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SUPPORTING INFORMATION

for

Recent climatological trends and potential influences on forest phenology around western Lake Superior, USA.

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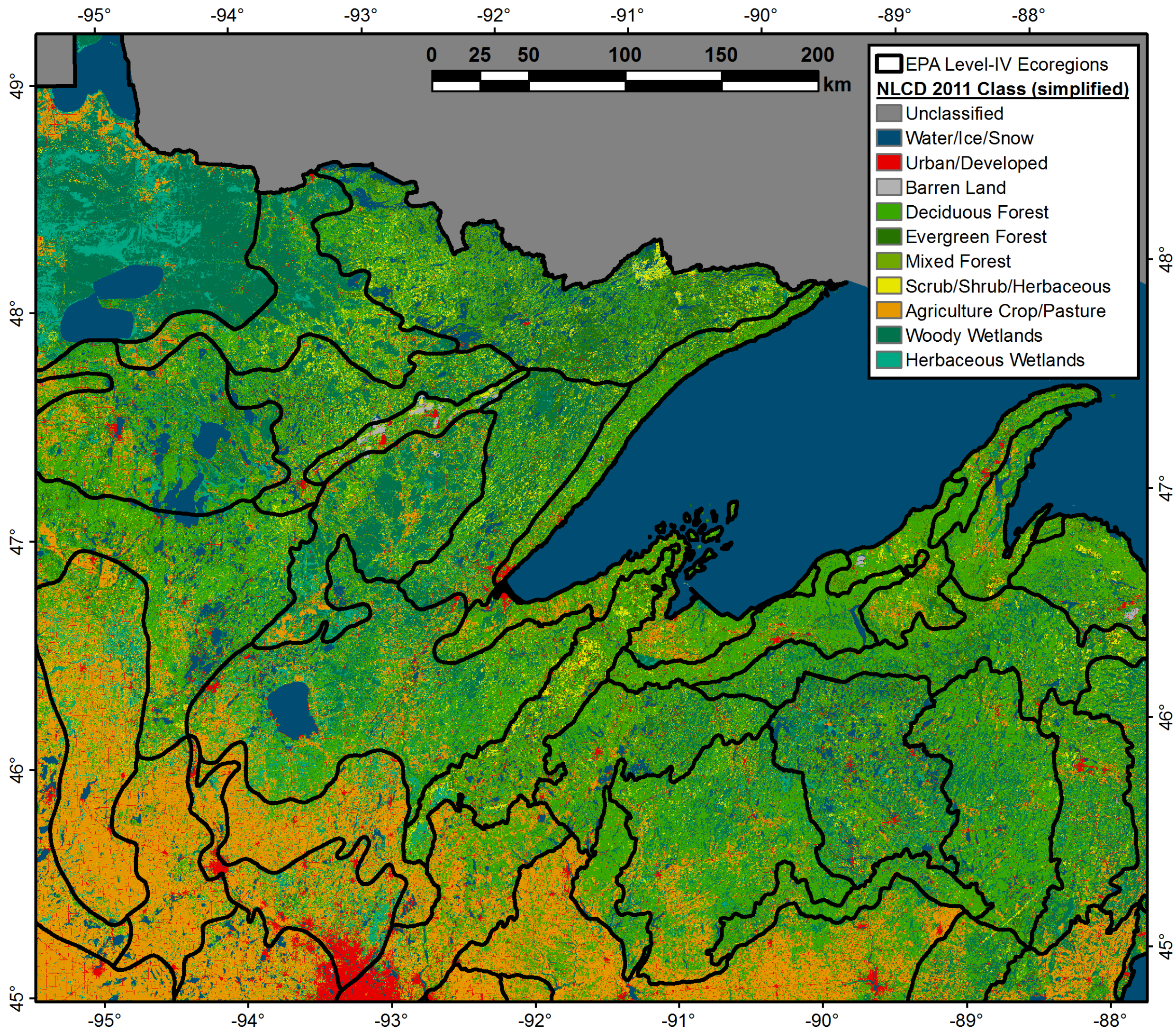
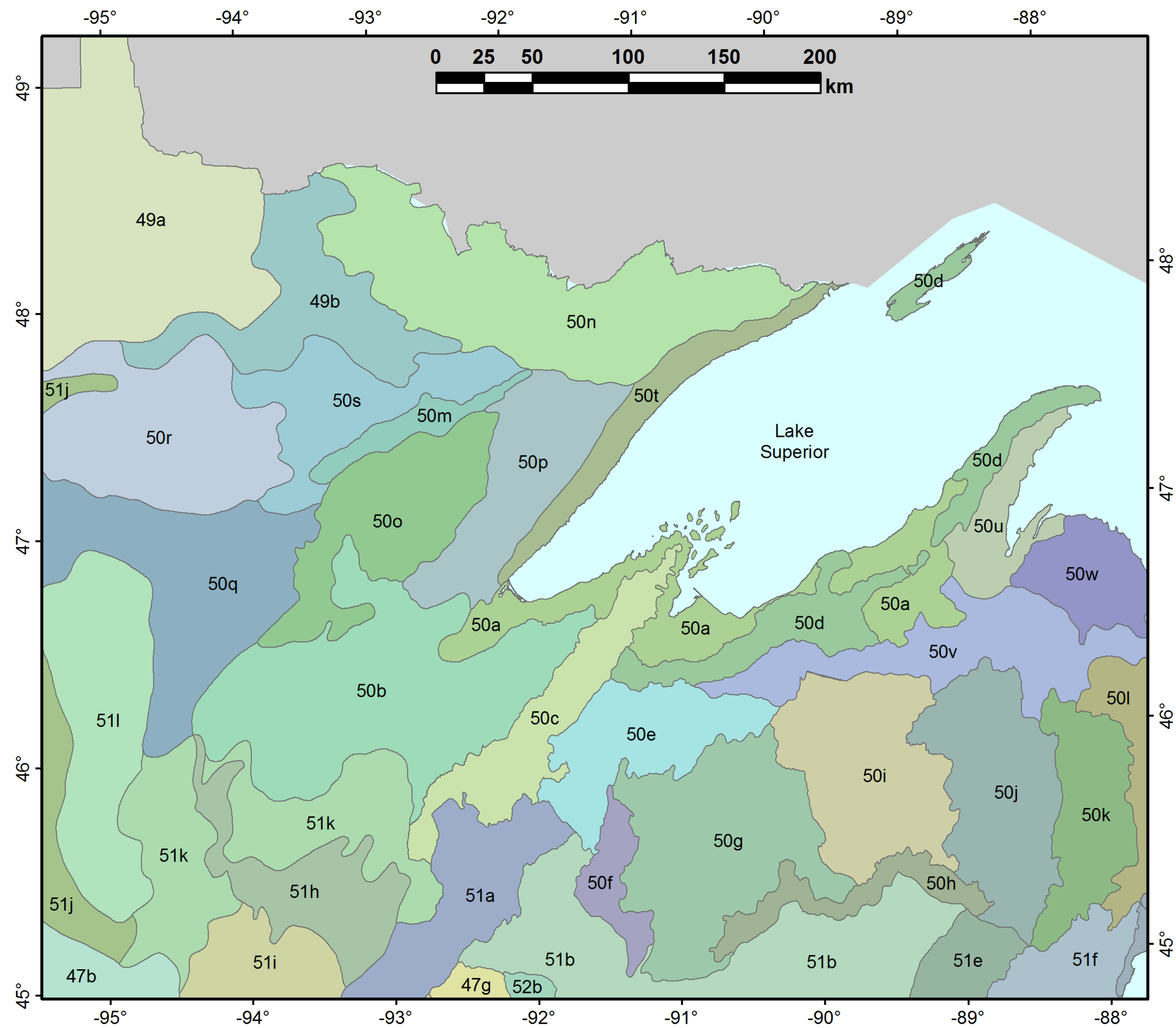


Figure S2: USEPA [2011] Level-IV ecoregions [Omernik et al., 2000; Omernik, 2004]. Ecoregion designations and additional information are given in Supplemental Appendix A.



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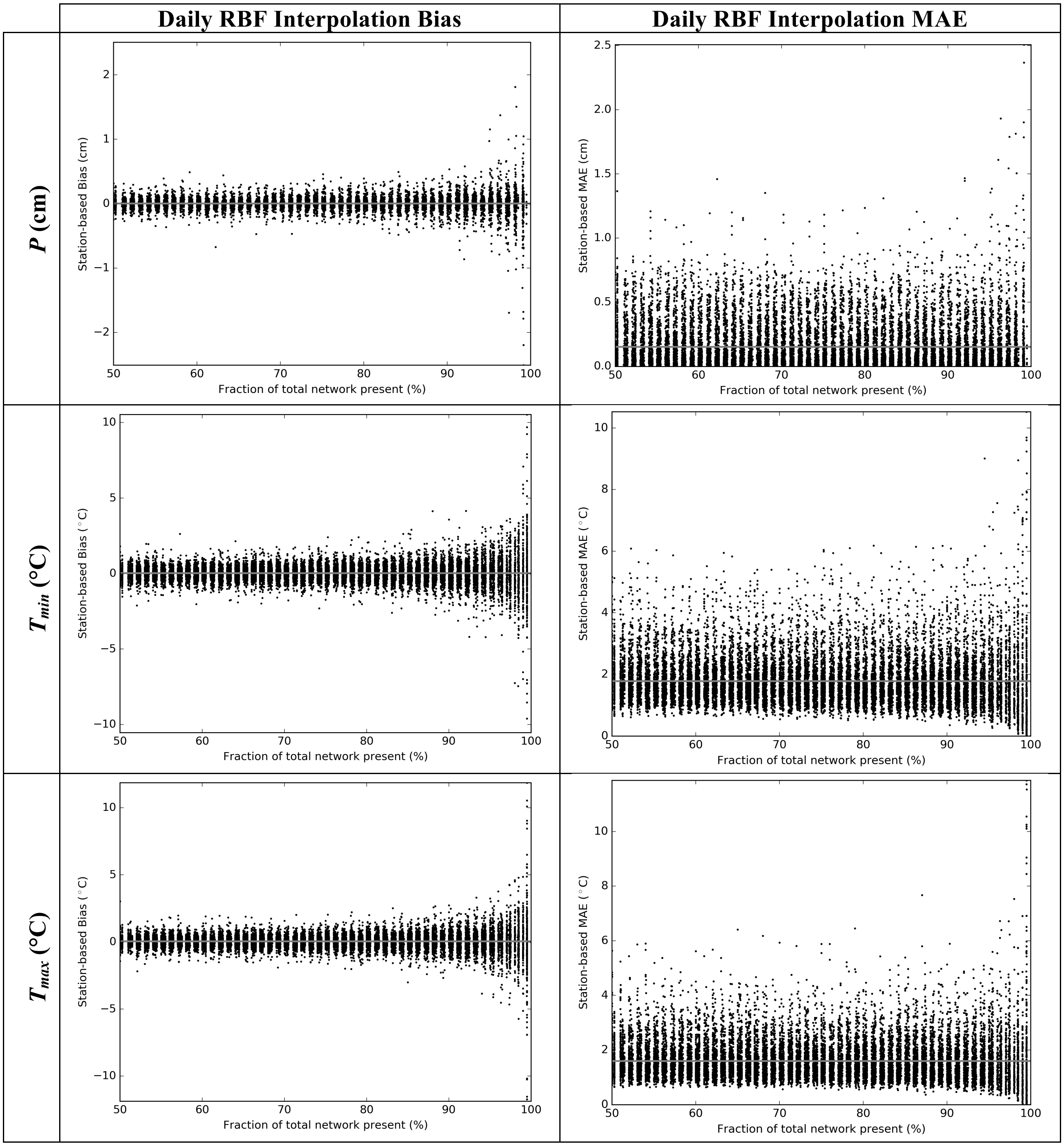


