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Great Lakes ice duration, winter severity index, cumulative freezing degree days, and atmospheric teleconnection patterns, 1973 – 2018

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UNITED STATES
DEPARTMENT OF COMMERCE

Wilbur L. Ross, Jr. Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

Dr. Neil Jacobs, Acting Administrator

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Great Lakes ice duration, winter severity index, cumulative freezing degree days, and atmospheric teleconnection patterns, 1973 – 2018

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1.0 Introduction

This report investigates interannual variability in ice coverage (Bai et al., 2012; Assel et al., 1998; Assel et al., 2013). We conduct analyses of the ice coverage records—freeze-up date, break-up date, duration and annual maximum ice coverage (AMIC)—with air temperature — cumulative freezing degree days (FDD), winter severity index (WSI)—and atmospheric teleconnections—El Niño–Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and Pacific Decadal Oscillation (PDO). In addition, we use scatter plots and linear / non-linear regression, to determinate whether they have linear or quadratic relationships. The purpose of this report is to provide users with the Great Lakes environmental parameters and in depth analyses that are easily digested and applied to resources management, projection, and planning.

2.0 Data Sets

2.1 Ice coverage data

The ice coverage ASCII gridded data is provided by national Ice Center (NIC) from November 1972 until Jun 2018. Before May 2007, the ice data was mapped with Mercator projection (Clarke 1866 ellipsoid) and re-sampled to a 510 x 516 pixels gridded data. Since November 2007, the data was changed to 1024 x 1024 pixels grid (with Mercator projection and WGS 1984 ellipsoid), to improve the resolution from 2.55 km to 1.275 km (Wang et al., 2012; Wang et al., 2017). In our process, the ice coverage data is averaged at each lake, so resampling method was not used for data before 2008 winter.

2.2 Air temperature data

GHCND (Global Historical Climate Network Daily, https://www.ncdc.noaa.gov/ghcn-daily-description) long-term daily air temperature data was used. The pre-processing and data cleaning was done and organized by Hunter et al (2015). In our process, maximum and minimum temperature are utilized, because most of the station don't have long-term averaged temperature. Therefore, averaging maximum and minimum temperature was used instead of averaged temperature. Because to there are around 700 stations around the Great Lakes, we set up some criteria to select the useful stations:

A. Stations within 50km outside the lake's basin

B. Time span includes 1973 – 2018

C. Data coverage (observation over a period of observed time) is more than 90%. However, some regions do not have enough stations, e.g. north side of Lake Superior, low data coverage stations are included for better station distribution.

The station locations are shown in Fig. 1. and the detail information is listed in Table 1.

2.3 Atmospheric teleconnection indices (Wang et al., 2018)

ENSO: is defined by the 3-month running mean of ERSST.v3 (Extended Reconstructed Sea Surface Temperature Version 3) SST anomalies in the Niño3.4 region (5°N-5°S, 120°-170°W. Data is obtained from the NOAA/CPC (Climate Prediction Center, http://www.cpc.noaa.gov/products/analysis monitoring/ensostuff/ensoyears.shtml).

NAO: is defined as the normalized sea level pressure difference between Azores and Iceland. Record was obtained from the Climatic Research Unit, UK. (http://www.cru.uea.ac.uk/cru/data/NAO.htm).

PDO: is the standardized principal component time series of leading empirical orthogonal function (EOF) of monthly sea surface temperature anomalies (SSTA) over the North Pacific (poleward of 20° N) after the global mean SST has been removed. The PDO index is derived from http://research.jisao.washington.edu/pdo/PDO latest; https://www.ncdc.noaa.gov/teleconnections/pdo/).

AMO: is defined from the patterns of SST variability in the North Atlantic once any linear trend has been removed. The AMO index is obtained from http://www.esrl.noaa.gov/psd/data/timeseries/AMO/.

3.0 Definition and methodology

A. Ice coverage: freeze-up date, break-up date, duration, and AMIC
    1. Freeze-up and break-up date: Compute the mean for each lake and all Great Lakes area per data, and assign the free-up date and break-up date if this is the first/last date when the mean greater than 10%. NA is assigned if the mean of ice coverages are all less than 10% in that year.

    2. Duration: subtract the break-up date by the freeze-up date. Duration is assigned to 1 if the freeze-up and break-up date are same.

    3. AMIC: compute the mean for each lake and all the Great Lakes area per data, and assign the maximum mean as AMIC

B. Air temperature: cumulative FDD, WSI, and WSI_GLERL

    For each lake, daily temperature is derived from averaging all station daily data.

    1. FDD: calculate how many days (from November 1th through June 30th) during which the averaged temperature is less than or equal to 0 °C.

    2. WSI: is developed by C. R. Snider in an earlier study, to define the Great Lakes winter severity. It is defined as average of the monthly-mean temperatures from November 1th through February 28th (or 29th for leap year) (Bai et al., 2011).

3. WSI_GLERL: average of the monthly-mean temperatures from December 1th through February 28th (or 29th for leap year).

C. Atmospheric teleconnections (ENSO, NAO, PDO, and AMO) are used to correlate with air temperature and ice coverage parameters.

