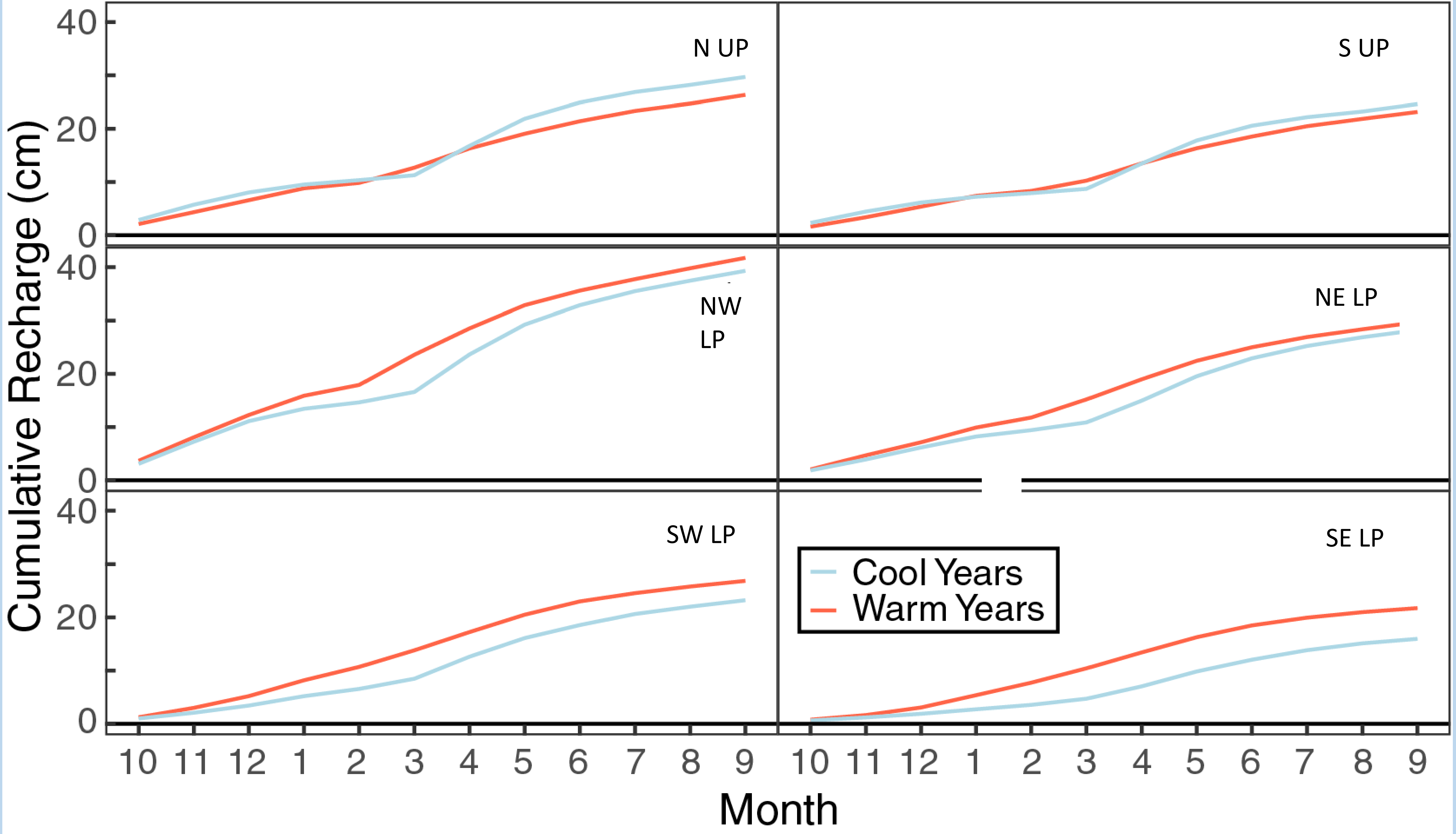
1. "Slice" model grid

2. HUC-10 basin aggregates

3. Regional breakdown across state to capture differences in snow amounts


N UP
S UP
NW LP
NE LP
SW LP
SE LP
Cool Years
Warm Years
Mean SWE (cm)
Month
0
20
60
10
11
12
1
2
3
4
5
6


N UP
S UP
NW LP
NE LP
SW LP
SE LP
Cool Years
Warm Years
Mean Recharge (cm)
0
2
4
6
10
11
12
1
2
3
4
5
6
7
8
9
Month


Cumulative Recharge (cm)
Month
N UP
S UP
NW LP
NE LP
SW LP
SE LP
Cool Years
Warm Years
0
20
40
10 11 12 1 2 3 4 5 6 7 8 9

Ch. 4: Real-world Consequences

Previous chapters have shown the hydrologic consequences for changing snow in warmer winters, but what about the human impact?

For scientific data to be meaningful to policy makers, tied results to something that hits close to home…

The ski and winter recreation industry has a significant role in Michigan's economy

The Midwest Ski Destination

40 ski areas located within Michigan, the most of any state in the Midwest (Scott et al., 2021)

In 2004-2005, MI had second highest number of ski slopes in the country (Shih et al., 2009)

In 2009-2010, skiing and snowboarding added $638.3 million to state’s economy, along with 10,889 associated jobs (Burakowski and Magnusson, 2012)

Outdoor rec and tourism is third largest industry in MI, behind only auto manufacturing and ag) (Shih et al., 2009)

- Skiing the most popular winter rec activity

An Industry Under Threat

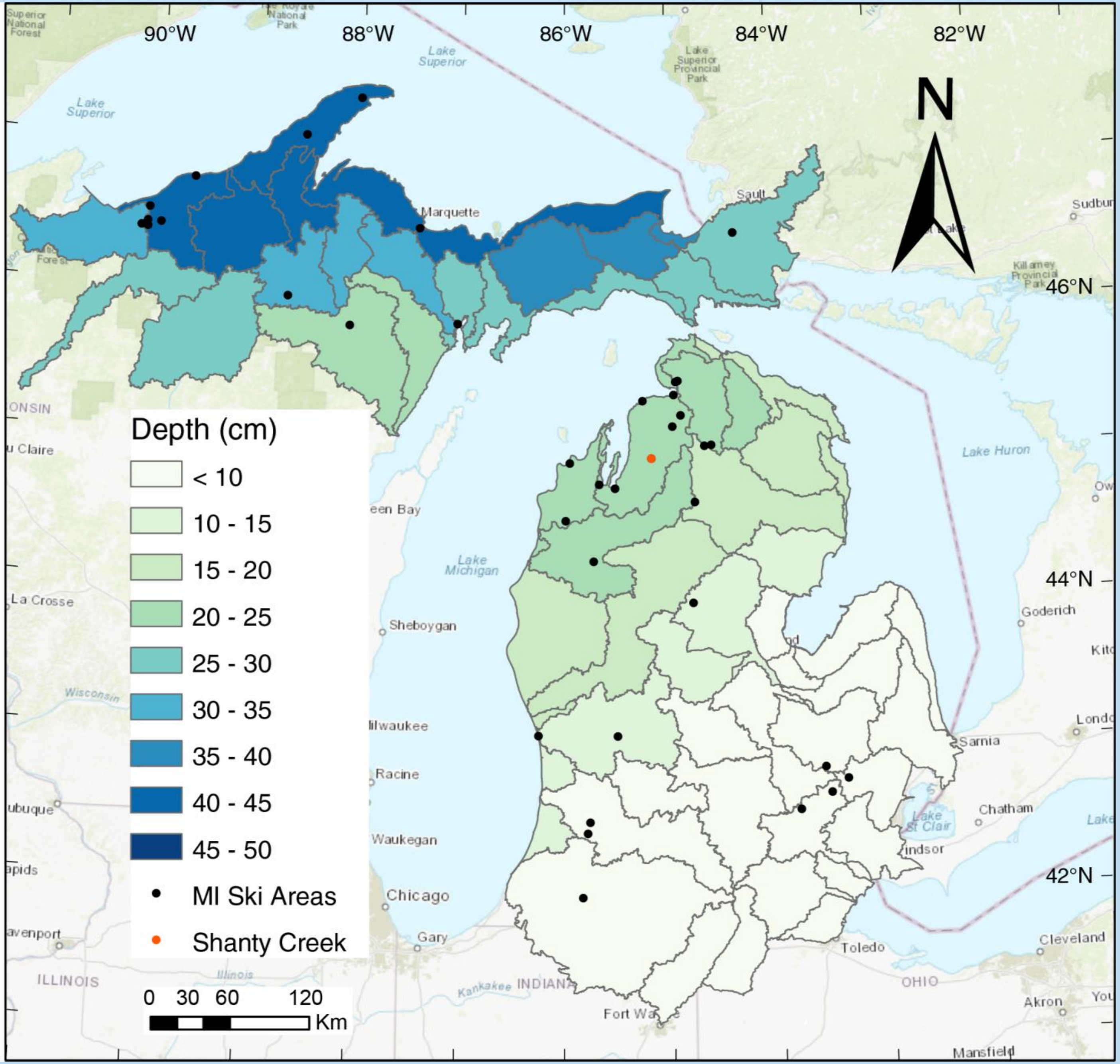
76% of Great Lakes ski slopes considered economically viable (Scott et al, 2021)

Under high emissions scenarios decreases to 7-8% by 2100

Under high emissions, holiday period ski days reduced by up to 66%, with a >50% decrease in snow depths during those weeks (Chin et al., 2018)

By 2080's, days with sufficient snow depths for winter recreation in the region could be up to a month shorter, with < 1 month per year with suitable temperatures for snowmaking (Chin et al., 2018)

Under high emissions, by 2100 snowmaking requirements increase 516% and states skiable terrane reduced by twice as much compared to low emissions scenarios (Scott et al., 2021)