Figure S3 (continued)

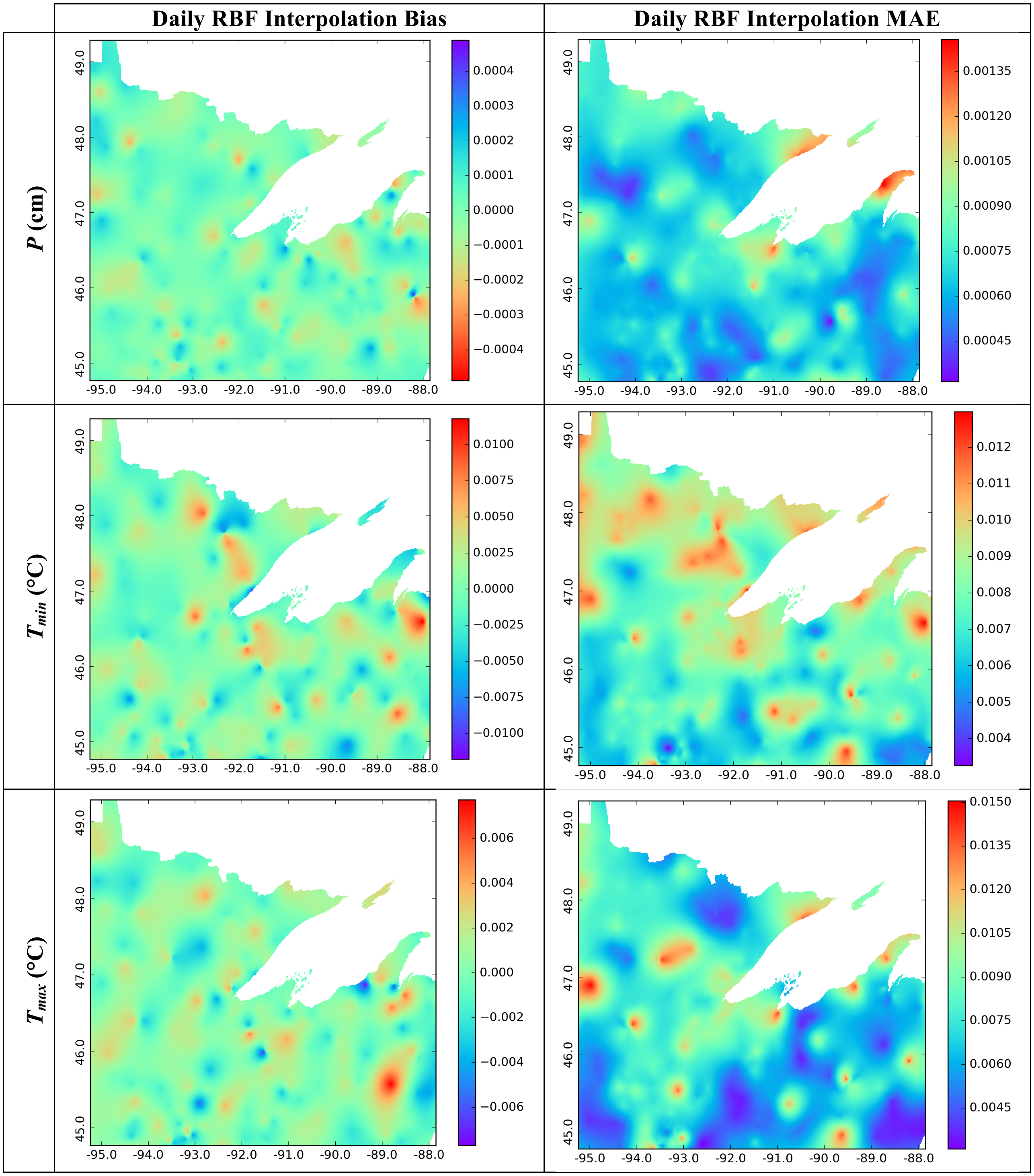
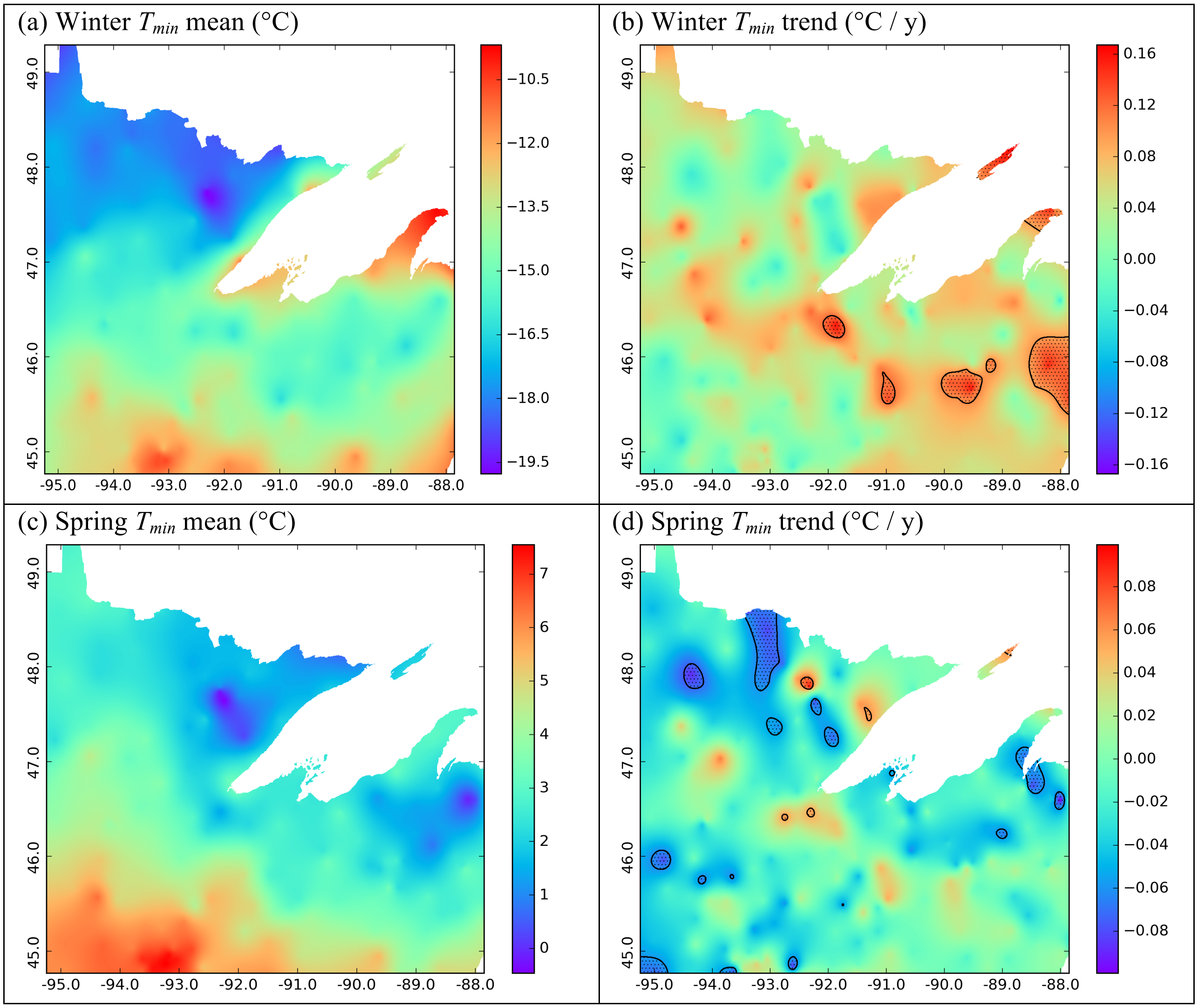


Figure S4: 1984-2013 mean seasonal T_{min} and trends across the US portion of our study area. Areas of trend significance at $p < 0.05$ in maps b, d, f, and h are stippled.