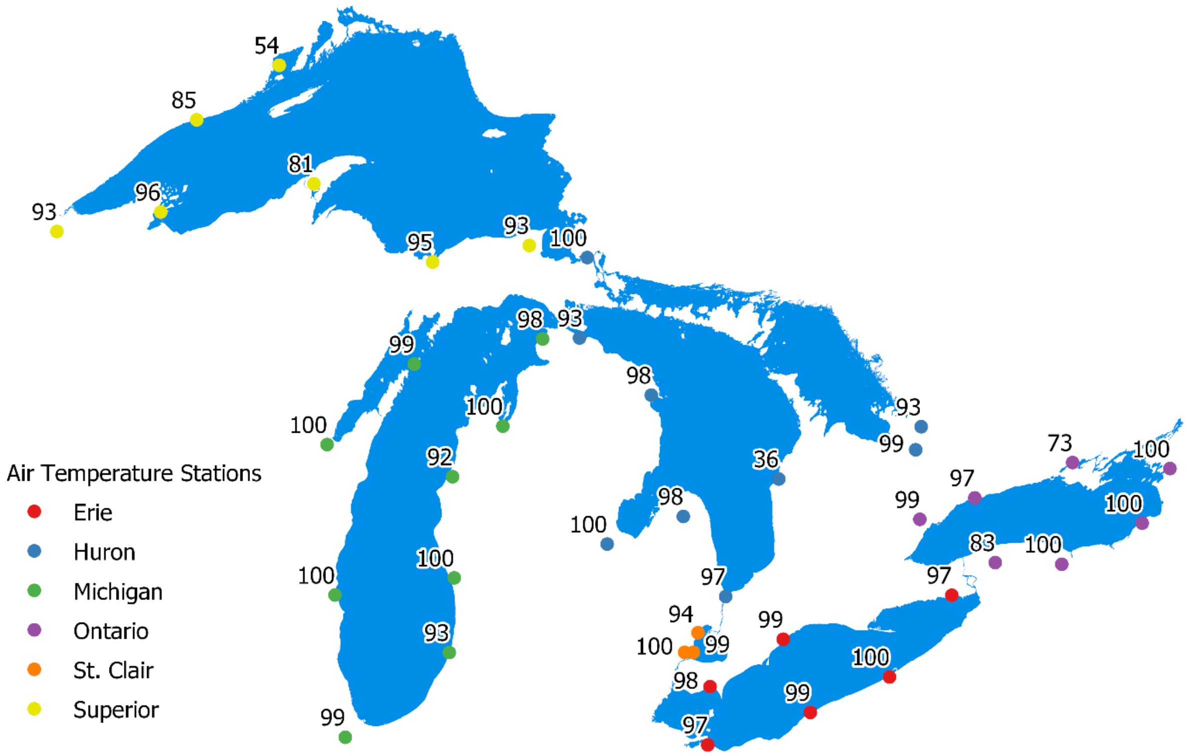

Fig. 1. Distribution of air temperature stations

(Annotated number: denote percentage of the data coverage, colors in circle: the stations are used for each lake)

Table 1. List of selected meteorological stations.

Region	Station ID	Latitude (deg)	Longitude (deg)	First Year	Last year	Data Coverage (%)
Superior	CA006049443	48.3667	-89.1167	1967	2018	54
	USC00205690	46.4122	-86.6625	1911	2018	95
	USC00208043	46.6014	-85.2239	1968	2018	93
	USC00213282	47.7517	-90.3283	1913	2018	85
	USC00474953	46.7781	-90.7653	1944	2018	96
	USC00472889	46.4856	-92.2875	1963	2018	93
	USW00014858	47.1686	-88.4889	1948	2018	81
Michigan	USC00116616	41.4947	-87.6803	1952	2018	99
	USC00201896	45.6414	-85.0142	1969	2018	98
	USC00205065	44.2114	-86.2939	1888	2018	92
	USC00207690	42.4014	-86.2825	1895	2018	93
	USC00478905	45.3583	-86.8911	1944	2018	99
	USW00014839	42.9550	-87.9044	1938	2018	100
	USW00014840	43.1711	-86.2367	1896	2018	100
	USW00014850	44.7408	-85.5825	1896	2018	100
	USW00014898	44.4983	-88.1111	1886	2018	100
Huron	CA006111769	44.6333	-79.5333	1971	2018	93
	CA006117684	44.4000	-79.6333	1973	2018	99
	CA006124127	44.1667	-81.6167	1872	2018	36
	USC00201492	45.6528	-84.4725	1891	2018	93
	USC00200417	43.8081	-82.9939	1925	2018	98
	USC00206680	42.9750	-82.4194	1933	2018	97
	USW00014814	45.0606	-83.4281	1948	2018	98
	USW00014845	43.5331	-84.0797	1898	2018	100
	USW00014847	46.4794	-84.3572	1931	2018	100
Erie	CA006134190	42.0500	-82.6667	1968	2018	98
	CA006135583	42.5167	-81.6333	1957	2018	99
	CA006136606	42.8833	-79.2500	1964	2018	97
	USC00336389	41.7525	-81.2956	1950	2018	99
	USW00014846	41.4500	-82.7167	1936	2018	97
	USW00014860	42.0800	-80.1825	1926	2018	100
Ontario	CA006155878	43.8667	-78.8333	1969	2018	97
	CA006158733	43.6833	-79.6333	1937	2018	99
	CA006150689	44.1500	-77.4000	1866	2018	73
	USC00304844	43.1878	-78.6092	1893	2018	83
	USC00306314	43.4622	-76.4933	1926	2018	100
	USW00014768	43.1167	-77.6767	1926	2018	100
	USW00094790	43.9922	-76.0217	1949	2018	100
St.Clair	USW00014804	42.6083	-82.8183	1896	2018	94
	USW00014822	42.4092	-83.0100	1948	2018	100
	USC00203477	42.4078	-82.8892	1950	2018	99