21 HUC-8 basins containing active ski areas

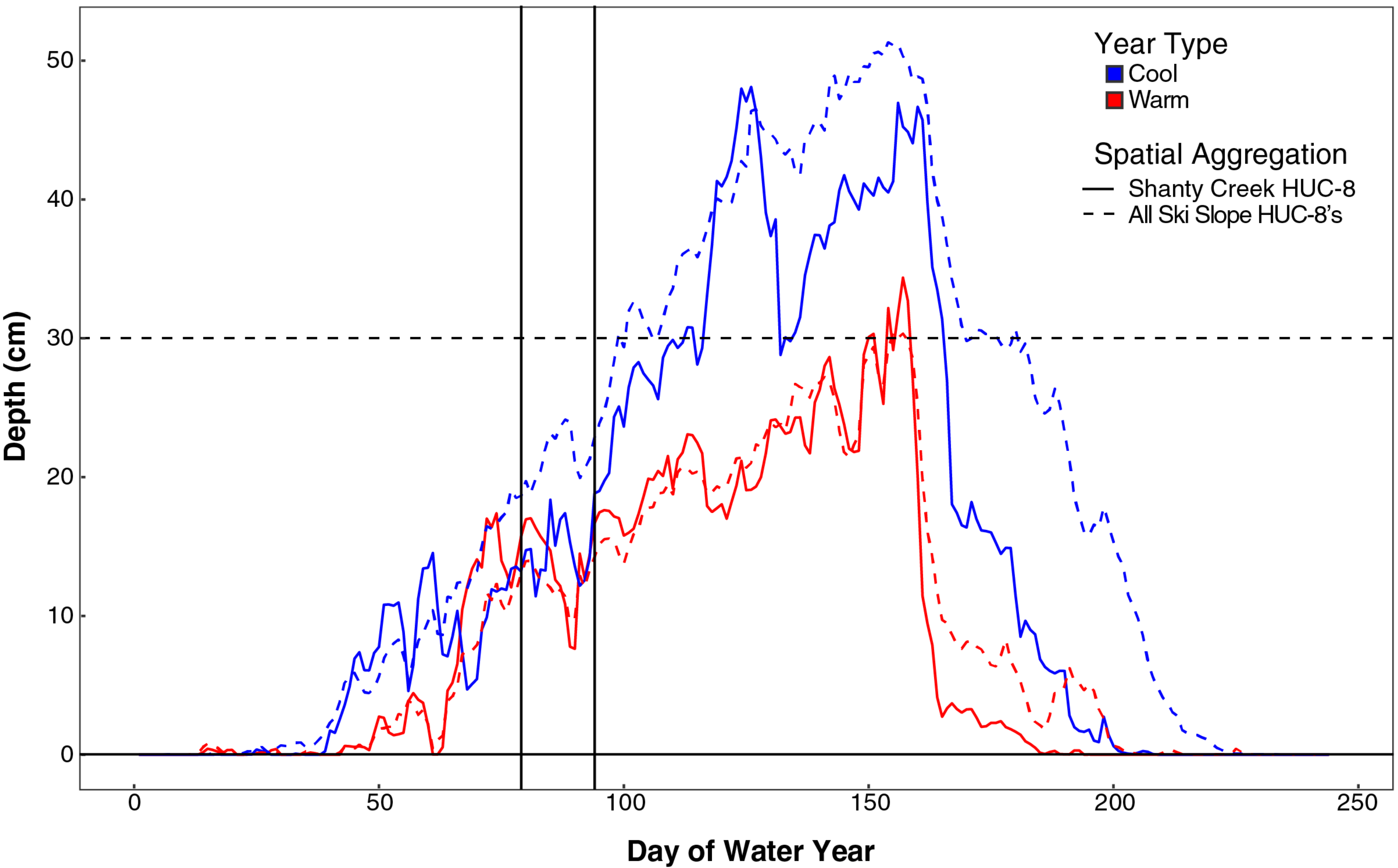
Study period from 2003 - 2020

Analyzed snow depth in warm/cool winters for those basins

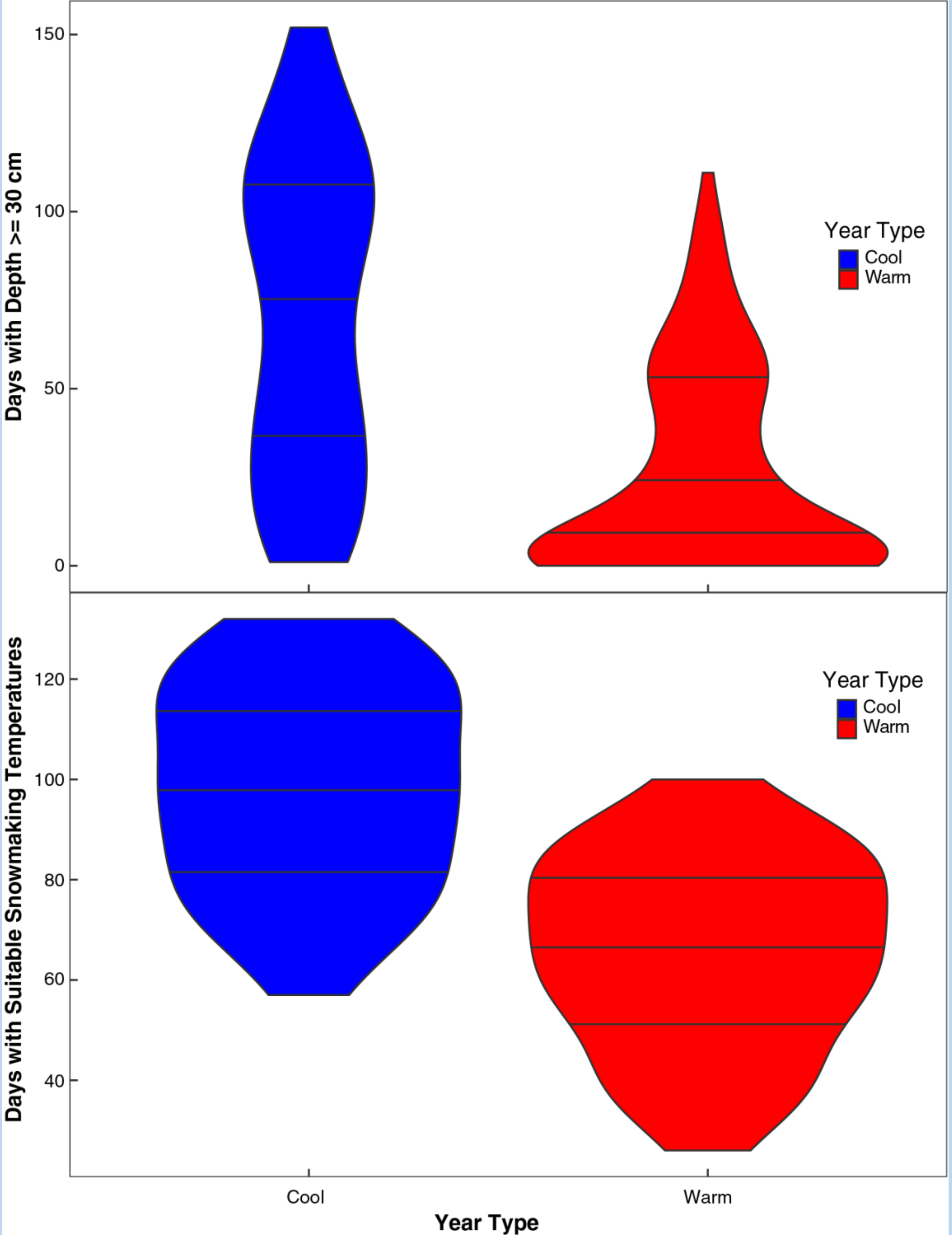
GHCN temperature data in those basins utilized to quantify snowmaking days

Visitor totals from National Ski Areas Association

Additional data for Shanty Creek Resorts from 2013-2021 provide by CEO Pete Bigford



Year Type
Cool
Warm
Spatial Aggregation
Shanty Creek HUC-8
All Ski Slope HUC-8's
Depth (cm)
Day of Water Year
50
40
30
20
10
0
0
50
100
150
200
250



Cool winters generally have several more weeks of days with >30 cm depths

Many basins in warm winters have almost no days with 30 cm depths

More than a month of days with suitable snowmaking temperatures in cool winters compared to warm