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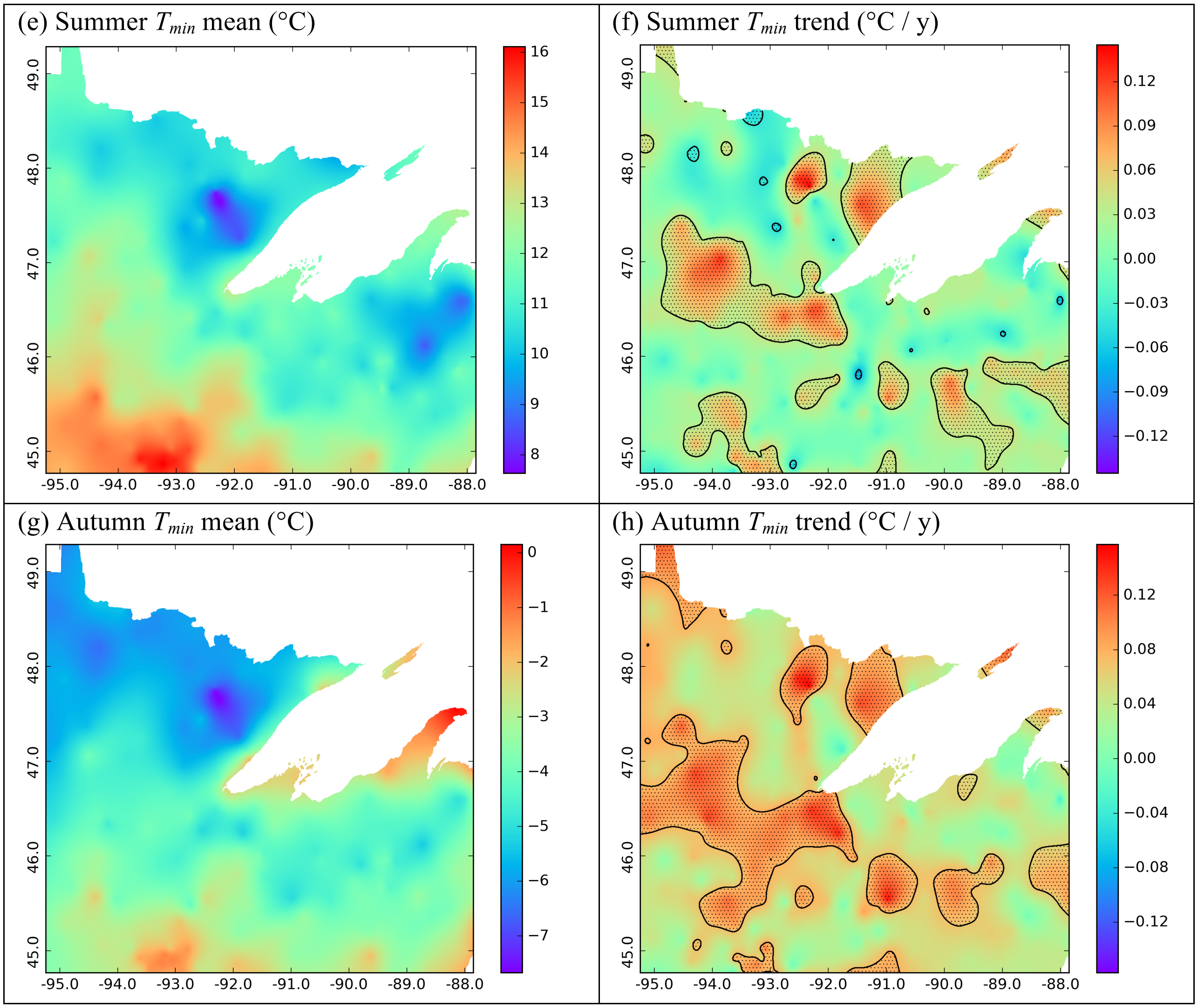

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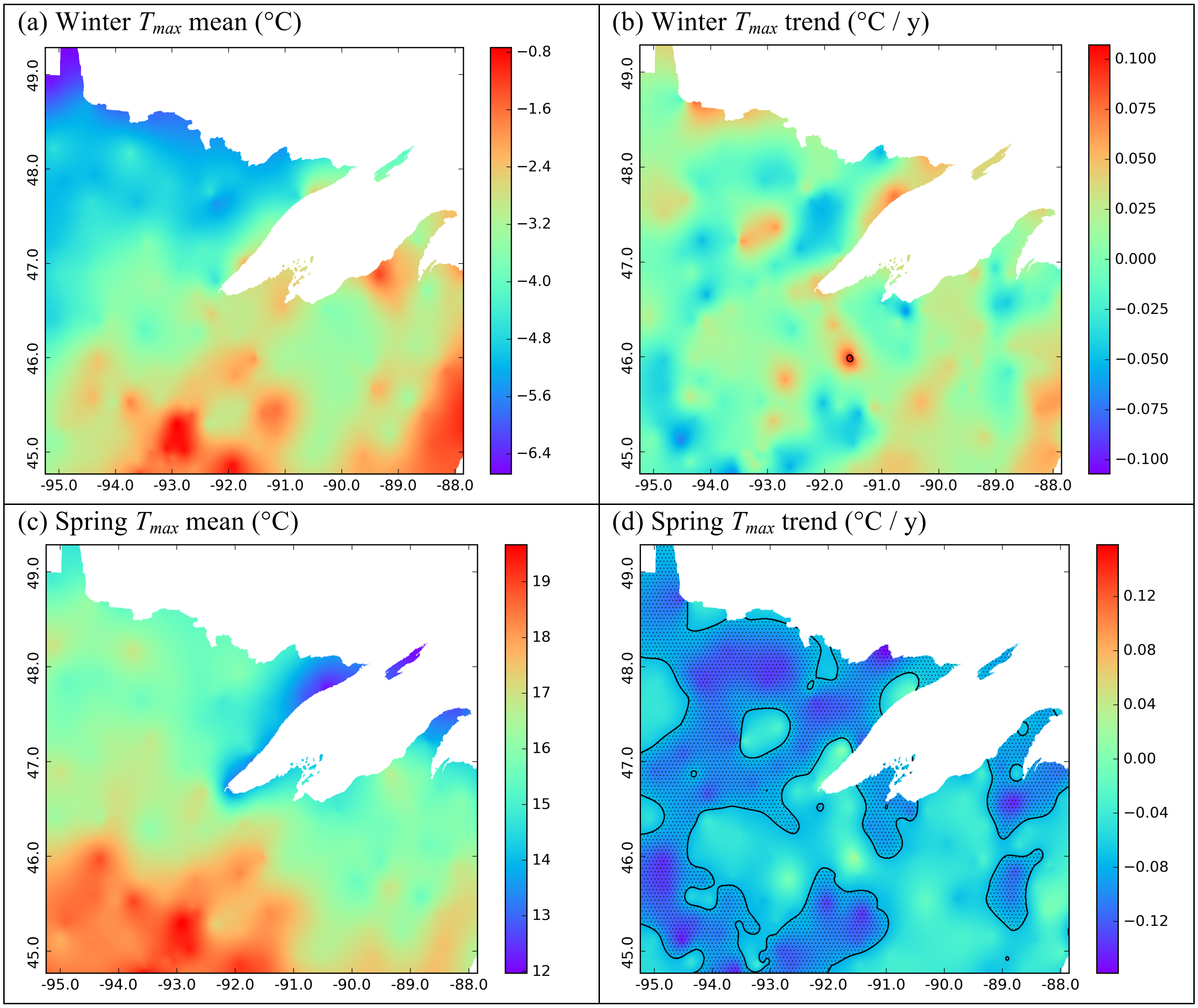

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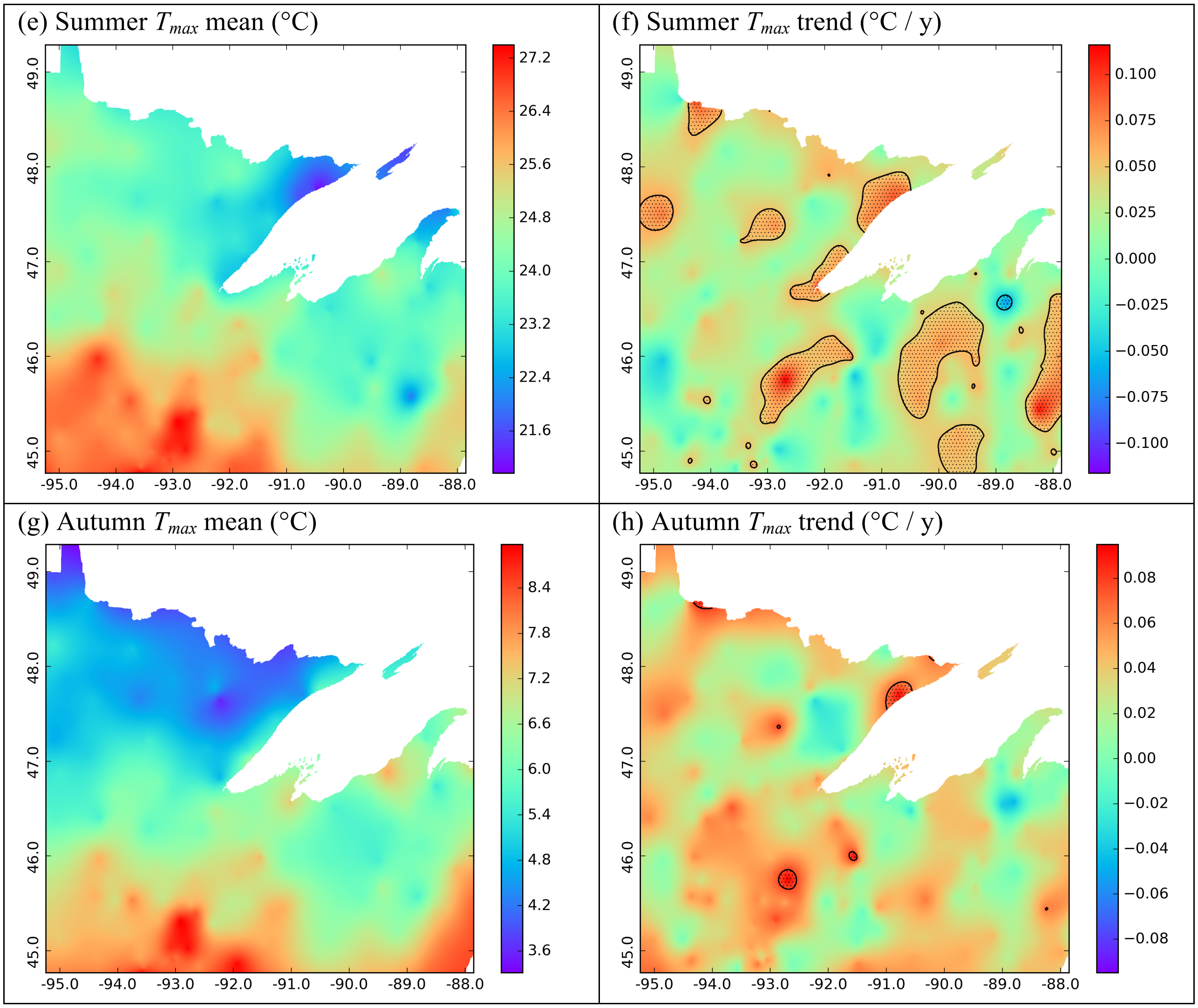