4.0 Results

4.1 Freeze-up and break-up dates

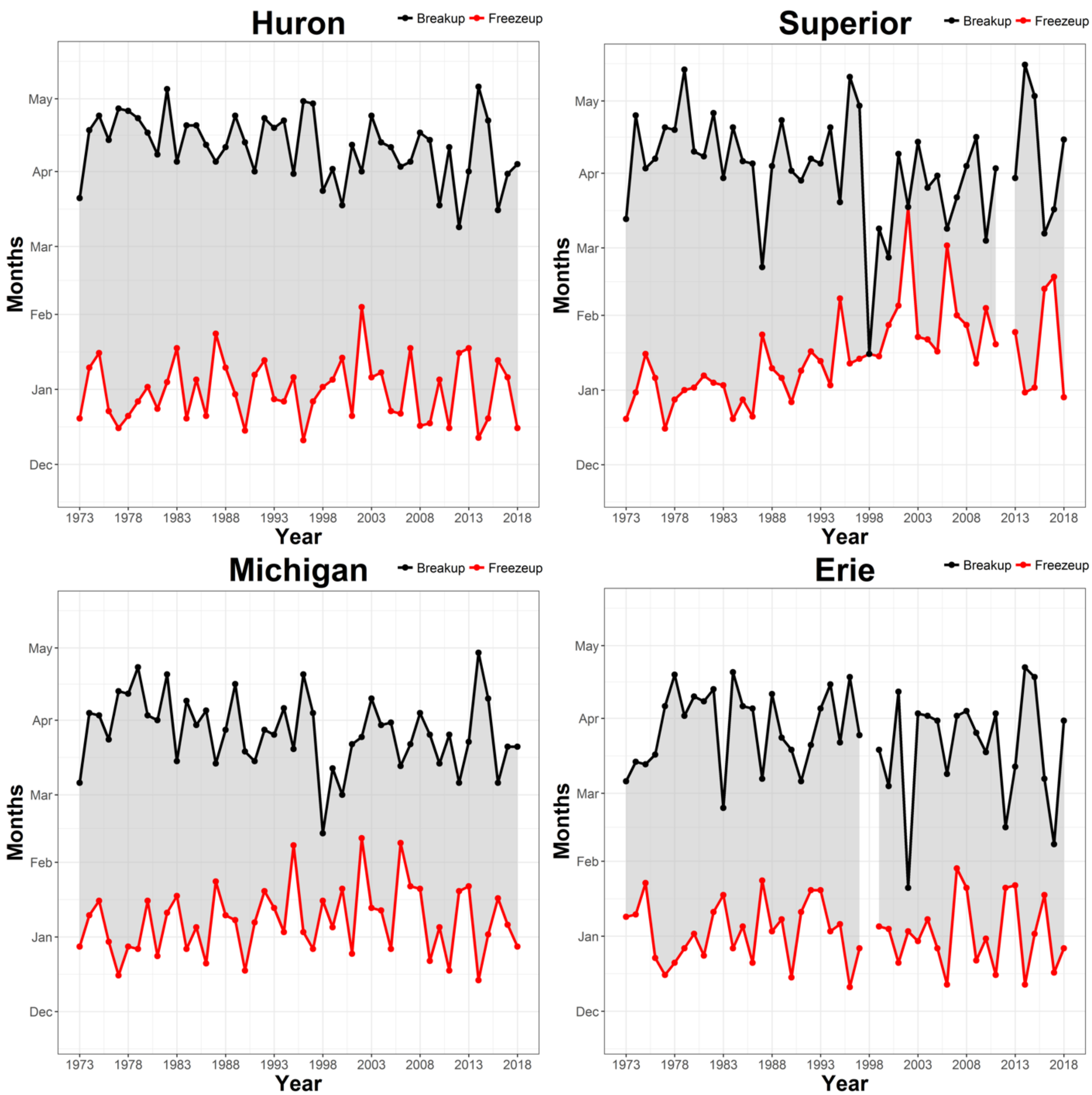

Fig. 2. Freeze-up and break-up dates – (1).

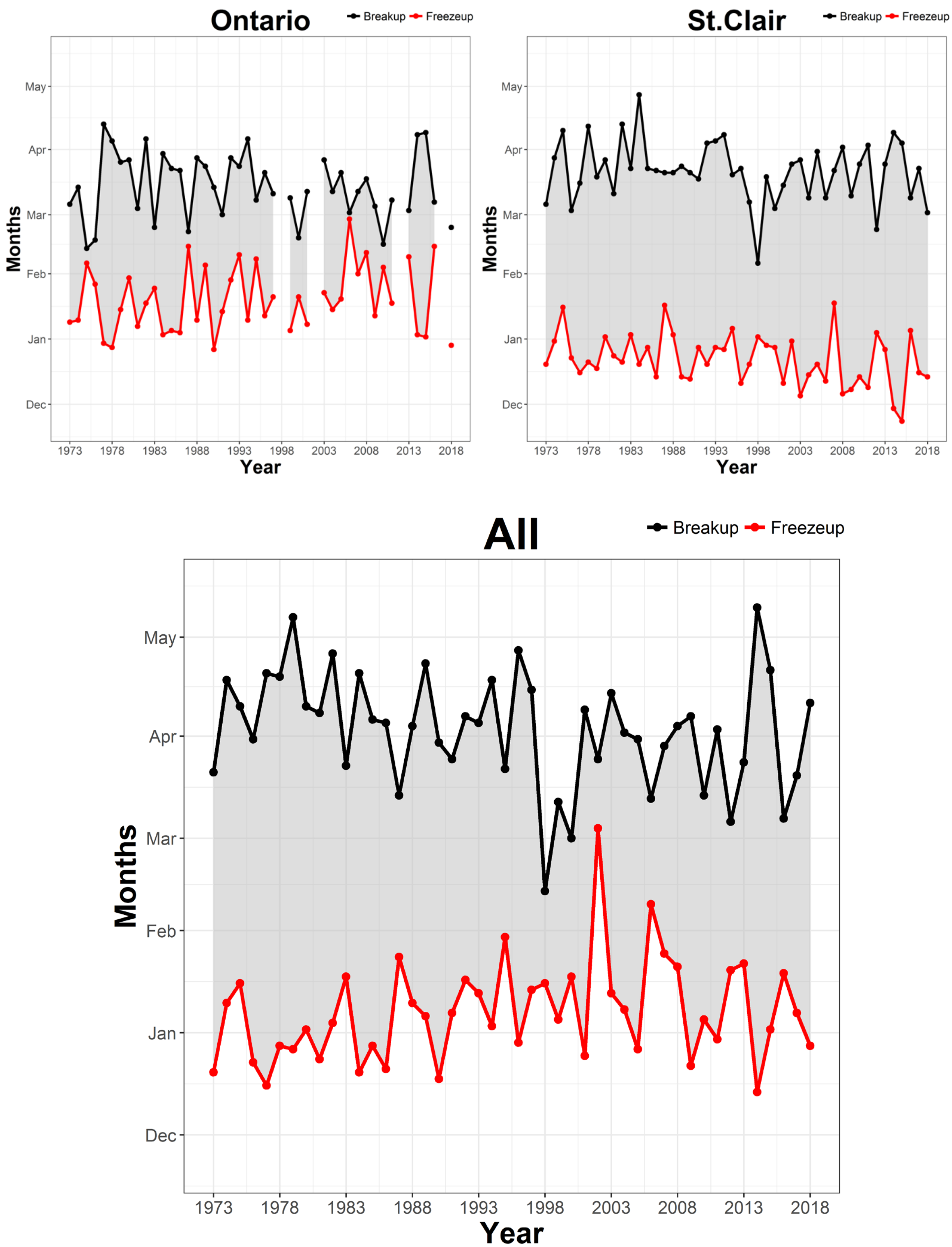

Fig. 3. Freeze-up and break-up dates – (2).