- Mean of 91 days in cool winters, 61 days in warm winters

Temperatures < -2°C for snowmaking

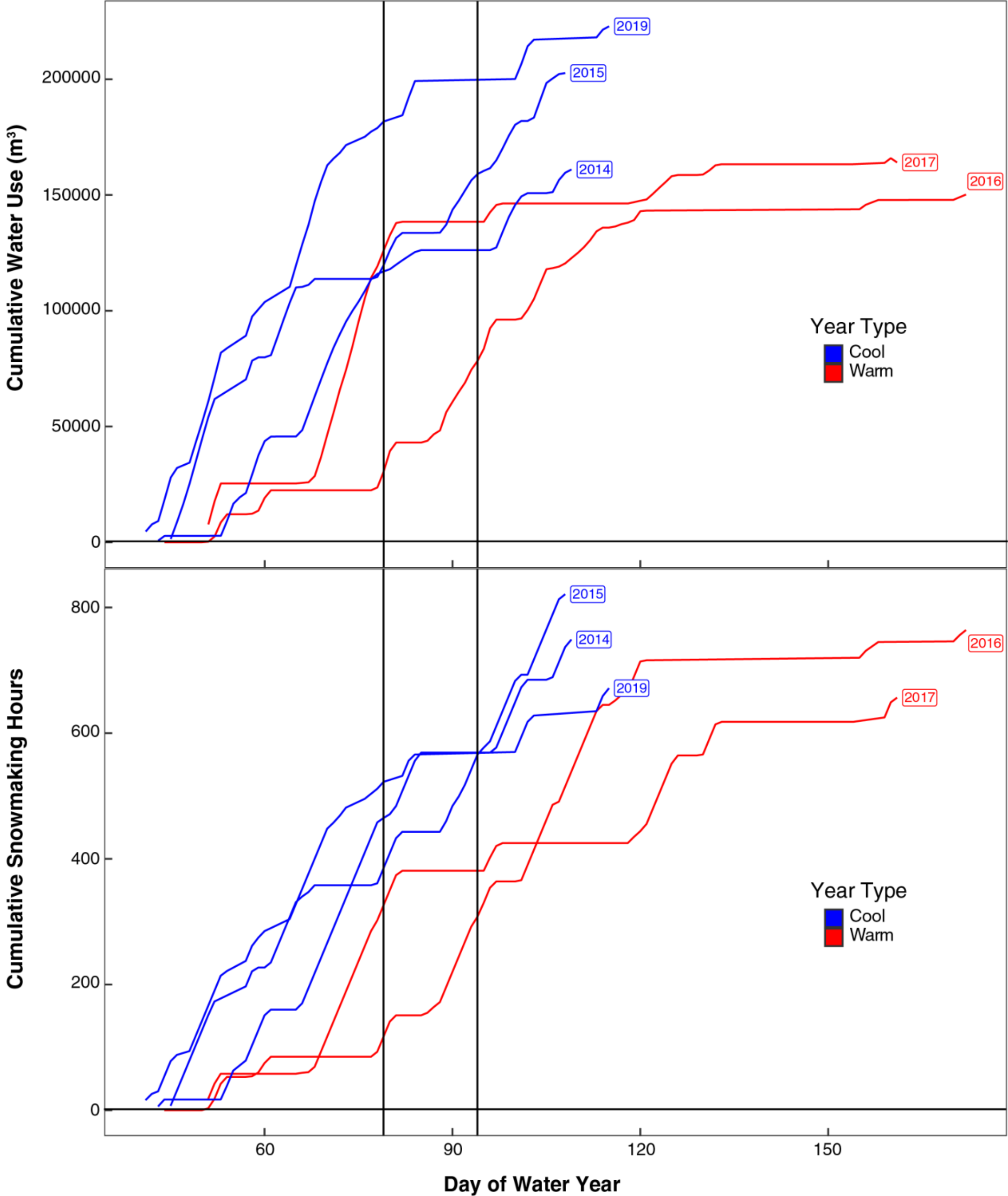
Higher water use for snowmaking and more snowmaking hours in cool winters

Cool winter snowmaking ends in late January; warm winters continue into March

More cool winter snowmaking likely in response to increased visitors

- Across Midwest, average annual visitor totals in cool winters = 7.1 million, 300,00 more than in warm winters
- Most snowmaking occurs in lead up to holiday weeks
- Deeper cool winters snowpacks sustain slopes through spring

Still a very limited dataset



Dissertation Conclusions

Warm winters are getting warmer and more frequent

These warmer winters result in:

- Decreased depth/SWE
- Decreased peak depths/SWE
- Earlier melting of snowpack
- More frequent melting throughout snow season
- Increased bare ground days

Dissertation Conclusions

Changes to snow in warmer winters contributes to:

- Higher winter streamflows
- Earlier, lower peak streamflows in spring
- Earlier CDV
- Increased shallow groundwater recharge, especially in winter and in southern basins

Less ski slope visitors in warmer winters

Less days with suitable snow depths for skiing and temperatures suitable for snowmaking

Effects on resource usage for snowmaking unclear

Acknowledgments – Funding Sources

- MSU Hydrogeology Lab and Dept. of Earth and Environmental Sciences
- Environmental Science and Public Policy (ESPP) Program
- USDA NIFA
- NASA
- NOAA

Environmental Science & Policy Program at Michigan State University

MSU Hydrogeology
hydrogeology.msu.edu @MSUHydro

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

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Department of Earth and Environmental Sciences
MICHIGAN STATE UNIVERSITY








SPARTAN
FOOTBALL

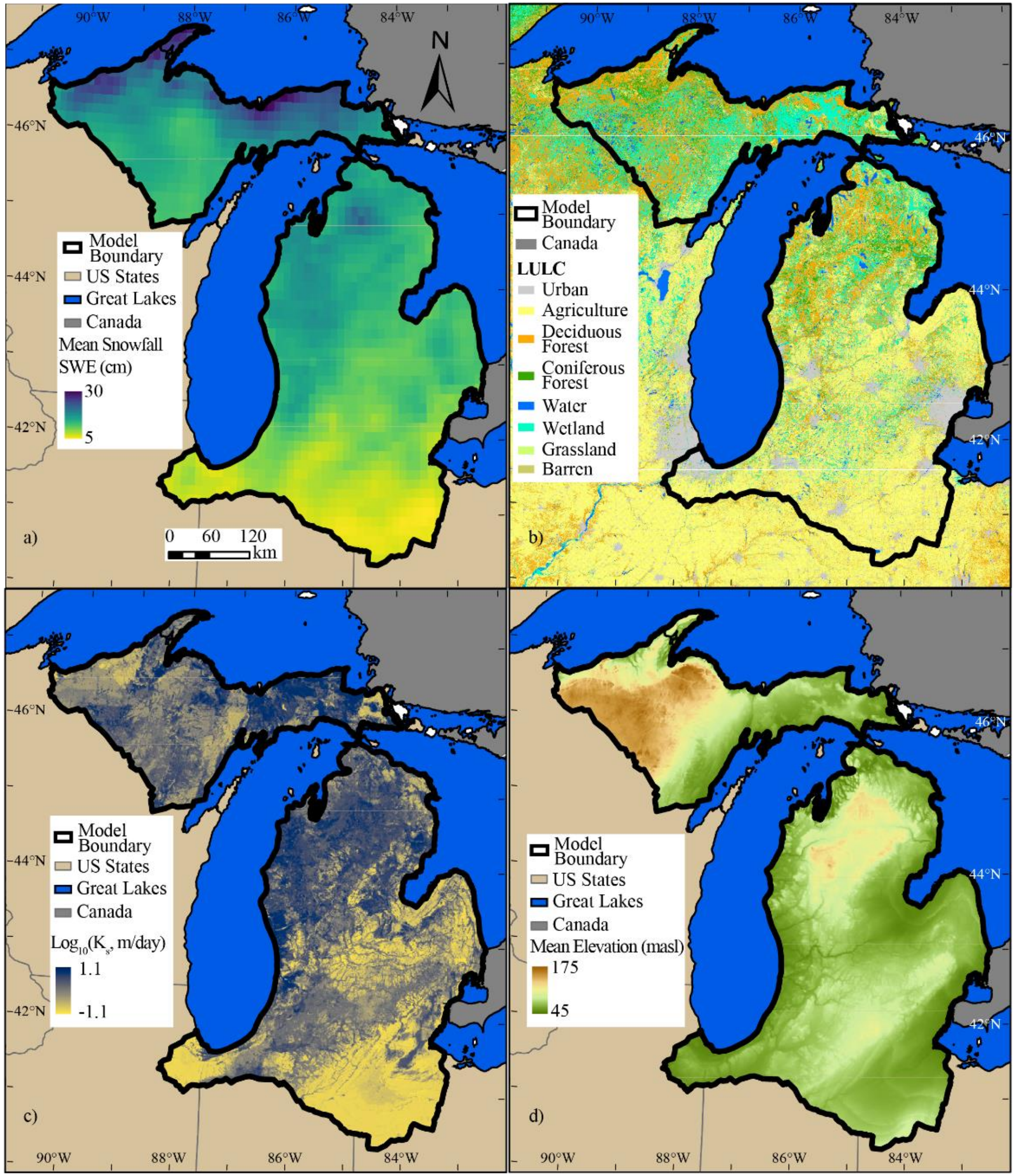

LHM inputs include:

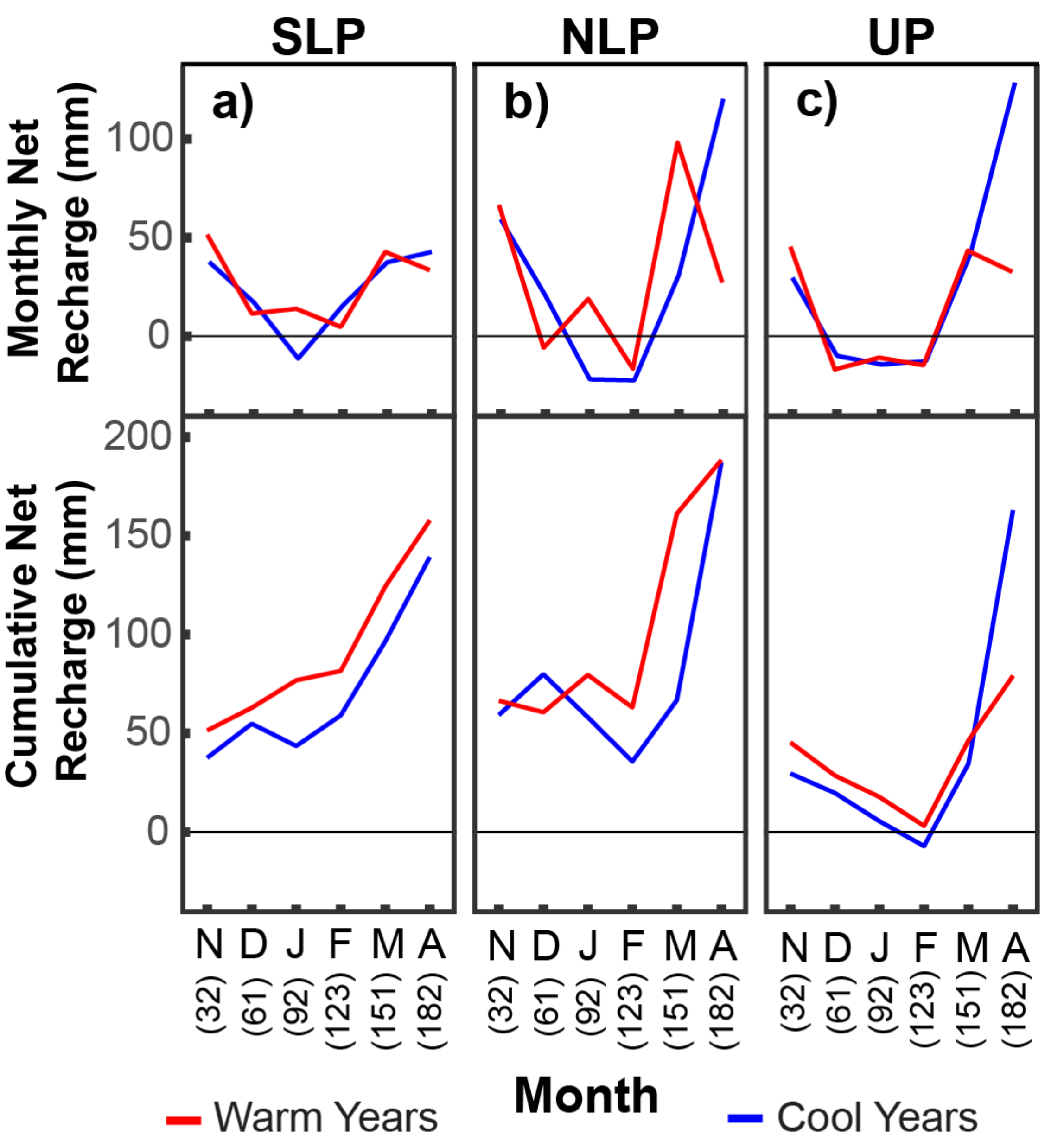
Climate
- NLDAS-2 forcing data (precip, air temp, etc.)

Landscape
- NLCD (LULC)
- National Elevations Dataset (DEM)
- MODIS (LAI)

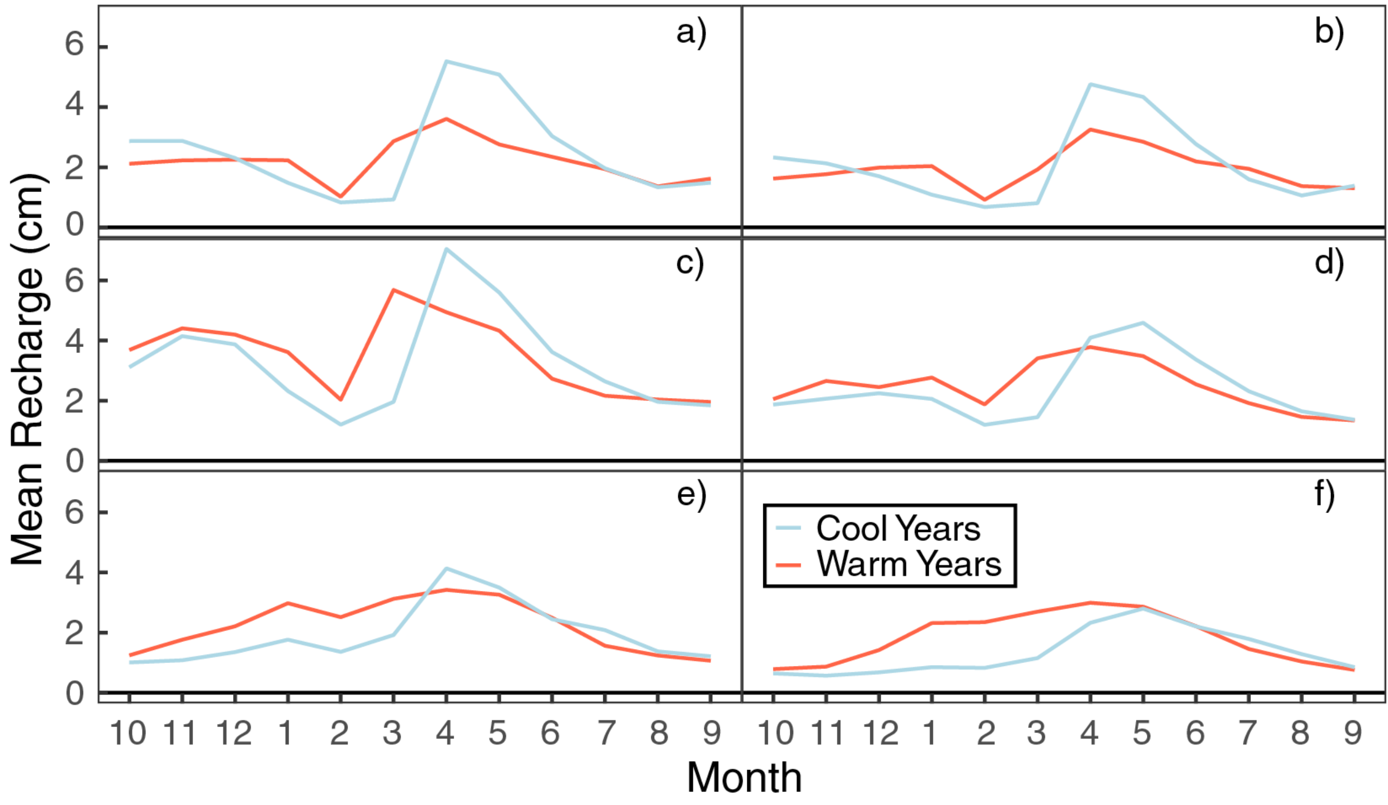
Static
- gSSURGO (soils)
- National Wetlands Inventory (wetland and lake depths)
- National Hydrography Dataset (hydrography)
- Lake Michigan Basin Model (bedrock K and Ss)

Observational data
- USGS stream gages
- Michigan Dept. of Environmental Quality (MDEQ, now EGLE) WelLogic database
  - Groundwater levels
  - Surficial K and Ss

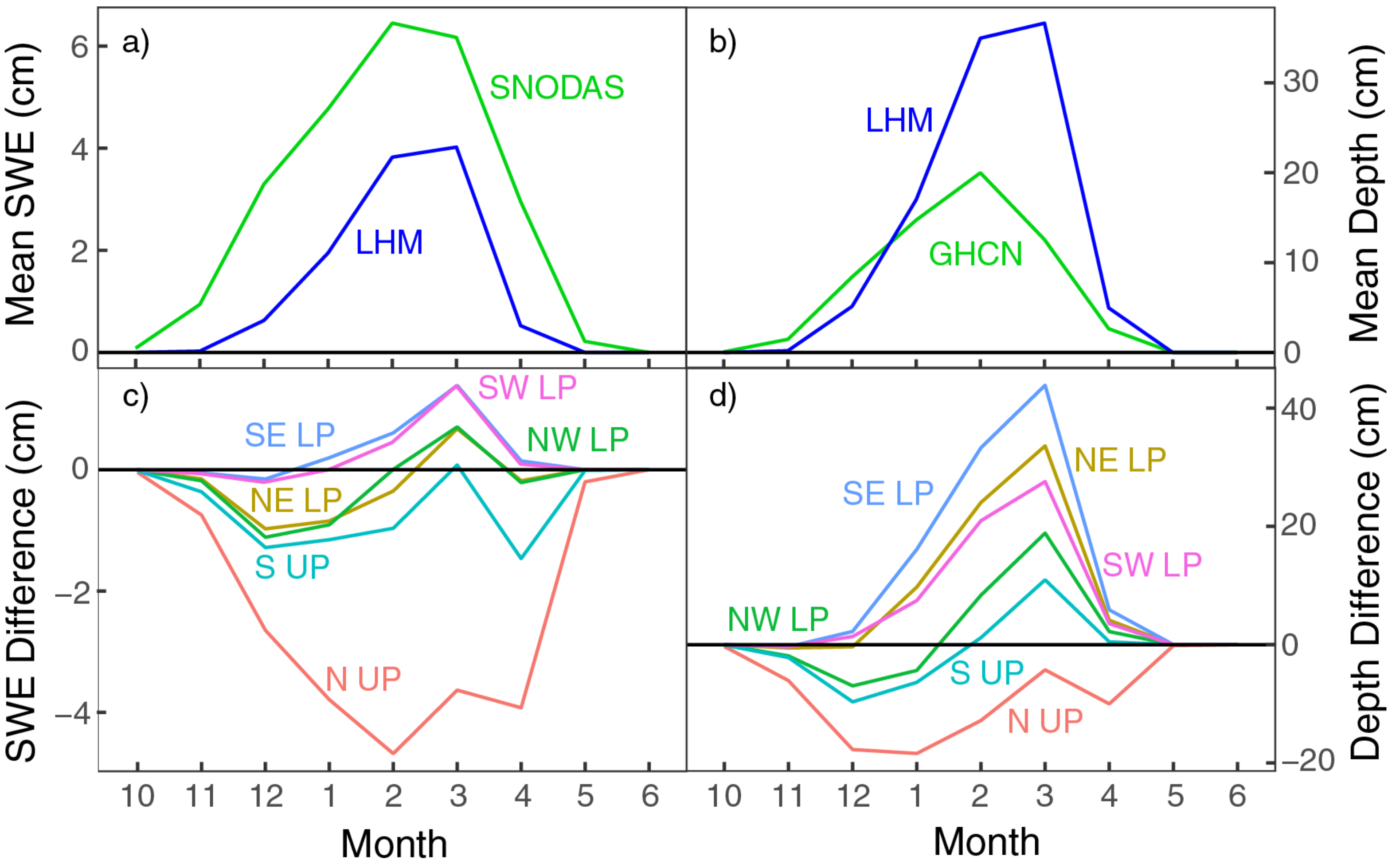




SLP
NLP
UP
a)
b)
c)
Monthly Net Recharge (mm)
Cumulative Net Recharge (mm)
100
50
0
200
150
100
50
0
N D J F M A
(32) (61) (92) (123) (151) (182)
Month
Warm Years
Cool Years



a)
b)
c)
d)
e)
f)
Mean Recharge (cm)
6
4
2
0
Cool Years
Warm Years
10 11 12 1 2 3 4 5 6 7 8 9
Month