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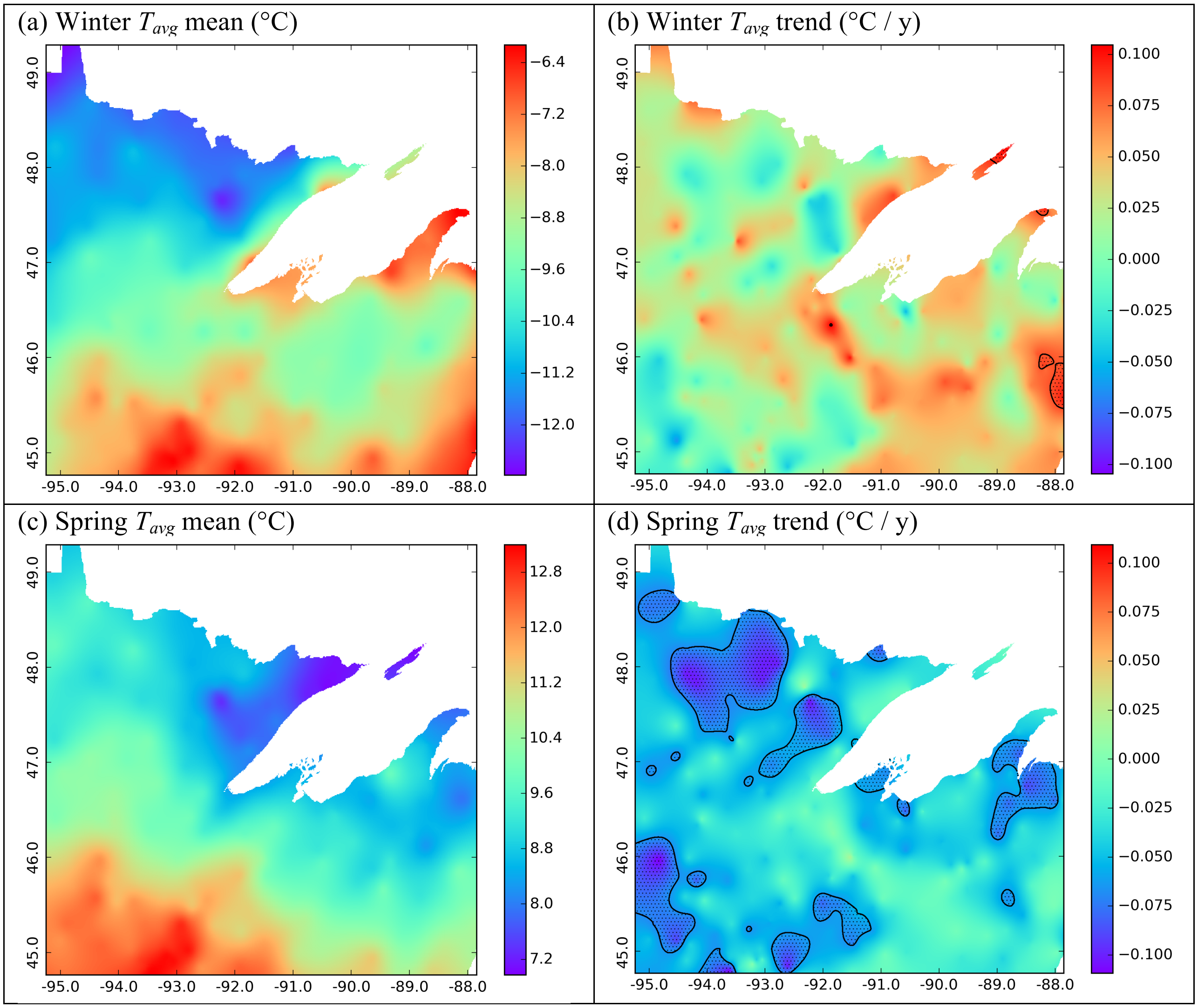


Figure S6 (continued)

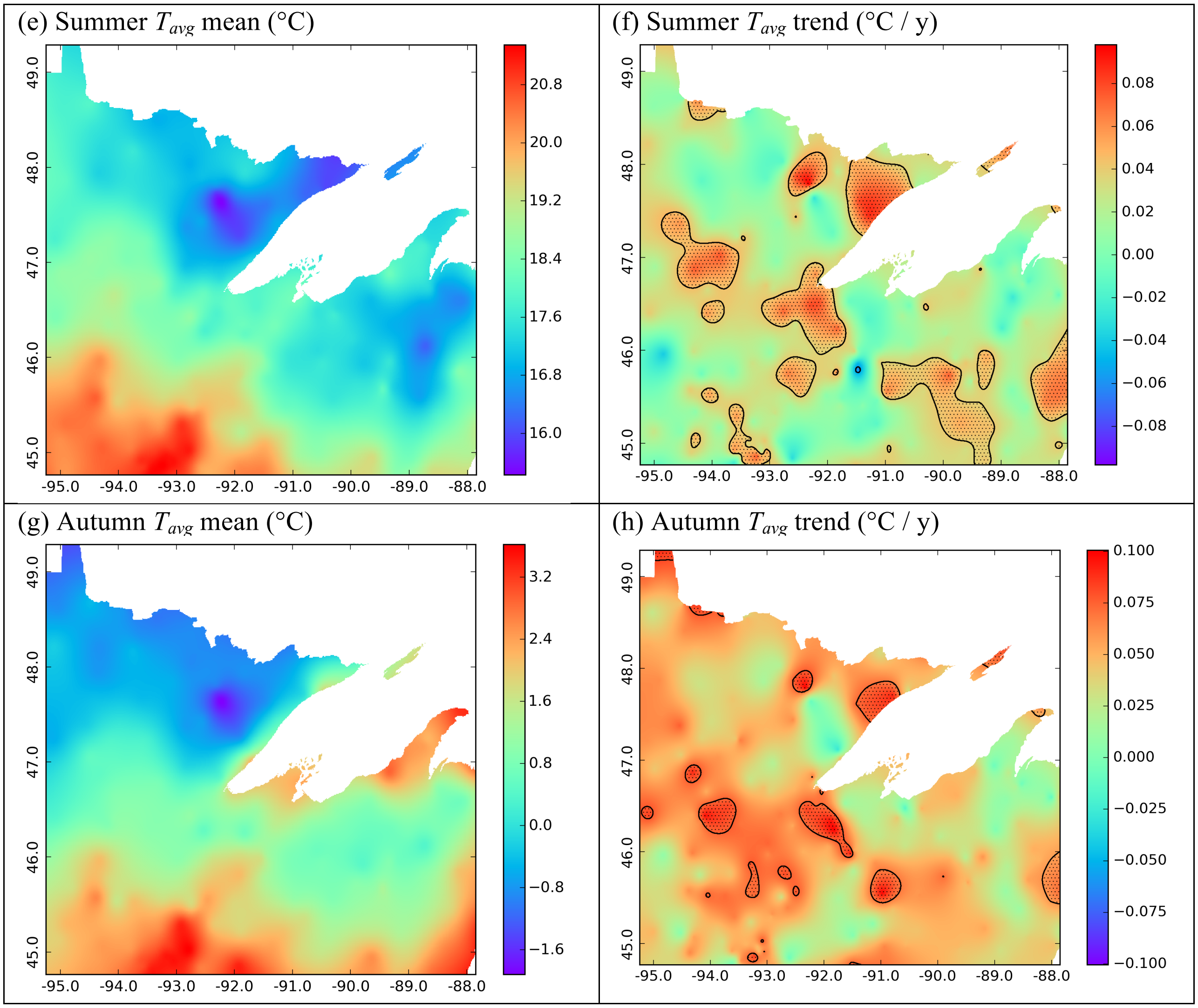


Figure S7: 1984-2013 mean seasonal P and trends across the US portion of our study area. Areas of trend significance at $p < 0.05$ in maps b, d, f, and h are stippled.