4.2 Ice duration

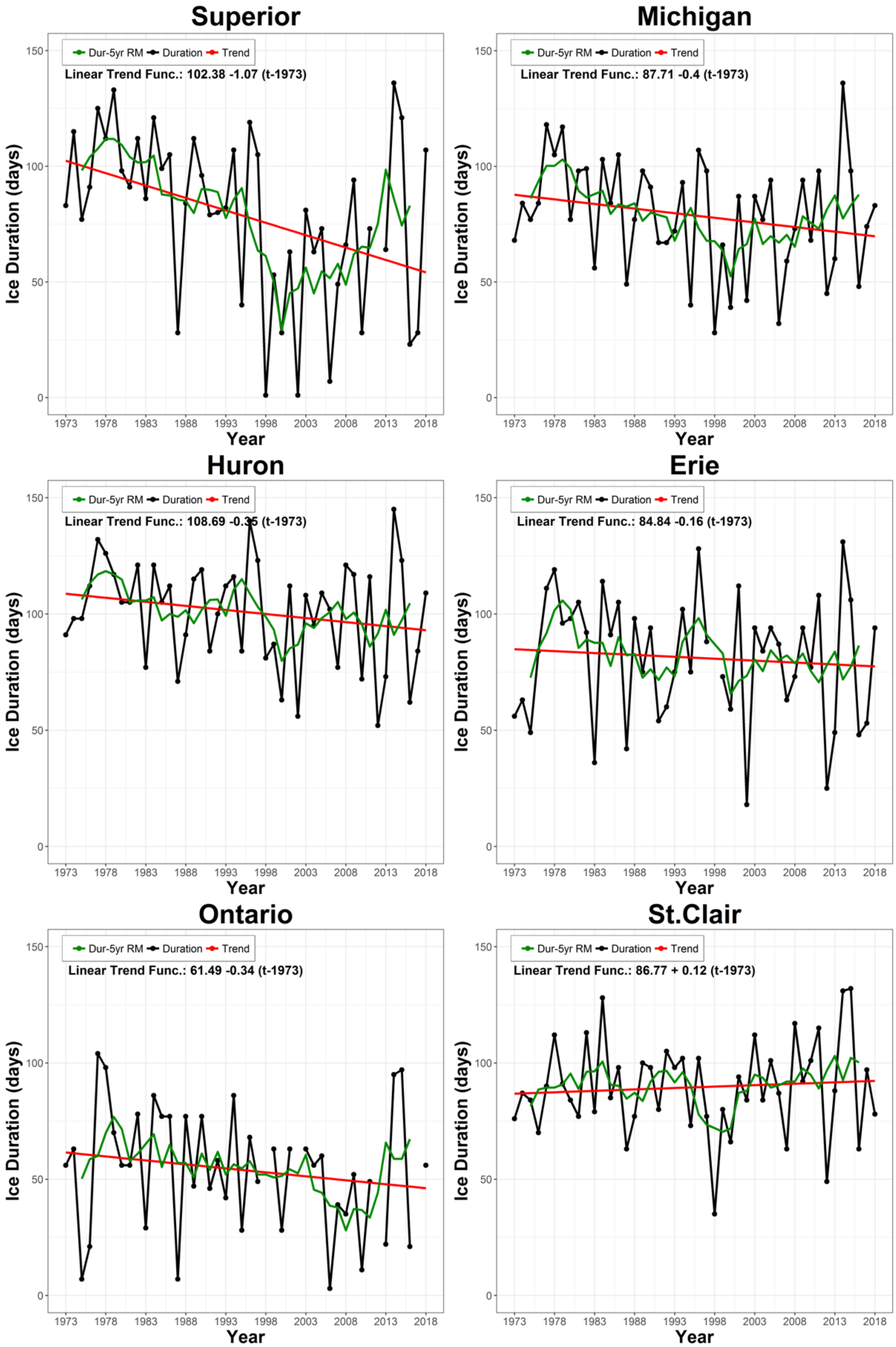

Fig. 4. Ice Duration – (1).

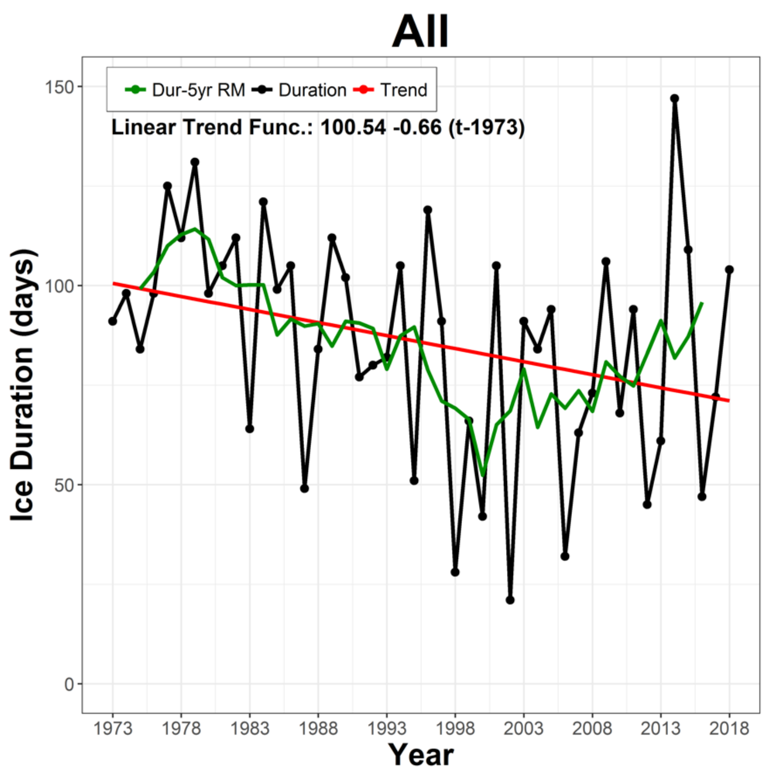

Fig. 5. Ice Duration – (2)

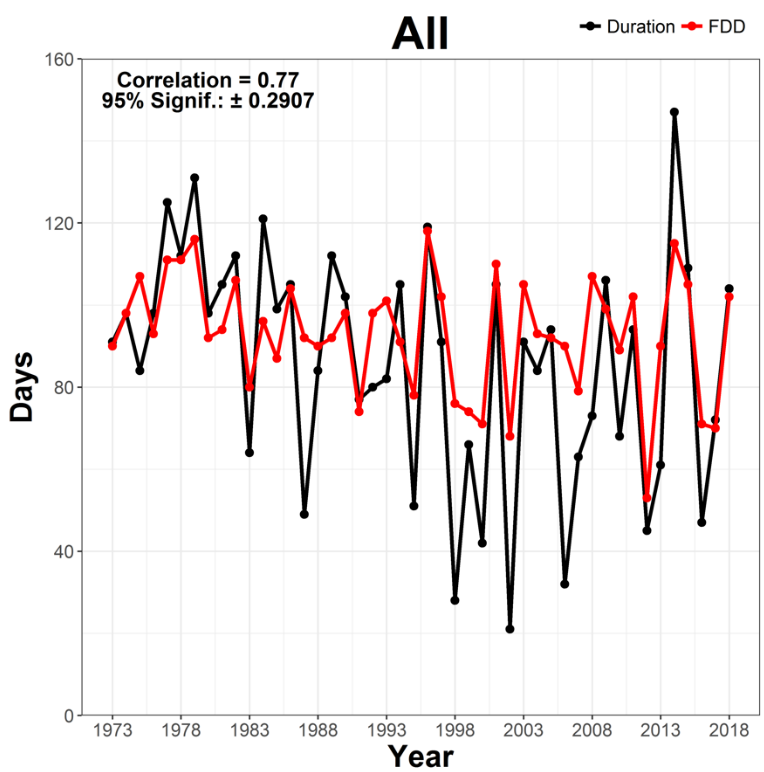

Fig. 6. Correlation between duration and FDD – (1).