Snow in LHM simulated using modified Utah Energy Balance (UEB) snow model (Tarboton and Luce, 1997)

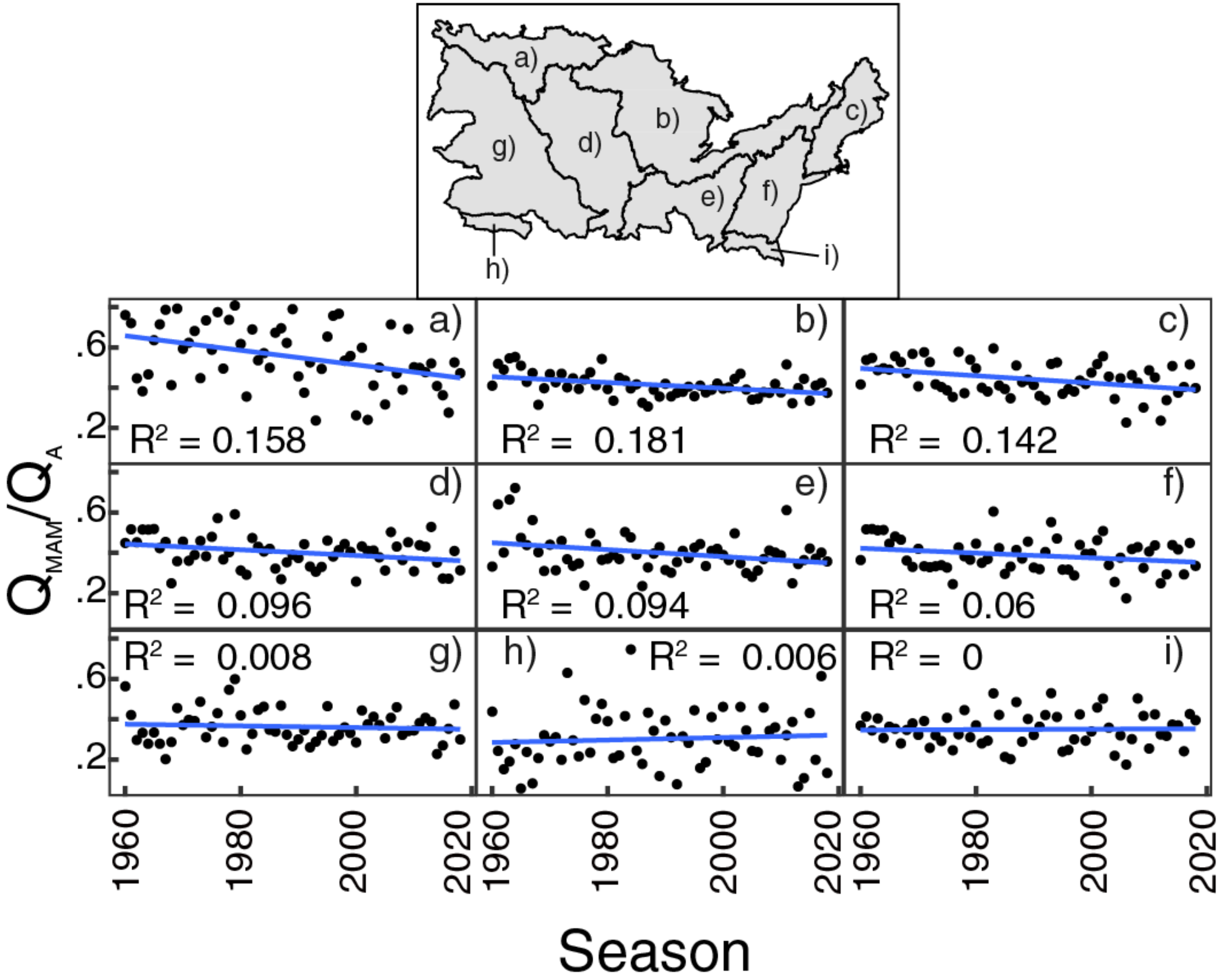
SWE simulations generally underpredict

- Worst in Northern UP, other regions much closer

Depth simulations overpredict

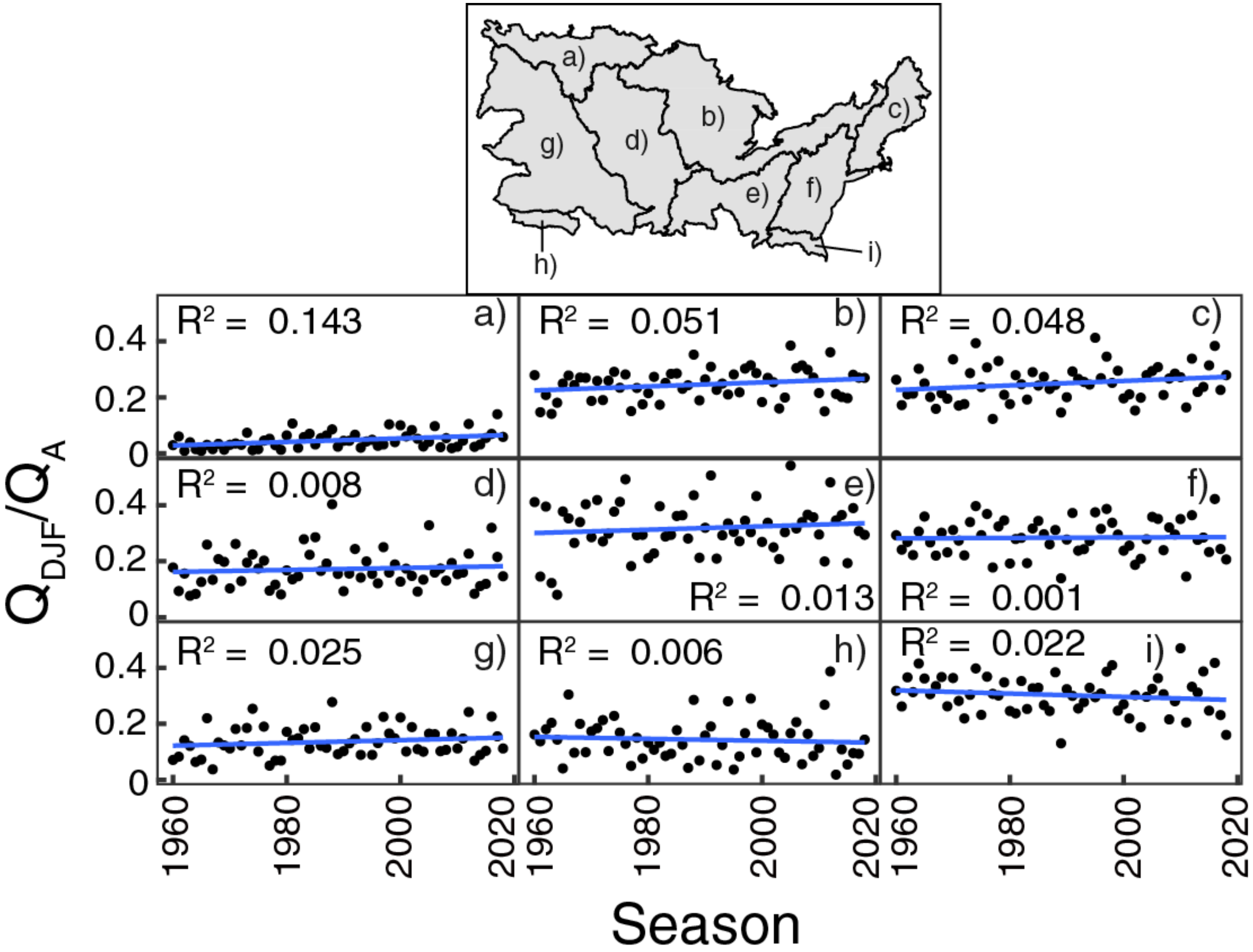
- Does much better in snowier regions

HUC-2 Trends in Spring Q/Annual Q