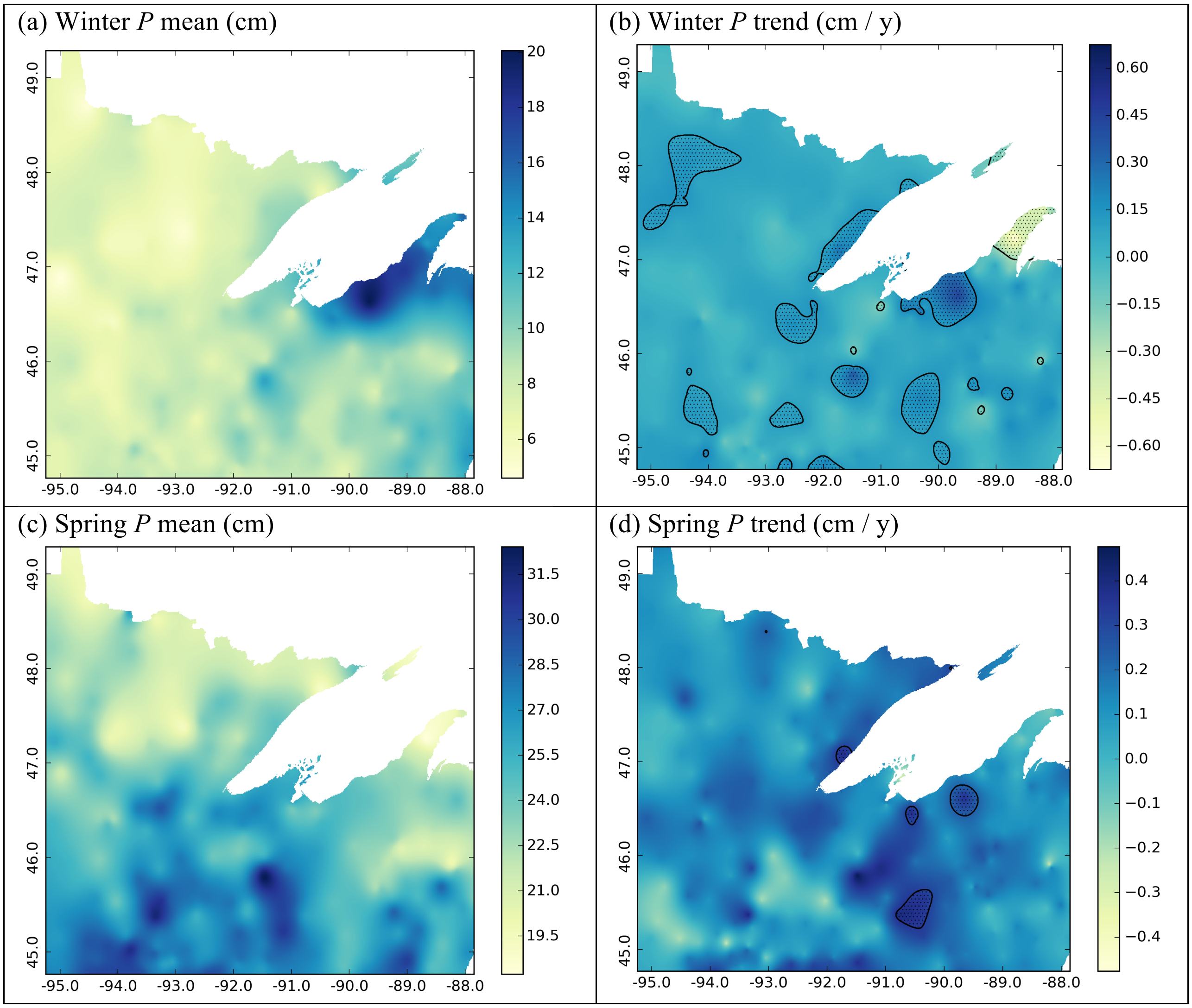
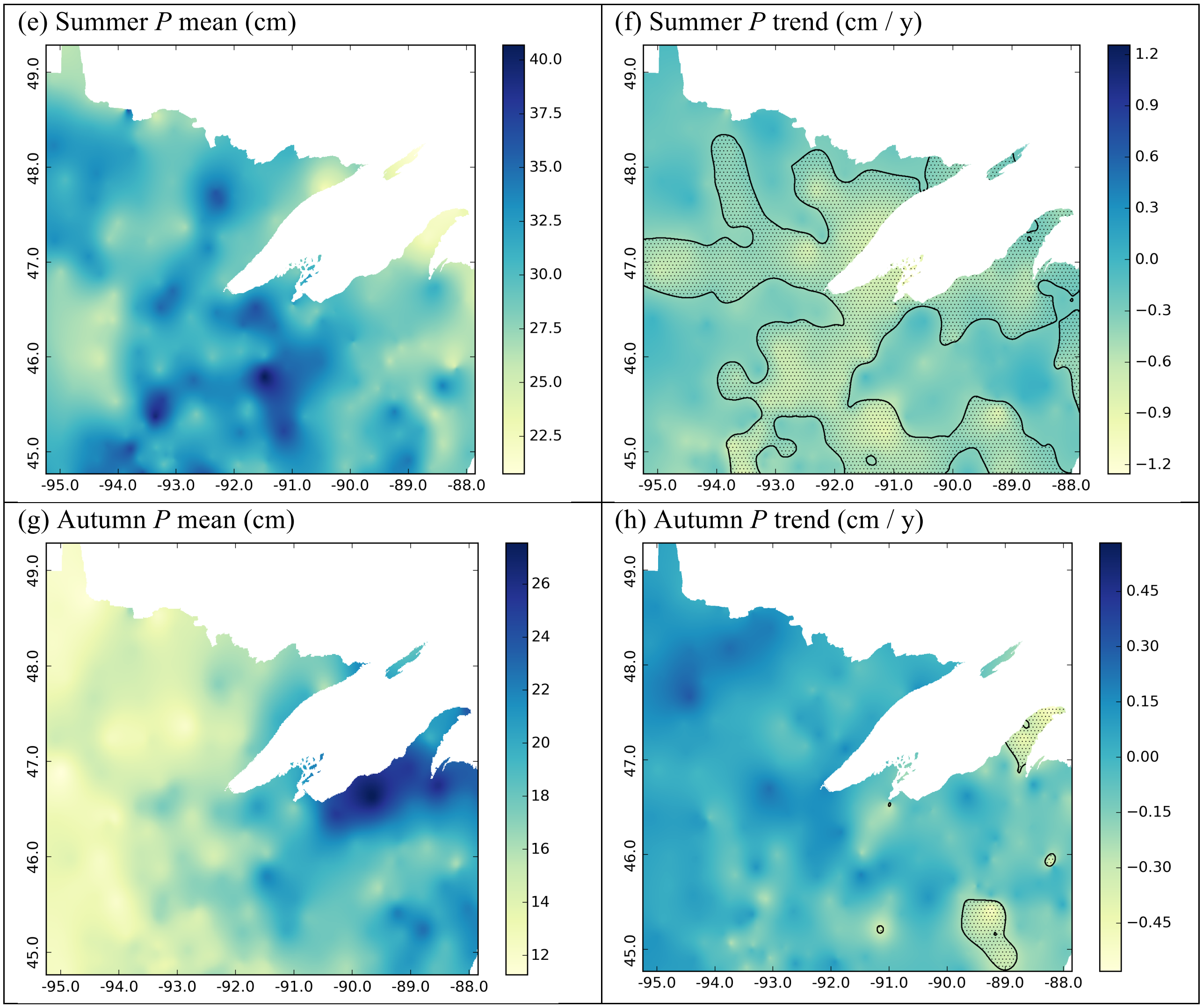


Figure S7 (continued)