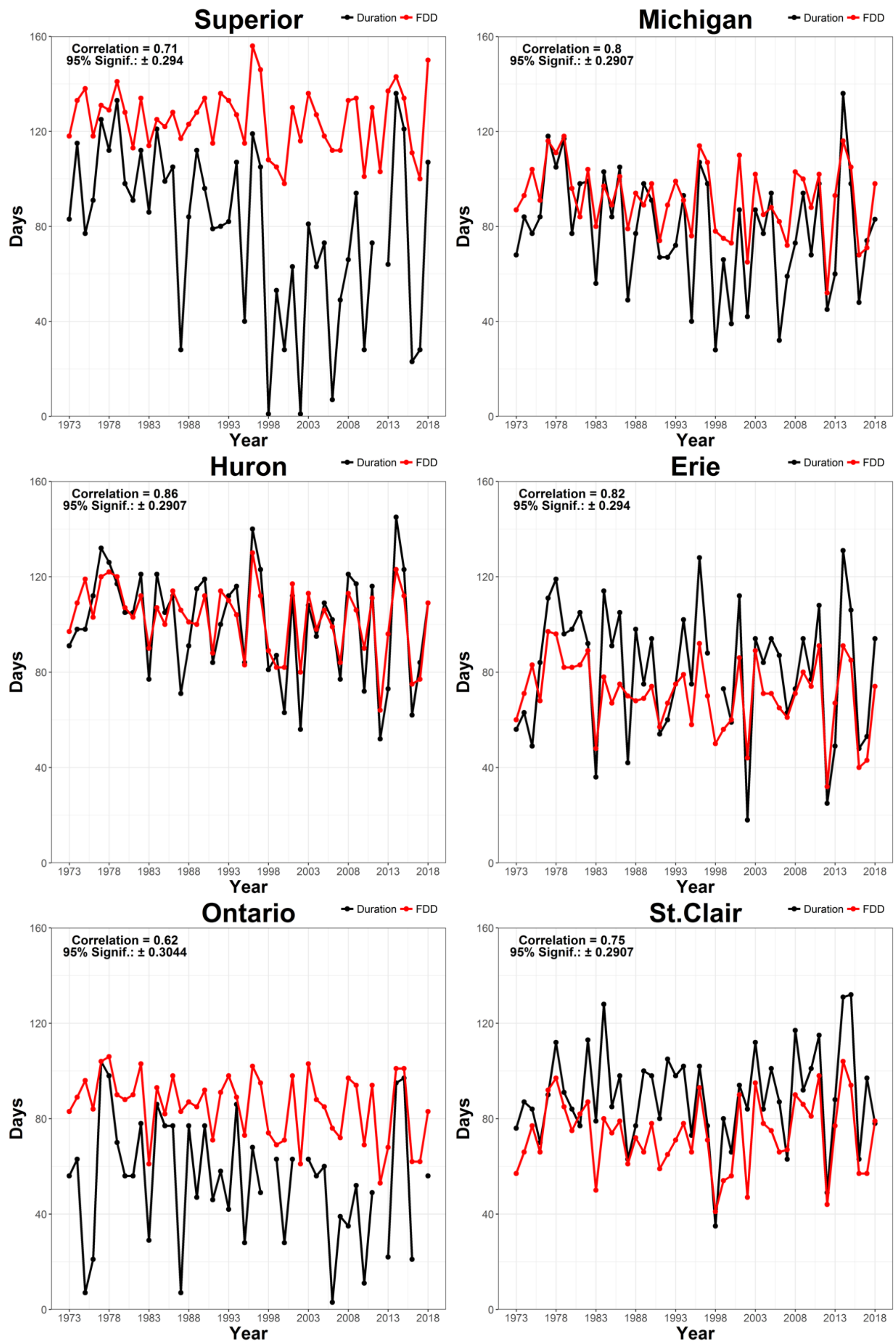

Fig. 7. Correlation between duration and FDD – (2).

4.3 Cumulative freezing degree days (FDD)

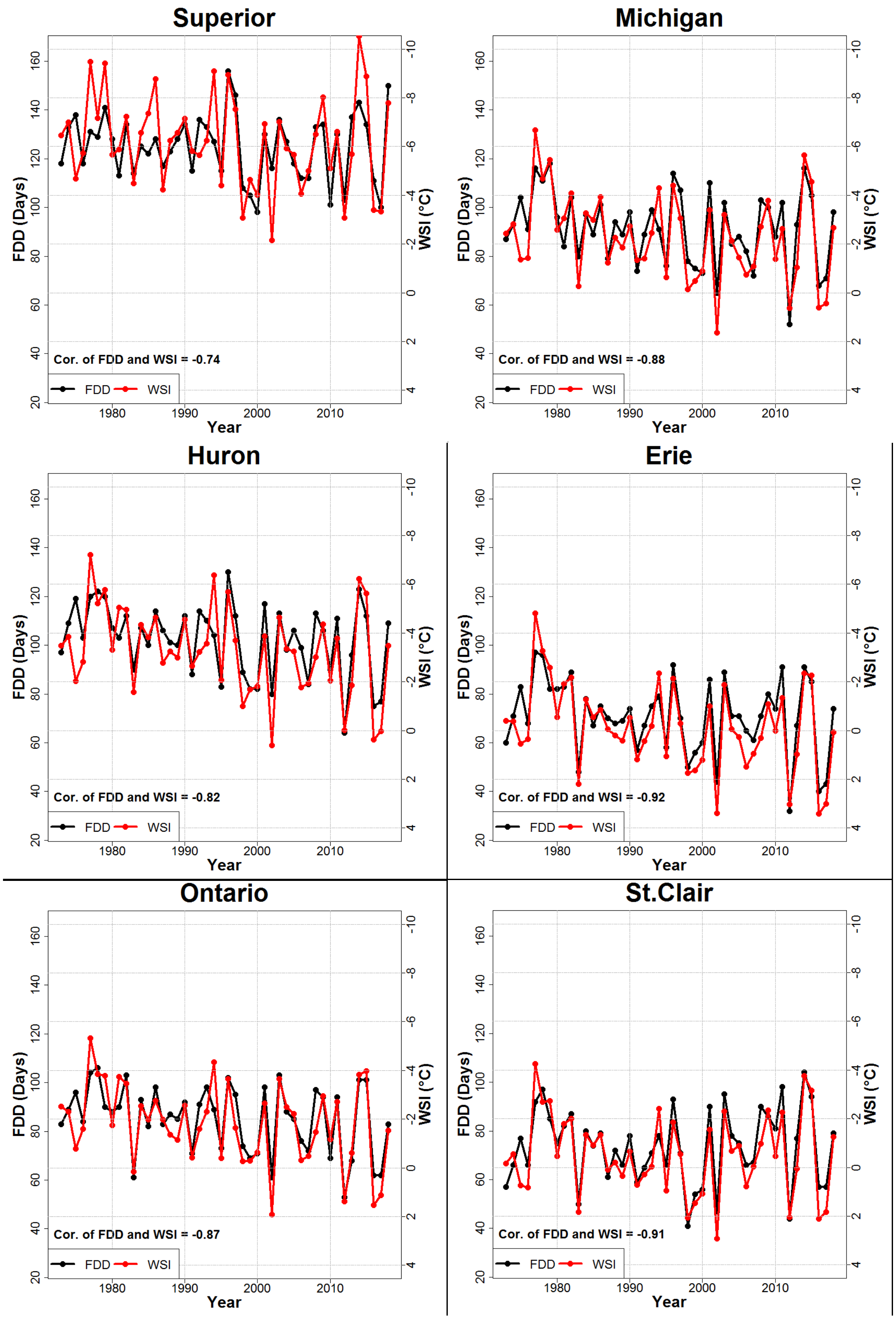

Fig. 8. Comparison between FDD and WSI – (1).