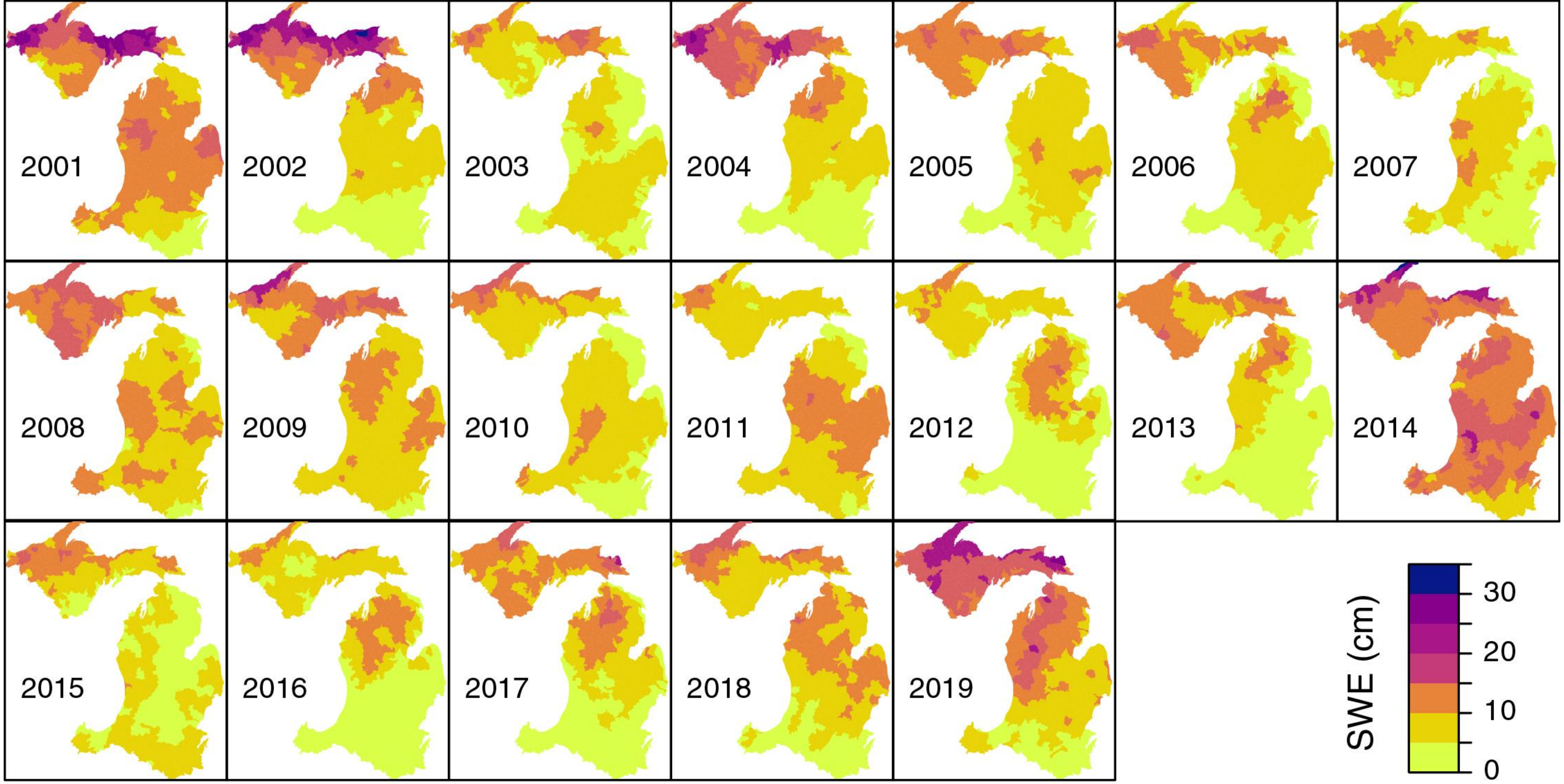


Contribution of winter (DJF) Q to the annual total is increasing

- All trends statistically significant at a 95% confidence threshold using t-test (p-val < 0.001)

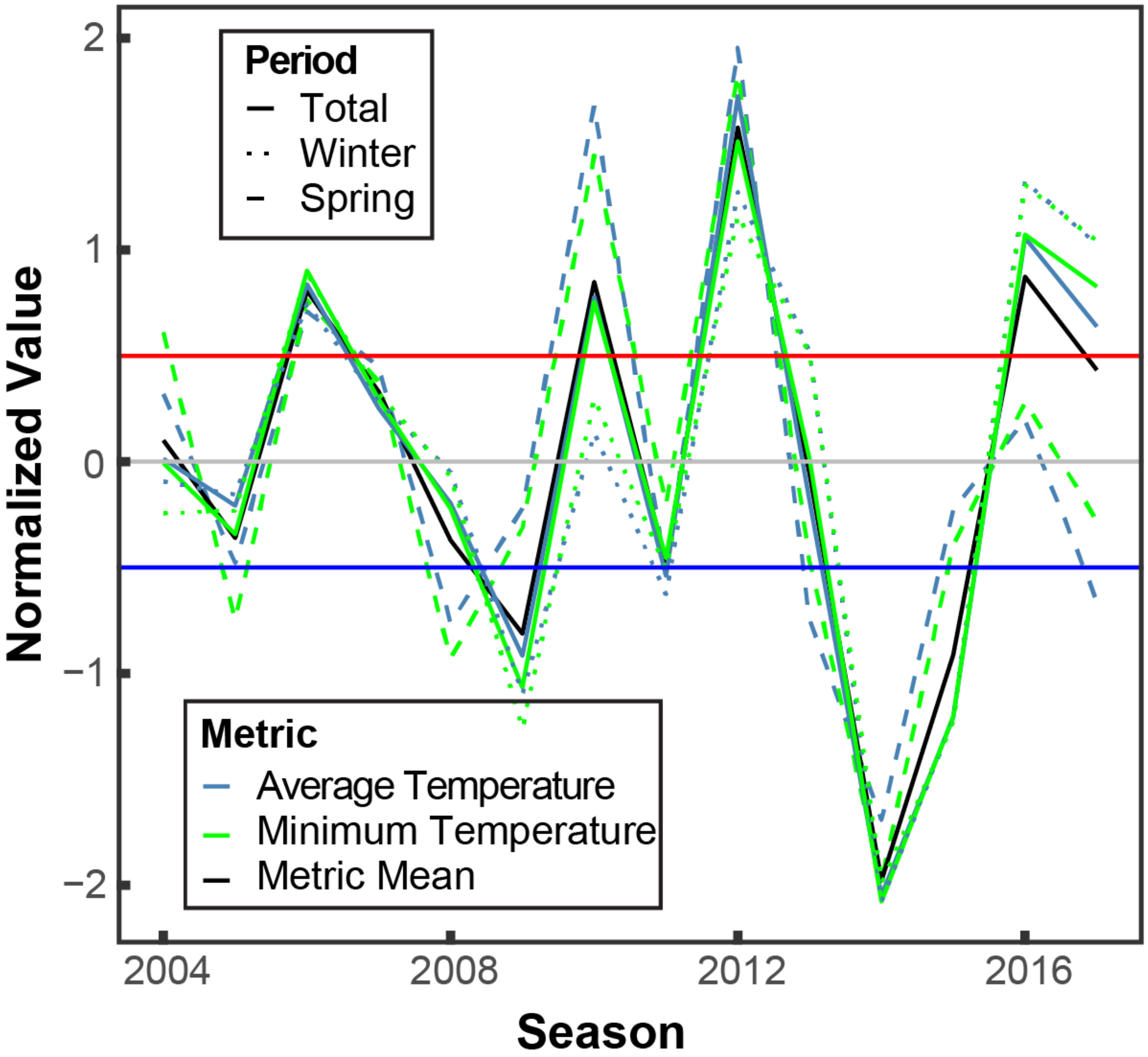


The contribution of spring (MAM) discharge (Q) to total annual (Q) is declining in most basins