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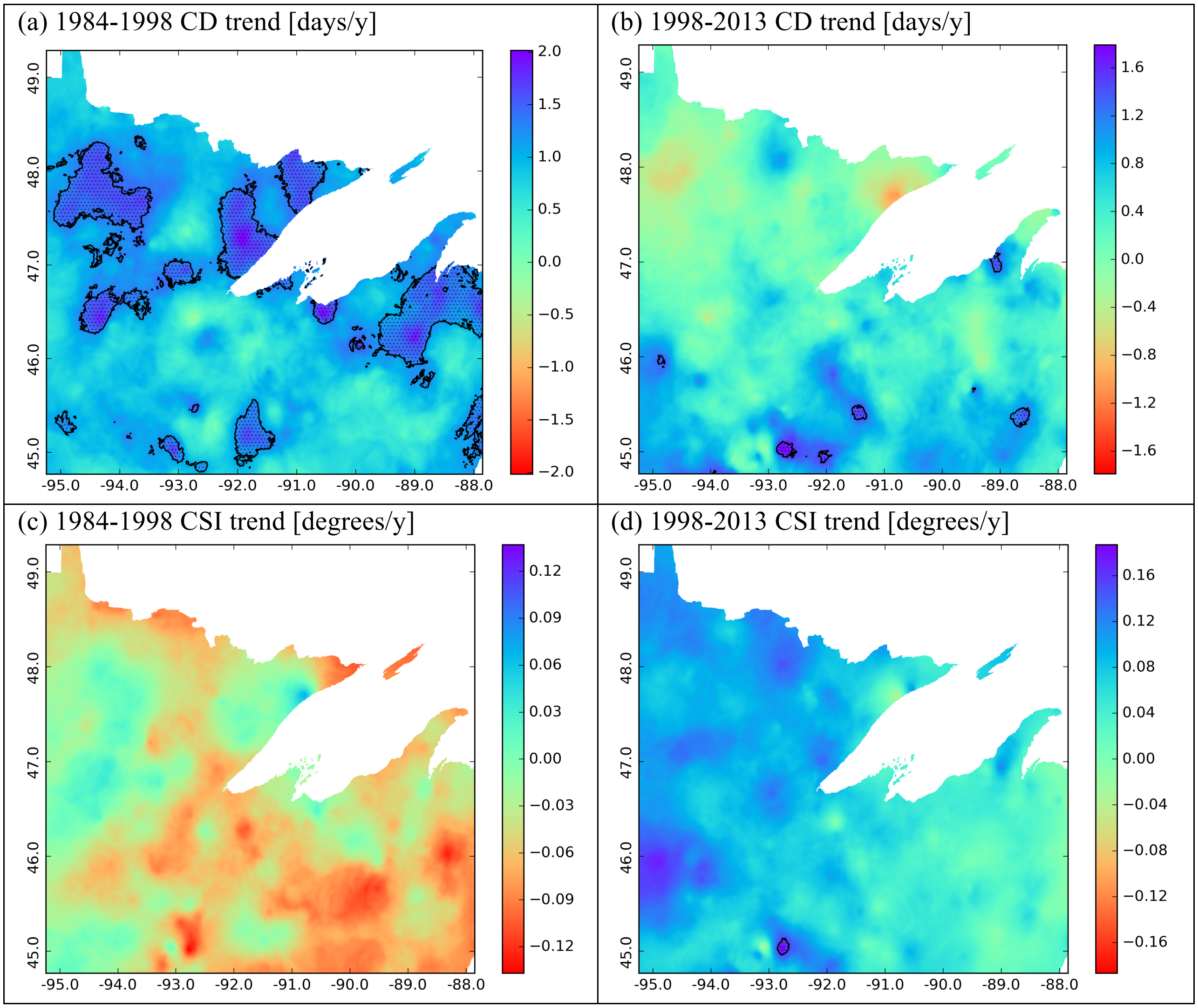
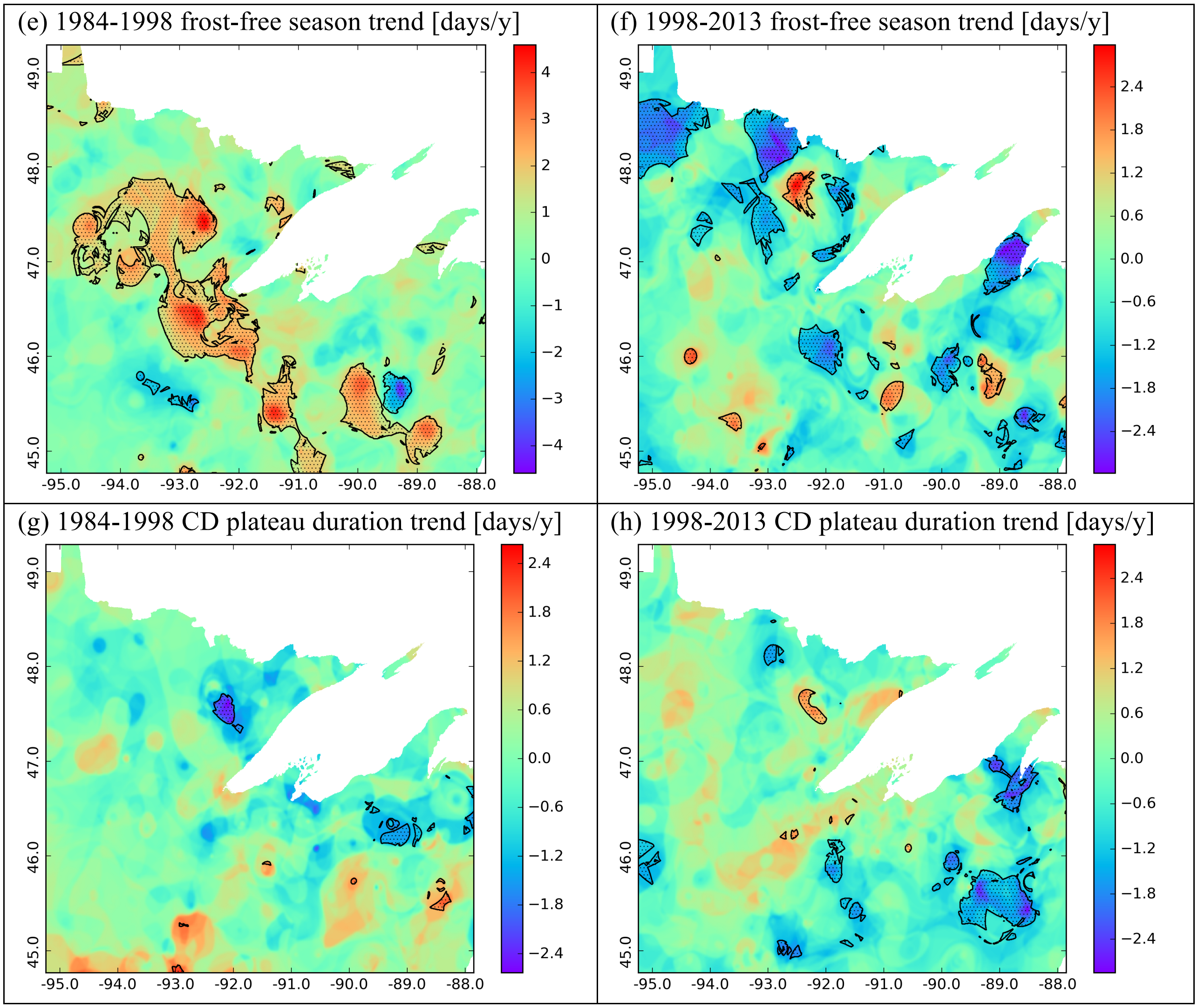


Figure S8 (continued)



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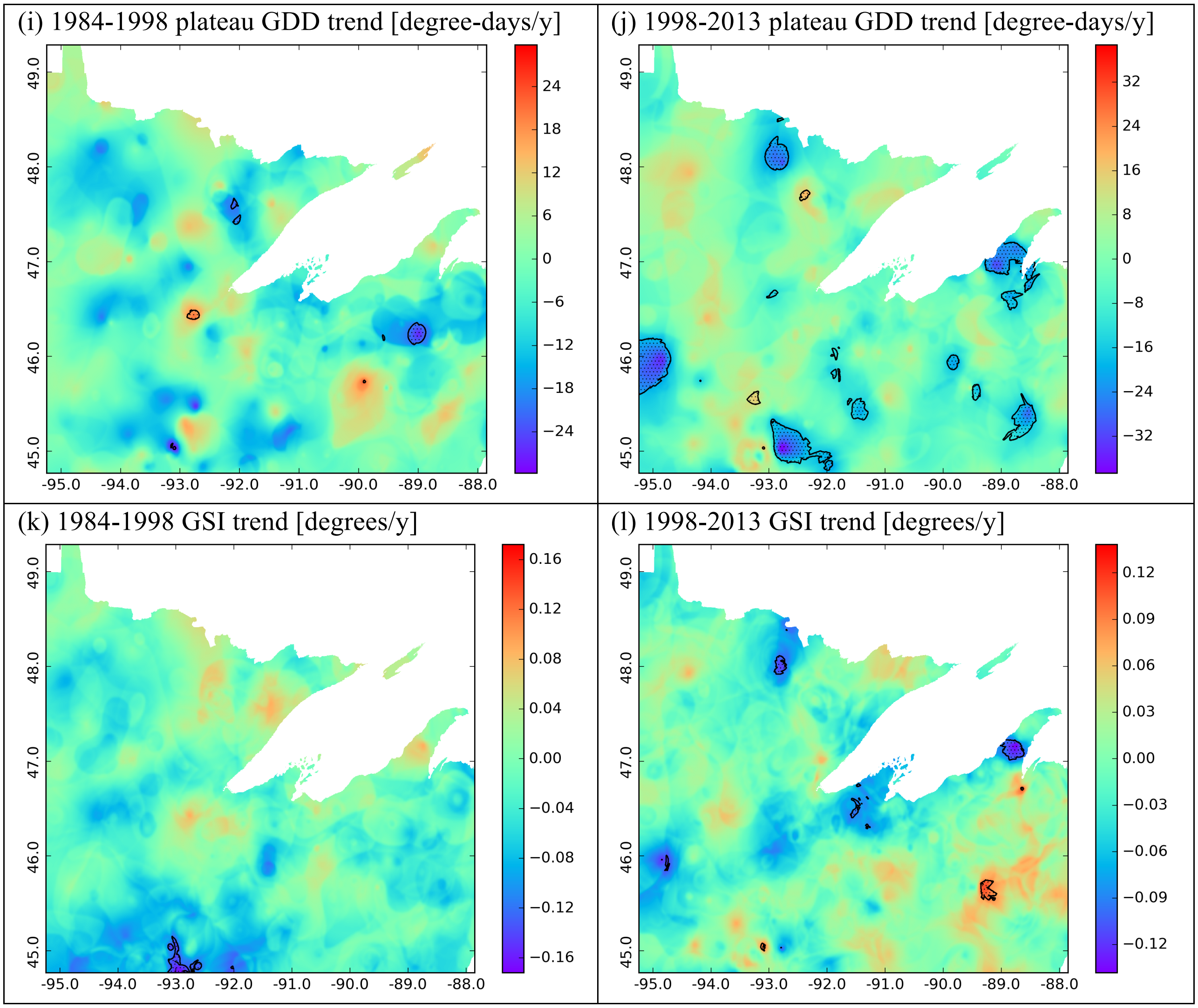

Figure S9: Study area ecoregion clusters (cf. Figs. S1 and S2) based on 1984-2013 climatological similarity analysis (Supplemental Appendix C).