[95% critical values for Pearson’s correlation coefficient (DoF=44): ±0.29].

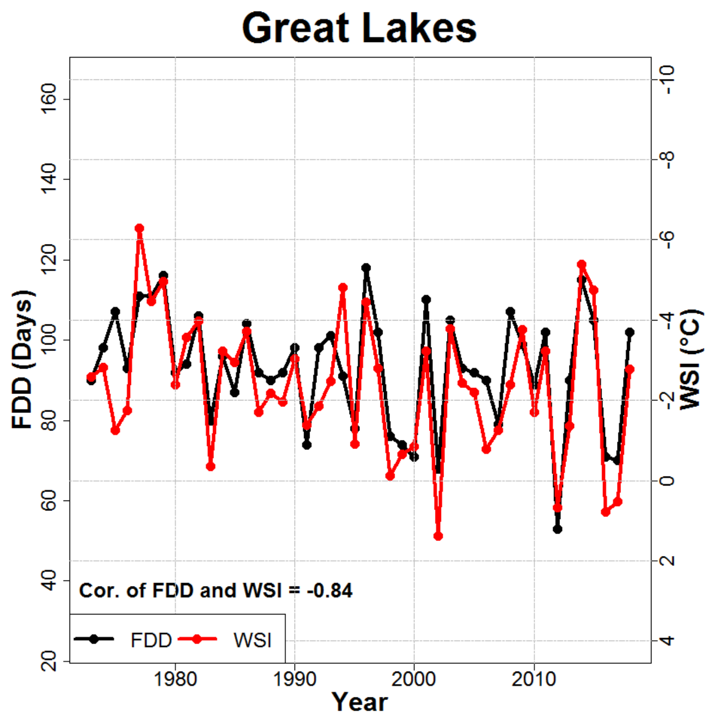

Fig. 9. Comparison between FDD and WSI – (2).

[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

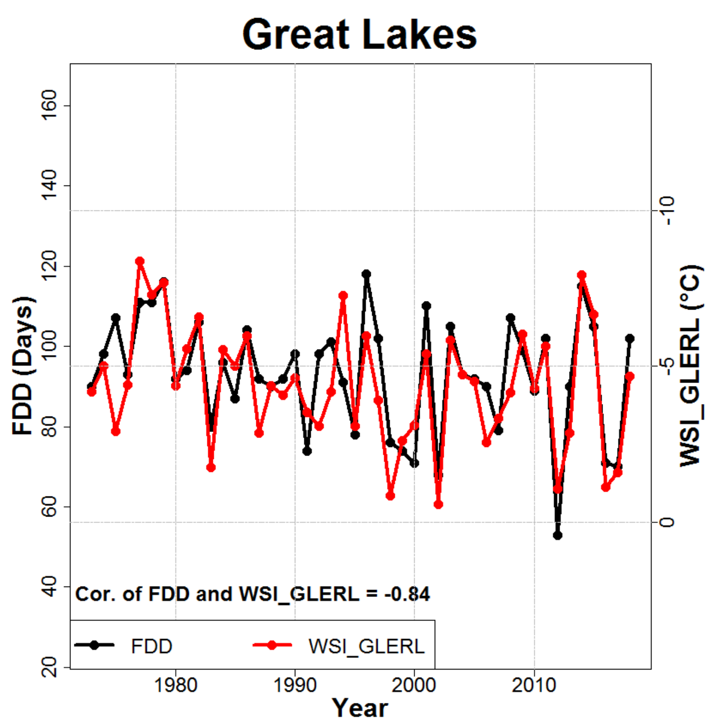

Fig. 10. Comparison between FDD and WSI_GLERL – (1).