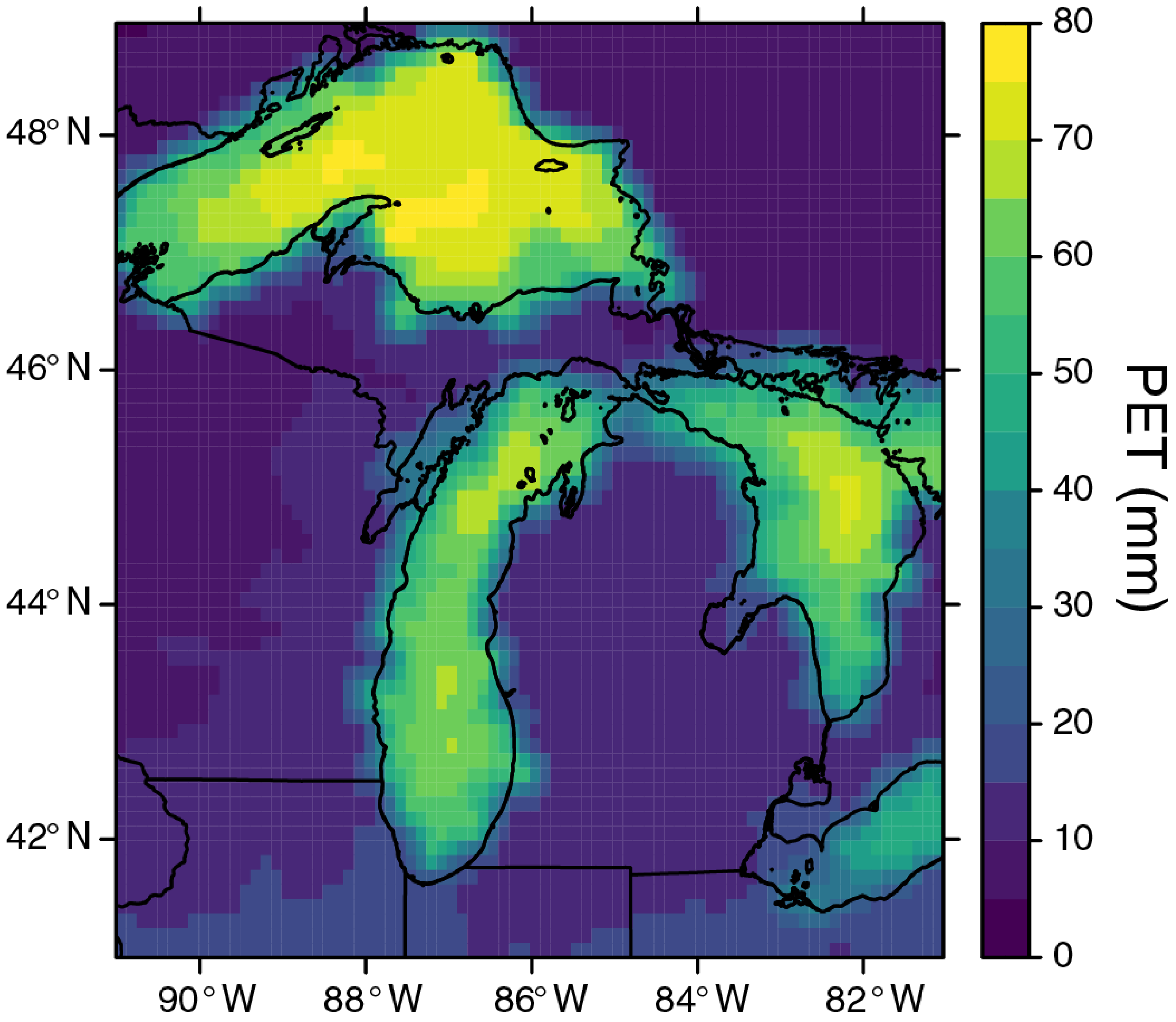


As expected, snow amounts generally increase northward regardless of water year

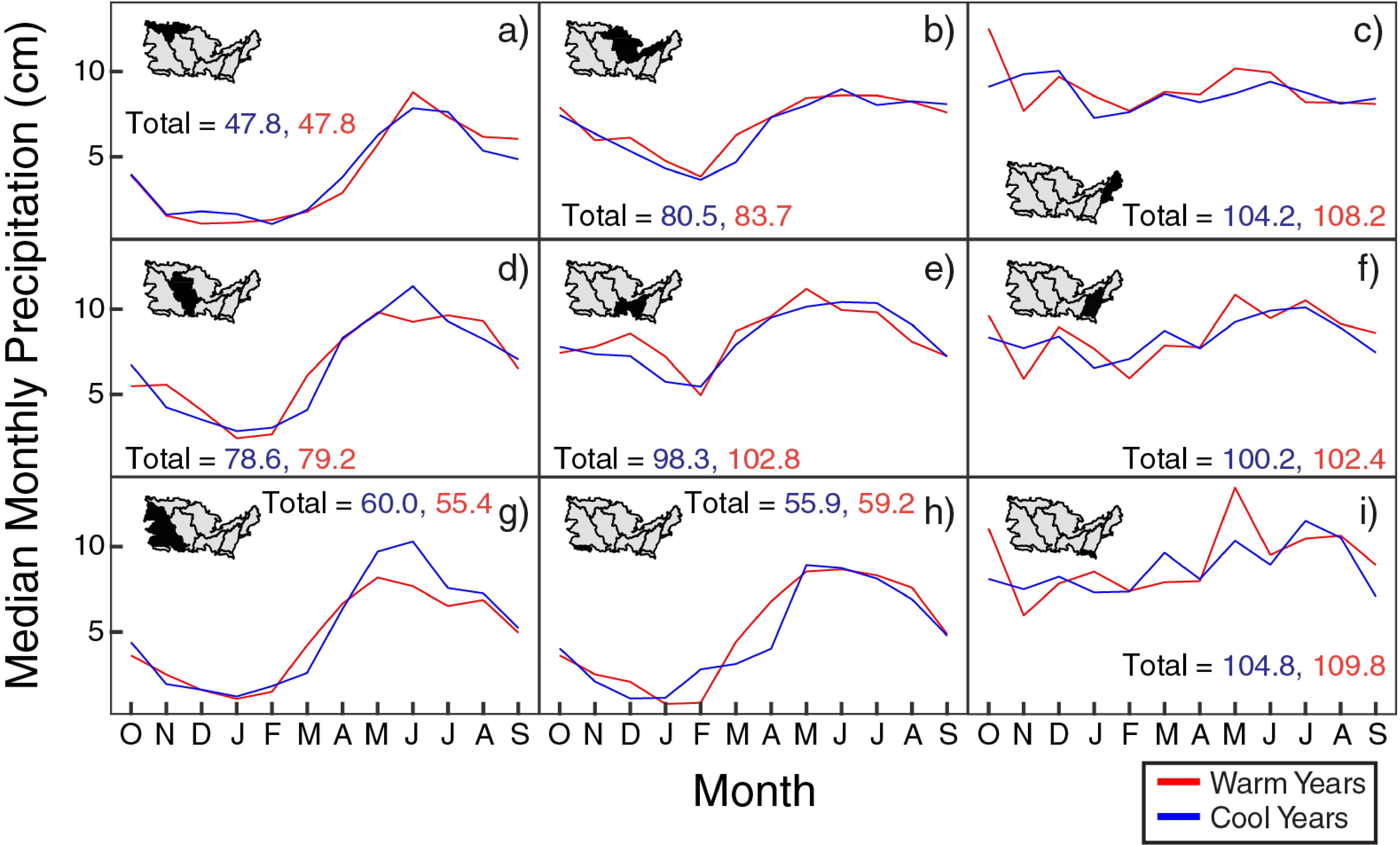
Lake Effect evident in most water years; N UP and W LP basins show more snow



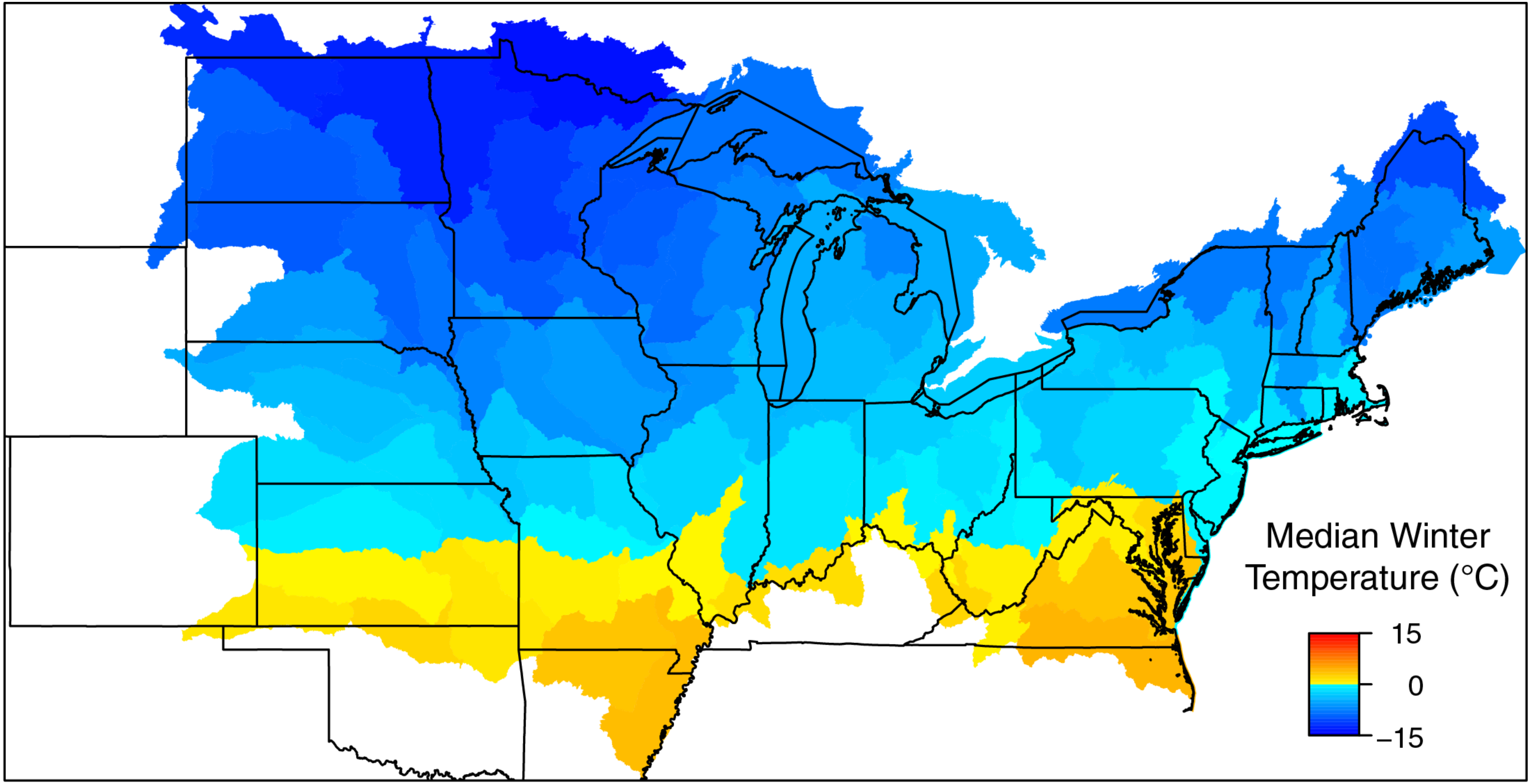
Period
Total
Winter
Spring
Metric
Average Temperature
Minimum Temperature
Metric Mean
Normalized Value
Season
2
1
0
−1
−2
2004
2008
2012
2016