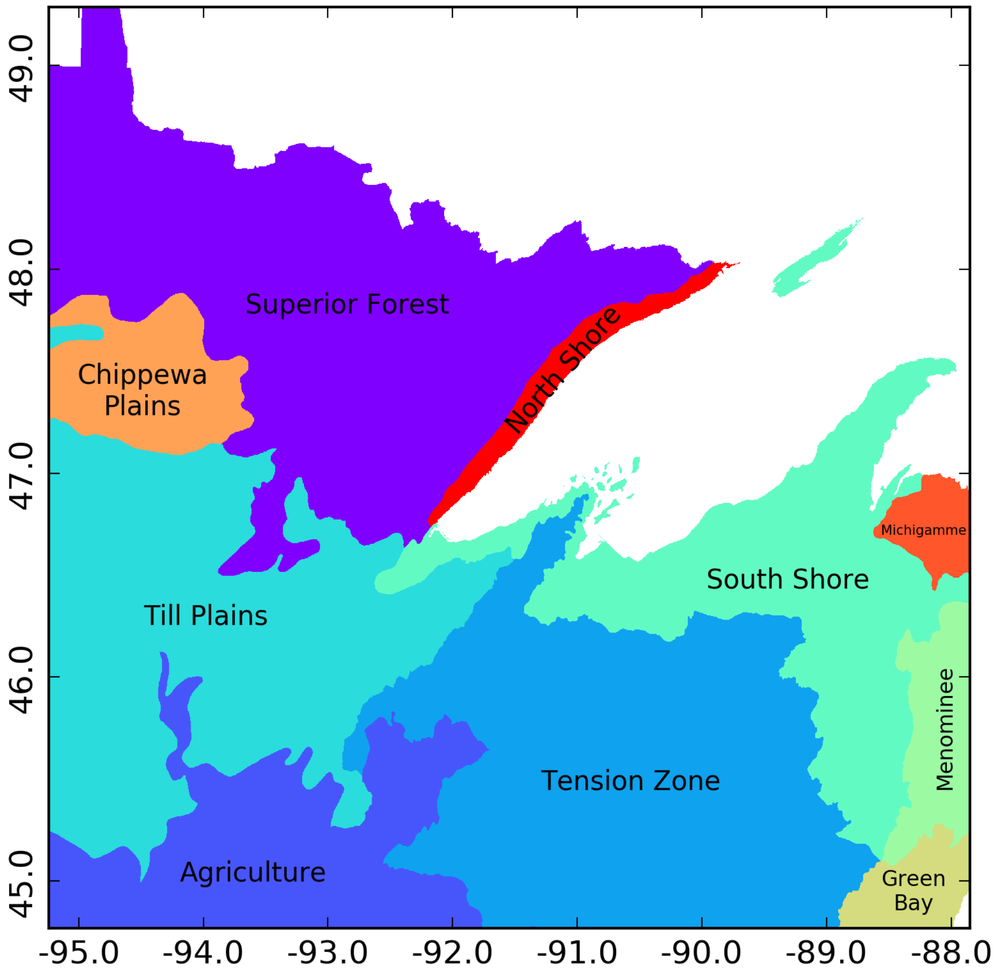

Table S1: 1984-2013 climatological indicator statistics (cf. Table 1) for selected ecoregion clusters in Fig. S6. Area-wide extremes for each indicator are noted in bold type.

	30y spatiotemporal mean ± 1 temporal standard deviation					
Temperature Indicators	**Agri-culture**	**Till Plains**	**Superior Forest**	**North Shore**	**South Shore**	**Tension Zone**
Winter Average Temperature (°C)	**−7.5 ± 2.3**	−9.2 ± 2.4	**−11.1 ± 2.4**	−9.1 ± 2.1	−8.4 ± 2.0	−8.5 ± 2.1
Spring Average Temperature (°C)	**12.2 ± 1.5**	10.7 ± 1.5	8.8 ± 1.5	**7.7 ± 1.2**	8.9 ± 1.4	10.3 ± 1.4
Summer Average Temperature (°C)	**20.3 ± 0.9**	19.0 ± 1.0	17.2 ± 0.9	**16.6 ± 1.0**	17.3 ± 0.9	18.3 ± 0.9
Autumn Average Temperature (°C)	**2.5 ± 1.7**	1.1 ± 1.7	**−0.6 ± 1.7**	0.7 ± 1.5	1.4 ± 1.4	1.5 ± 1.6
Annual Average Temperature (°C)	**6.9 ± 1.7**	5.4 ± 1.7	**3.6 ± 1.7**	4.0 ± 1.5	4.8 ± 1.5	5.4 ± 1.6

Precipitation Indicators	**Agri-culture**	**Till Plains**	**Superior Forest**	**North Shore**	**South Shore**	**Tension Zone**
Winter Total Precipitation (cm)	7.9 ± 2.2	7.4 ± 2.2	**7.1 ± 1.9**	9.0 ± 2.6	**12.7 ± 3.1**	9.5 ± 2.7
Spring Total Precipitation (cm)	**27.9 ± 8.3**	25.6 ± 7.4	**22.2 ± 5.3**	23.1 ± 6.7	23.6 ± 5.0	26.5 ± 7.1
Summer Total Precipitation (cm)	**32.1 ± 9.2**	29.5 ± 7.9	30.0 ± 7.0	**27.1 ± 7.5**	28.2 ± 6.1	32.0 ± 8.7
Autumn Total Precipitation (cm)	14.6 ± 5.9	**14.3 ± 5.9**	14.6 ± 5.6	18.4 ± 6.9	**21.4 ± 5.3**	18.6 ± 5.3
Annual Total Precipitation (cm)	84.4 ± 13.7	78.8 ± 10.8	**75.5 ± 8.9**	79.1 ± 10.0	87.3 ± 11.0	**88.1 ± 13.4**

Cold Season Indicators	**Agri-culture**	**Till Plains**	**Superior Forest**	**North Shore**	**South Shore**	**Tension Zone**
Freezing Days (using T_{min})	**162.0 ± 11.7**	176.1 ± 11.1	**193.7 ± 10.0**	183.0 ± 11.3	187.1 ± 9.6	179.5 ± 10.5
Chilling Days (using T_{avg})	**157.6 ± 11.6**	168.2 ± 11.0	182.6 ± 10.5	**183.1 ± 11.6**	177.5 ± 10.2	169.7 ± 11.1
CSI (degrees)	10.3 ± 1.4	11.1 ± 1.4	**12.0 ± 1.3**	10.4 ± 1.2	**10.2 ± 1.1**	10.5 ± 1.2
Last Spring Freezing Night (DOY)	**120.6 ± 9.0**	128.6 ± 7.1	142.4 ± 6.3	138.2 ± 7.6	**145.3 ± 6.9**	137.7 ± 6.7
1st Autumn Freezing Night (DOY)	**276.7 ± 7.4**	272.1 ± 7.0	**264.3 ± 5.4**	271.9 ± 7.0	267.3 ± 5.5	268.8 ± 5.4

Warm Season Indicators	**Agri-culture**	**Till Plains**	**Superior Forest**	**North Shore**	**South Shore**	**Tension Zone**
Last Spring Freezing Night (GDD)	124.5 ± 57.9	134.4 ± 50.0	174.6 ± 62.8	**106.4 ± 43.0**	**205.7 ± 74.6**	197.9 ± 63.6
Frost-free Season (days)	**156.0 ± 9.5**	143.5 ± 7.8	**121.9 ± 7.8**	133.7 ± 10.1	122.0 ± 8.9	131.1 ± 7.1
Beginning of CD Plateau (DOY)	**114.8 ± 9.7**	120.2 ± 9.3	128.5 ± 7.9	**134.7 ± 8.9**	132.7 ± 7.1	123.3 ± 9.0
End of CD Plateau (DOY)	**281.1 ± 8.9**	277.9 ± 8.3	**272.2 ± 6.9**	275.7 ± 7.2	273.5 ± 5.2	275.3 ± 6.5
Plateau Duration (days)	**166.2 ± 12.1**	157.7 ± 10.8	143.7 ± 8.8	141.0 ± 11.5	**140.8 ± 7.1**	152.0 ± 8.1
Plateau GDD (degree-days)	**2164.4 ±156.5**	1909.7 ± 148.7	1569.9 ± 146.6	**1420.7 ± 150.7**	1554.2 ± 133.4	1786.1 ± 134.8
GSI (degrees)	**13.1 ± 0.9**	12.1 ± 0.9	10.9 ± 0.8	**10.1 ± 0.8**	11.1 ± 0.9	11.8 ± 0.8

Table S2: 1984-2013 climatological trends for selected ecoregion clusters in Table 2 and Fig. 10. Trend statistical significance is marked as * at $p < 0.05$, ** at $p < 0.01$, and *** at $p < 0.001$.

	30-year trend (units/y)					
Temperature Indicators	**Agri-culture**	**Till Plains**	**Superior Forest**	**North Shore**	**South Shore**	**Tension Zone**
Winter Average Temperature (°C)	0.003	0.019	0.016	0.048	0.035	0.038
Spring Average Temperature (°C)	−0.052	−0.047	−0.059	−0.024	−0.046	−0.031
Summer Average Temperature (°C)	0.022	0.027	0.023	0.049*	0.017	0.025
Autumn Average Temperature (°C)	0.047	0.057	0.046	0.051	0.030	0.046
Annual Average Temperature (°C)	0.005	0.014	0.006	0.031	0.009	0.019
Precipitation Indicators	**Agri-culture**	**Till Plains**	**Superior Forest**	**North Shore**	**South Shore**	**Tension Zone**
Winter Total Precipitation (cm)	0.06	0.04	0.06	0.12*	0.04	0.06
Moderate Precipitation Days	0.03	0.02	0.02	0.07**	0.00	0.01
Spring Total Precipitation (cm)	0.08	0.11	0.11	0.24	0.13	0.18
Moderate Precipitation Days	0.02	0.04	0.02	0.05	0.07	0.08
Summer Total Precipitation (cm)	−0.42*	−0.35*	−0.32*	−0.53***	−0.34**	−0.43*
Moderate Precipitation Days	−0.15*	−0.12*	−0.13*	−0.29***	−0.11*	−0.15*
Autumn Total Precipitation (cm)	−0.02	0.04	0.07	0.06	−0.11	−0.08
Moderate Precipitation Days	−0.01	0.02	0.03	0.03	−0.02	−0.02
Annual Total Precipitation (cm)	−0.26	−0.15	−0.08	−0.09	−0.26	−0.27
Cold Season Indicators	**Agri–culture**	**Till Plains**	**Superior Forest**	**North Shore**	**South Shore**	**Tension Zone**
Freezing Days (using T_{min})	−0.26	−0.38	−0.09	−0.23	−0.14	−0.31
Chilling Days (using T_{avg})	−0.11	−0.22	−0.06	−0.18	−0.03	−0.17
CSI (degrees)	−0.01	−0.02	−0.02	−0.03	−0.02	−0.03
Last Spring Freezing Night (DOY)	0.08	−0.10	−0.12	−0.16	−0.19	−0.18
1st Autumn Freezing Night (DOY)	0.29	0.22	0.18	0.11	0.12	0.11
Warm (Growing) Season Indicators	**Agri–culture**	**Till Plains**	**Superior Forest**	**North Shore**	**South Shore**	**Tension Zone**
Last Spring Freezing Night (GDD)	0.52	−1.38	−2.98*	−1.71	−3.30*	−2.26
Frost–free Season (days)	0.21	0.32	0.30	0.28	0.31	0.29
Beginning of CD Plateau (DOY)	0.15	0.17	0.25	0.19	0.18	0.18
End of CD Plateau (DOY)	0.50**	0.46**	0.14	0.44**	0.05	0.20
Plateau Duration (days)	0.36	0.29	−0.10	0.25	−0.12	0.02
Plateau GDD (degree-days)	1.53	1.62	−0.81	5.48	−0.04	1.38
GSI (degrees)	−0.02	−0.01	0.00	0.02	0.01	0.01

SUPPLEMENTAL APPENDIX A

USEPA [2011] Level-III and -IV ecoregion designations for the maps in Figs. S1 and S2. Additional information, including detailed descriptions of ecoregion characteristics, are available online at http://www.epa.gov/wed/pages/ecoregions/level_iii_iv.htm.