[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

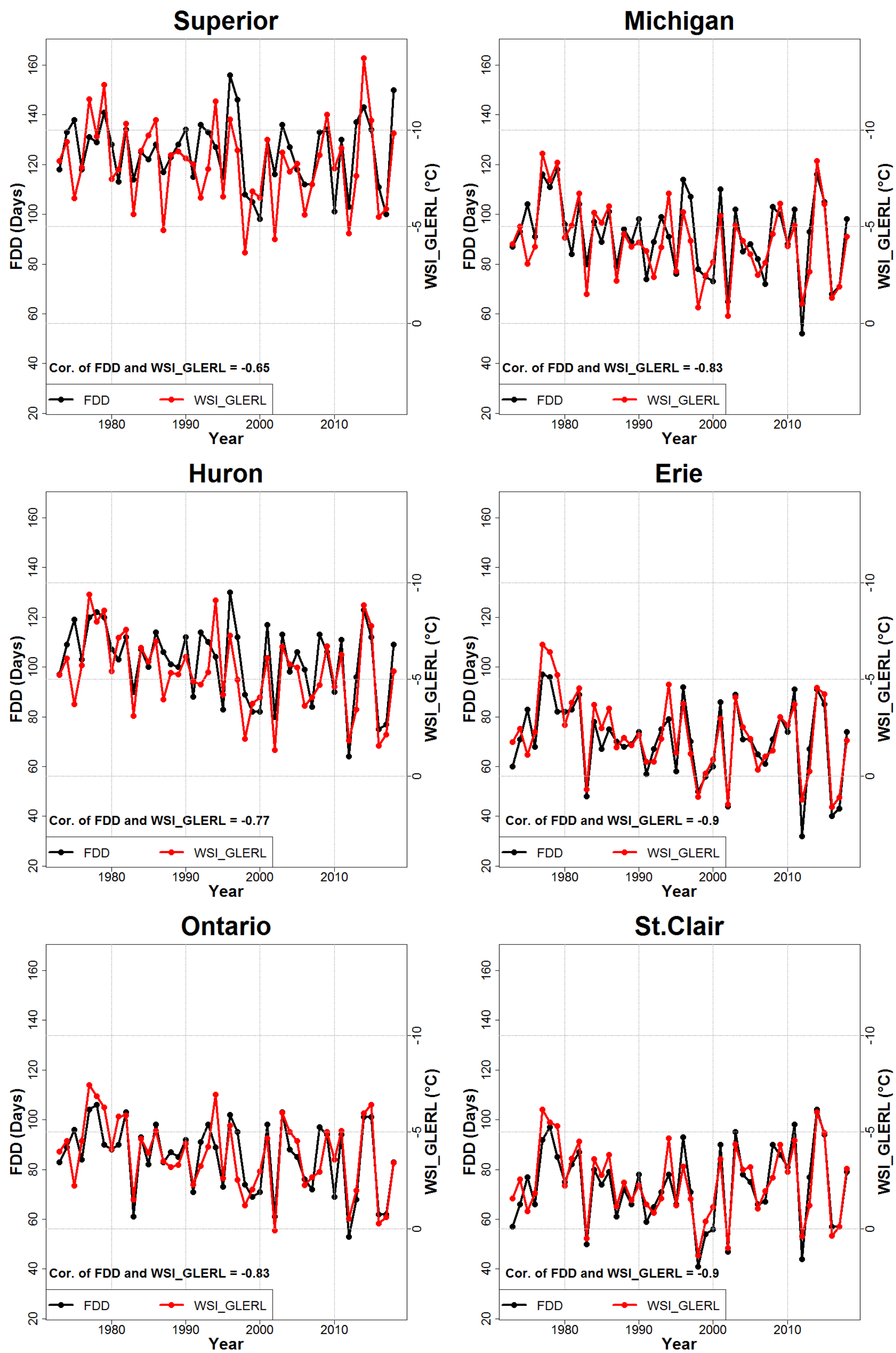

Fig. 11. Comparison between FDD and WSI_GLERL – (2).

[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

4.4 WSI/WSI_CLERL vs. atmosphere (circulation) teleconnection patterns

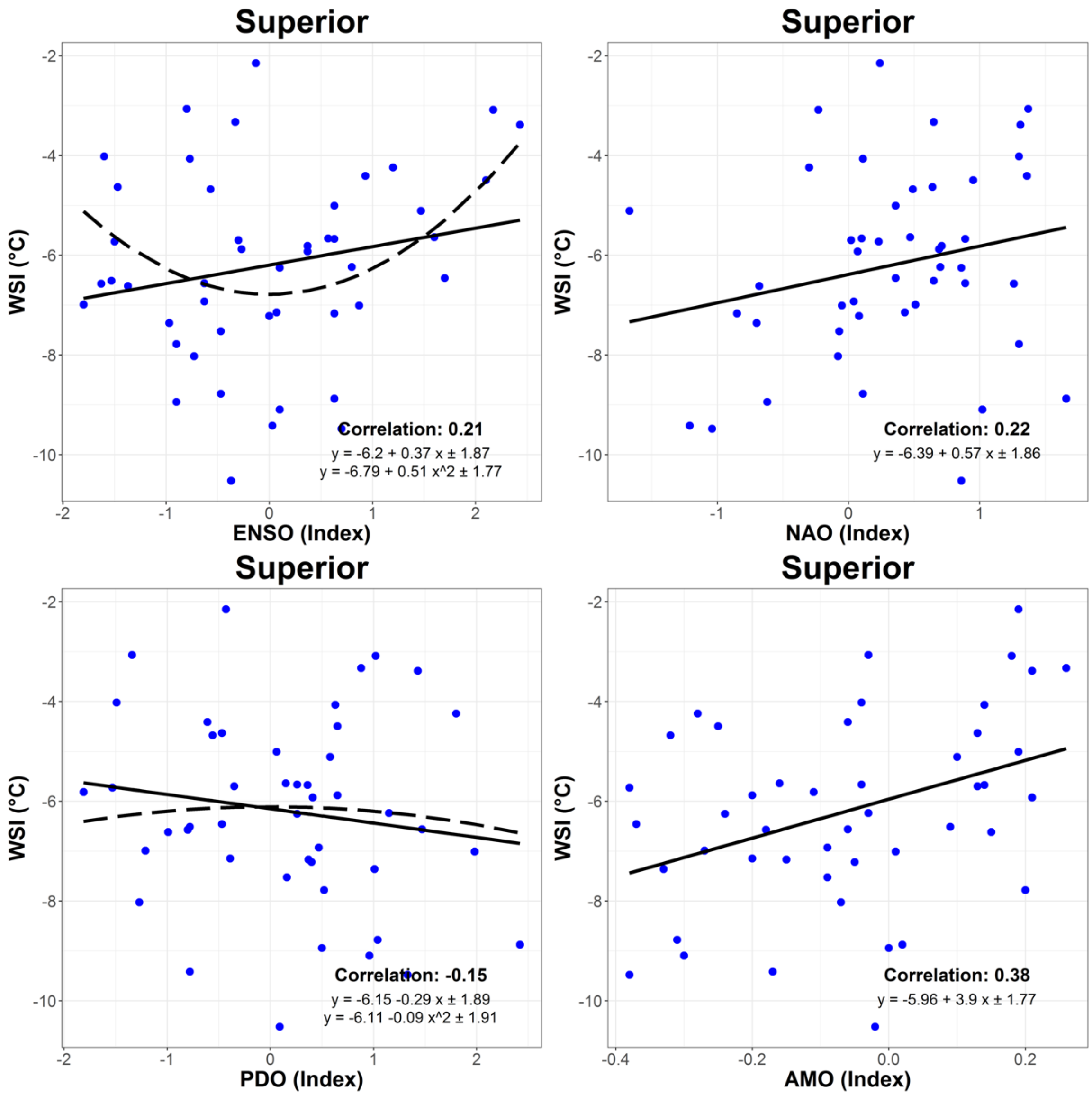

Fig. 12. Comparison between WSI and atmospheric teleconnection patterns [Superior].