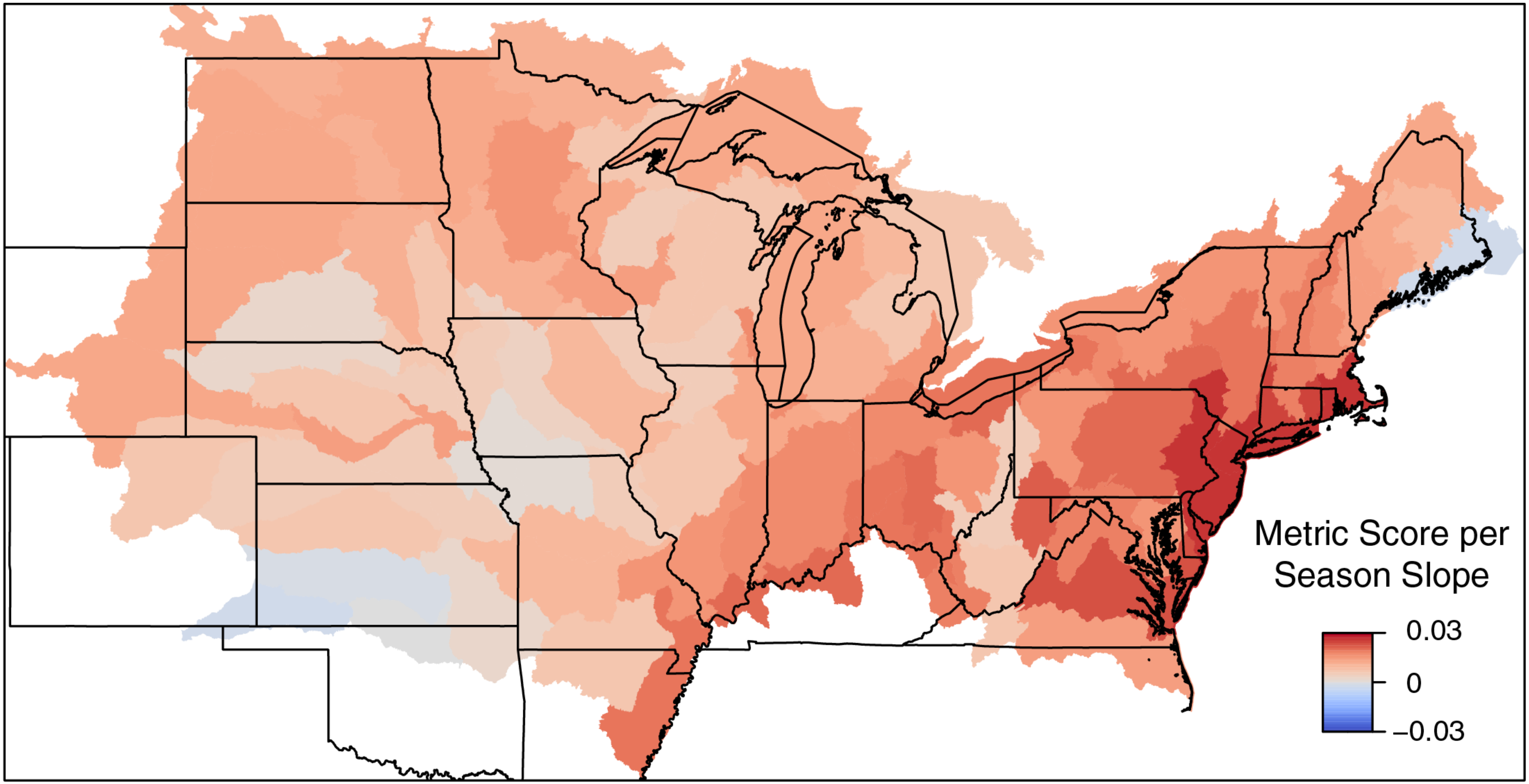


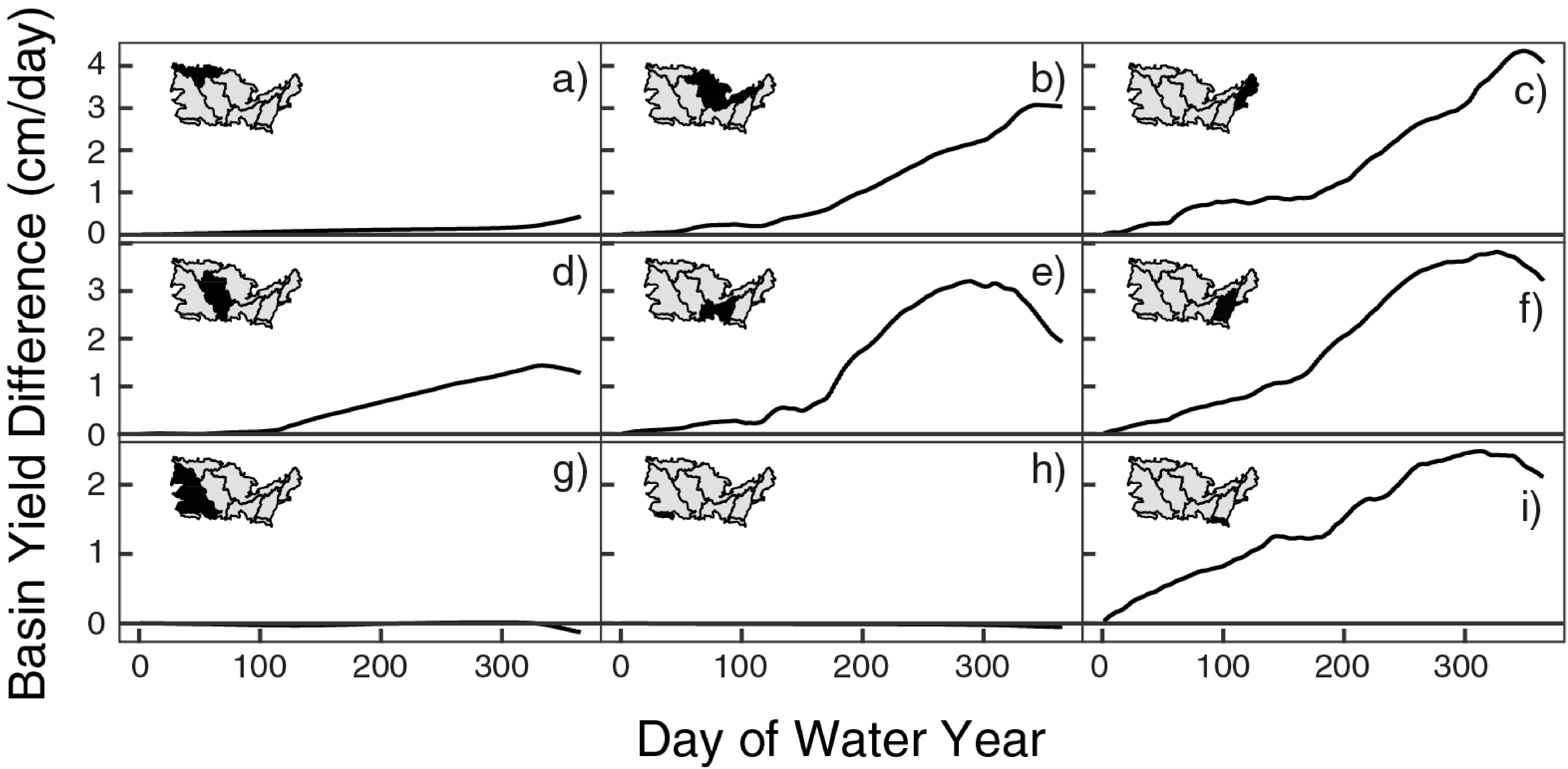
48° N
46° N
44° N
42° N
90° W
88° W
86° W
84° W
82° W
0
10
20
30
40
50
60
70
80
PET (mm)



Median Monthly Precipitation (cm)
Month
a)
Total = 47.8, 47.8
b)
Total = 80.5, 83.7
c)
Total = 104.2, 108.2
d)
Total = 78.6, 79.2
e)
Total = 98.3, 102.8
f)
Total = 100.2, 102.4
g)
Total = 60.0, 55.4
h)
Total = 55.9, 59.2
i)
Total = 104.8, 109.8
5
10
O N D J F M A M J J A S
Warm Years
Cool Years


Median Winter
Temperature (°C)
15
0
−15


Metric Score per
Season Slope
0.03
0
−0.03



Basin Yield Difference (cm/day)
Day of Water Year
a)
b)
c)
d)
e)
f)
g)
h)
i)
0
1
2
3
4
100
200
300

Region	Southern LP		Northern LP		UP	
Year Type	*Cool*	*Warm*	*Cool*	*Warm*	*Cool*	*Warm*
Peak SWE (mm)	72	35	99	74	167	123
Peak SWE Day of Water Year	132	119	132	147	159	153
Bare Ground Days	128	157	90	135	60	100
Peak Melt (mm)	38	23	38	40	40	29
Peak Melt Day of Water Year	121	140	158	167	217	174
50% Melt Day of Water Year	157	140	177	163	210	180
Total Melt (mm)	304	215	420	296	581	420
Melt Events	9	8	7	8	5	7
Melts to Completion	5	4	2	5	2	4
Melt Event Amount (mm)	24	20	15	10	26	13
Melt Event Length (days)	9	7	10	7	24	10

Region	Southern Lower Peninsula		Northern Lower Peninsula		Upper Peninsula	
Year Type	*Cool*	*Warm*	*Cool*	*Warm*	*Cool*	*Warm*
Total Basin Yield (mm)	200	199	231	222	194	161
Peak Basin Yield (mm)	2.0	2.2	1.6	1.9	3.0	1.6
Peak Basin Yield Day of Water Year	166	165	196	165	205	169
Center of Volume Day of Water Year	164	147	140	136	178	148
Coefficient of Variation (%)	45	39	23	24	69	37

Region	Southern Lower Peninsula		Northern Lower Peninsula		Upper Peninsula	
Year Type	*Cool*	*Warm*	*Cool*	*Warm*	*Cool*	*Warm*
Total Net Recharge (cm)	139	158	187	188	163	79
Peak Monthly Recharge (cm)	43	51	120	98	128	45
Total Rain (cm)	186	233	150	197	53	69
Mean S/P	0.42	0.30	0.58	0.46	0.83	0.68

Grouping	Variable	Winter Type	
		Warm	Cool
Climate	Metric Score	1.06	-0.93
	Winter Temp (°C)	-1.5	-5.5
	Annual Precipitation (cm)	92.6	88.7
	Seasonal Snowfall (cm)	80.0	130.1
Snowpack	Max Snow Depth (cm)	23.5	37.9
	Max Depth (DOWY)	111	123
	Season Length (days)	86	110
	Bare Ground Days	202	168
Streamflow	Total Basin Yield (cm)	24.1	21.2
	Max Basin Yield (cm)	0.12	0.14
	Max Basin Yield (DOWY)	192	195
	CDV (DOWY)	172	186