Level III	Level IV	Name
47		**Western Corn Belt Plains**
	47b	Des Moines Lobe
	47g	Lower St. Croix and Vermillion Valleys, a.k.a. Prairie Pothole Region
49		**Northern Minnesota Wetlands**
	49a	Peatlands
	49b	Forested Lake Plains
50		**Northern Lakes and Forests**
	50a	Lake Superior Lacustrine Clay Plain
	50b	Minnesota/Wisconsin Upland Till Plain
	50c	St. Croix Pine Barrens
	50d	Ontonagon Lobe Moraines and Gogebic Iron Range
	50e	Chequamegon Moraine and Outwash Plain
	50f	Blue Hills
	50g	Chippewa Lobe Rocky Ground Moraines
	50h	Perkinstown End Moraine
	50i	Northern Highlands Lakes Country
	50j	Brule and Paint River Drumlins
	50k	Wisconsin/Michigan Pine and Oak Barrens
	50l	Menominee Drumlins and Ground Moraine
	50m	Mesabi Range
	50n	Boundary Lakes and Hills
	50o	Glacial Lakes Upham and Aitken
	50p	Toimi Drumlins
	50q	Itasca and St. Louis Moraines
	50r	Chippewa Plains
	50s	Nashwauk/Marcell Moraines and Uplands
	50t	North Shore Highlands
	50u	Keweenaw-Baraga Moraines
	50v	Winegar Dead Ice Moraine
	50w	Michigamme Highland
	50aa	Menominee–Drummond Lakeshore
51		**North Central Hardwood Forests**
	51a	St. Croix Outwash Plain and Stagnation Moraines
	51b	Central Wisconsin Undulating Till Plain
	51e	Upper Wolf River Stagnation Moraine
	51f	Green Bay Till and Lacustrine Plain
	51h	Anoka Sand Plain and Mississippi Valley Outwash
	51i	Big Woods
	51j	Alexandria Moraines and Detroit Lakes Outwash Plain
	51k	McGrath Till Plain and Drumlins
	51l	Wadena/Todd Drumlins and Osakis Till Plain
52		**Driftless Area**
	52b	Blufflands and Coulee Section

SUPPLEMENTAL APPENDIX B

Our code and data supplement is available online at https://megarcia.github.io/WxCD. This supplement contains all of the Python scripts and supporting datasets that would be required to reproduce the results that we present. The code has been written and commented such that the package can be used to reproduce our analytical procedures in other locations where station datasets provide adequate coverage of daily temperature and precipitation. The code package is distributed free of charge under the Gnu General Public License (GPL, v3) that allows for modification and redistribution. Researchers who find bugs and/or make improvements and additions to the code package are encouraged to send those to the corresponding author for incorporation in, and improvement of, the original code package. Our positioning of the code package on GitHub provides a number of functional efficiencies for the collaborative improvement of such software.

Interested researchers will find an extensive README file with the code package that explains the set-up and sequence of operations for using these Python scripts. A set-up script is included that checks for the presence of all intended code, data, and documentation files. This script also establishes the directory structure required for output as the analysis progresses, and checks ensure that all Python package dependencies are already installed on the user's computer. The original code package is then archived, should the user need to revert to the original code while making modifications for their own work.

The code package relies on sequential operations of data generation and analyses that begin with a GHCN-Daily dataset downloaded from NCEI. A sample dataset consisting of the data used to generate the analyses and results in this paper is included for example and testing. Instructions are included for users to obtain their own datasets for other locations, as some of the options required by our QA/QC and processing scripts are very specific. The NCEI documentation of the GHCN-Daily product is also included with this package.

Several datasets are included with this code package in addition to the GHCN-Daily temperature and precipitation data sample. Subset areas of the USGS NLCD and EPA Level-IV Ecoregions geospatial products (i.e., those used to produce the maps in Figs. 1 and S1 and the mask used in all other maps presented here) are included in binary ('.bil') formats with the requisite grid information in separate ('.hdr') files. As mentioned in the comments for one of these scripts, a '.hdr' file may be "spoofed" by the user in order to define a working study area without the binary datasets present, and/or the requirement for such files may be removed from the scripts by the researcher. In either case, it is necessary to define an area and grid to which the GHCND station data will be interpolated. Several interpolation methods are included in the code package, with instructions on how to change the selection of method.

Should users wish to replicate the analyses that include NLCD and USEPA Ecoregion maps (see Supplemental Appendix C), we obtained those from the source agencies (USGS and USEPA, respectively) and created subset areas using ArcGIS. We have also included sample NCEP-CPC climatological datasets for several global and hemispherical teleconnection indices, currently analyzed late in the process, as well as the NSIDC/MIFL Lake Superior ice coverage information that we obtained for this work.

Finally, the code package itself consists of original routines (except where specifically noted) written in Python using NumPy, SciPy, Pandas, GDAL, and various other libraries and packages that the set-up script will verify are installed before use. There are 16 analysis scripts (and several alternate versions) intended for execution in order using the commands listed near the beginning of each, along with 7 modules that are needed for the execution of these scripts. Researchers are encouraged to read the header information in each script file for information that may not be included in the code package README file. There is also one utility script that can be used to query the generated daily meteorological fields and climatological derivatives for desired locations and times.

SUPPLEMENTAL APPENDIX C

In an additional analysis of spatiotemporal climatological patterns and trends for our study area and period, we aggregated our gridded climate indicators according the USEPA [2011] ecoregion map (Figs. S1 and S2) and applied a simple clustering procedure to characterize climatological similarities and differences among subregions. Our clustering procedure used pairwise comparisons across ecoregion-mean annual time series for each climatological indicator based on statistical tests for correlation (Pearson's coefficient) and differences in time series mean (Student's t-test) and variance (Levene's test).

We used the correlation coefficient along with statistical significance measure of each test as indicators of time series similarity for each ecoregion pair, and we defined a climatological dissimilarity index:

$$D = [(1 - r)^2 + r_s^2 + (1 - t_s)^2 + (1 - l_s)^2]^{1/2}$$

Here r is Pearson's correlation coefficient (where both sign and value are important), r_s is its statistical significance level (smaller for strongly-correlated time series), t_s is the significance level of Student's t-test result (smaller for *less* similar time series means), and l_s is the significance level of Levene's test result (smaller for *less* similar time series variance measures).

This calculation results in lower index (D) values for ecoregion pairs that are alike in trend, variability, mean and variance of a given climatological indicator: perfectly correlated ($r = 1$) and statistically equivalent ecoregion pairs have a value of $D = 0$; uncorrelated ecoregion pairs ($r = 0$) have a value up to $D = 2$; perfectly anti-correlated ecoregion pairs ($r = -1$) have a value in the range $2 \leq D \leq 2.45$. We then averaged these index values for each ecoregion pair over the (equally weighted) set of climatological indicators to provide a composite dissimilarity index value, and analyzed these results to identify clusters of ecoregions that were most climatologically alike. No conditions for spatial contiguity of ecoregions forming a cluster were imposed on this process.

Our ecoregion cluster results (Fig. S9, Tables S1 and S2) are consistent with spatial variations in land cover (Fig. S1) and climatology across our study area. The cluster in the southwest corner of our study area contains a mixture of agriculture and other land cover types, where land–atmosphere interactions influenced by irrigation and seasonal crop cycles would appear quite different from those in adjacent, primarily forested areas. Our ecoregion clusters generally demonstrate the influences of several factors: (a) the Upper Midwest prairie–forest Tension Zone across Wisconsin [Curtis and McIntosh, 1951; Bockheim and Schlieman, 2014], contiguous with the Till Plains across northern Minnesota [Wheeler et al., 1992], based on associations among climate, soils, and vegetation types [Schaetzl et al., 2005; Danz et al., 2013]; (b) proximity to Lake Superior and its influence on land–lake temperature and moisture interactions; (c) the passage of storm systems across the study area generally toward the southeast in most seasons.

SUPPLEMENTAL APPENDIX D

Based on the discussion presented in Section 5.1, with diminishing *P* in the warmest months of the year we can postulate a trend of decreasing summer soil moisture. To provide evidence of this possibility, we performed a preliminary comparison of *T* and *P* time series with dendrochronology datasets for three oak sites within our study area [Voelker et al., 2012] that are available through the NOAA NCEI International Tree-Ring Data Bank (ITRDB). We converted tree ring width measurements to basal area increments and extracted co-located annual *T* and *P* observations from our own climate data products.

For the available tree ring measurements that extended through our study period from 1984 through 2008, this cursory analysis showed no immediately apparent correlations between basal area increment and our climatological indicators for the same year. Basal area increments did correlate with autumn *T* if both are averaged over at least 2 years, and inverse correlations with spring *T* if both are averaged over at least 5 years. We also found direct correlations between basal area increments and both autumn and annual *P* if both are averaged over at least 4 years. However, there was no particular indication of summer temperature- or precipitation-related impact on tree growth at these locations.

These results are inconclusive for our study, and therefore not included in the main text. These results are, however, consistent with studies showing that the majority of new stemwood production occurs early in the growing season [Delpierre et al., 2016] and that spring moisture availability (and moisture stress) has a greater impact on tree ring width and density than summer and autumn climatological conditions [Teskey et al., 1987; Bouriaud et al., 2005; Arend and Fromm, 2007]. Given that these preliminary results represent only a few individuals of a single species in northwestern Wisconsin, we hope to expand and explore more generalized connections between climatology, phenology, and dendrochronology through our ongoing work.