[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

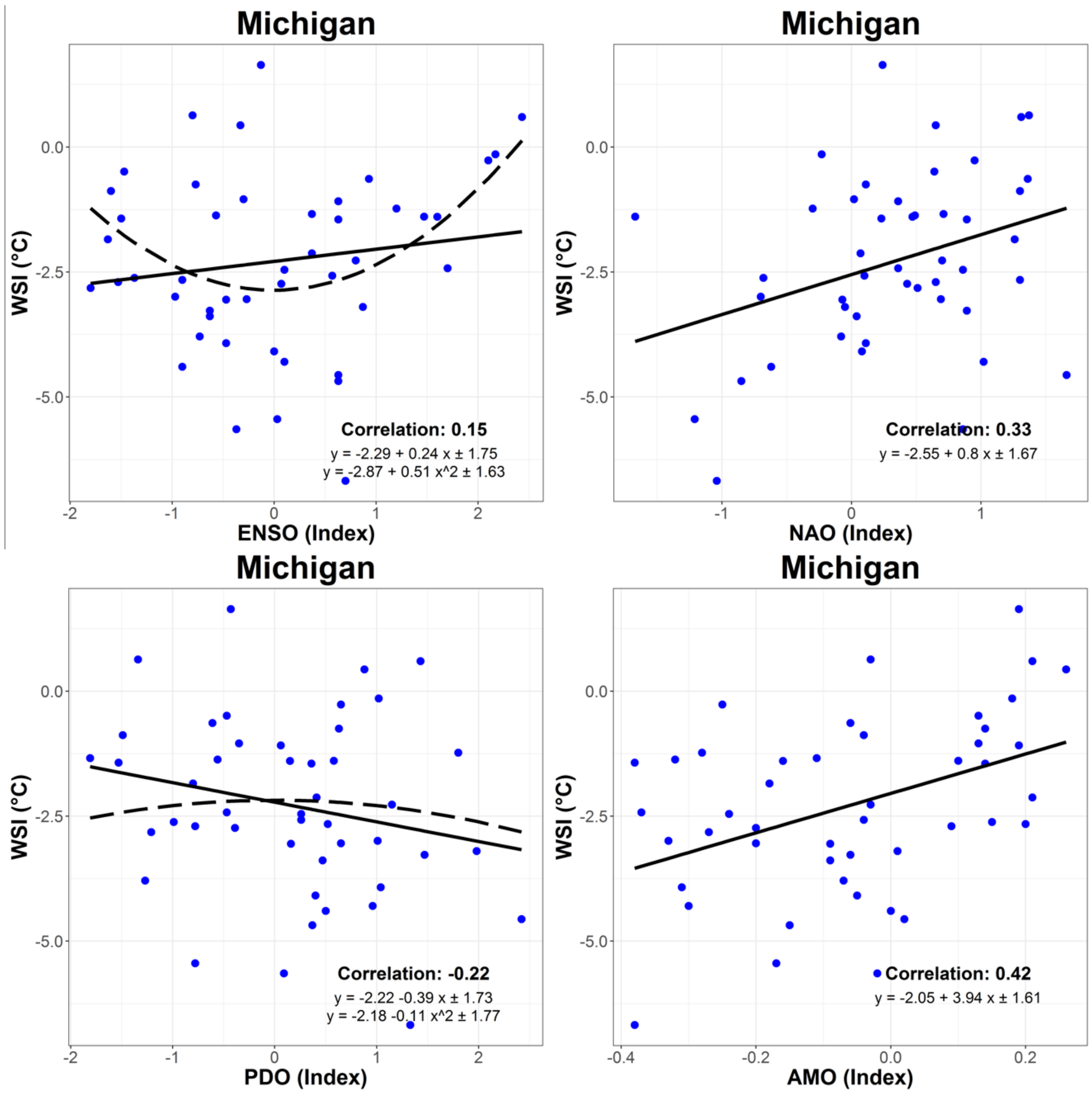

Fig. 13. Comparison between WSI and atmospheric teleconnection patterns [Michigan].

[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

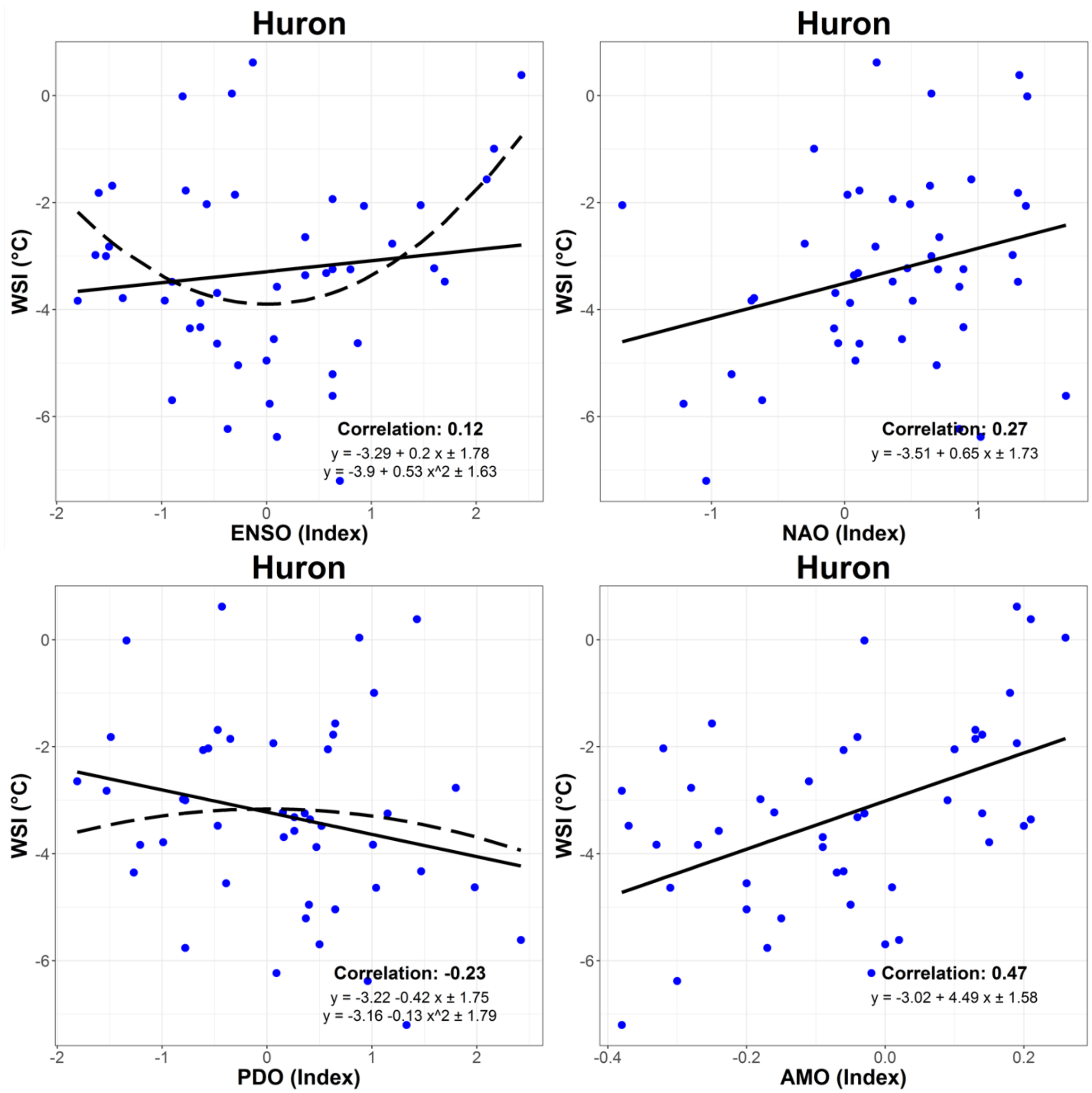

Fig. 14. Comparison between WSI and atmospheric teleconnection patterns [Huron].

[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

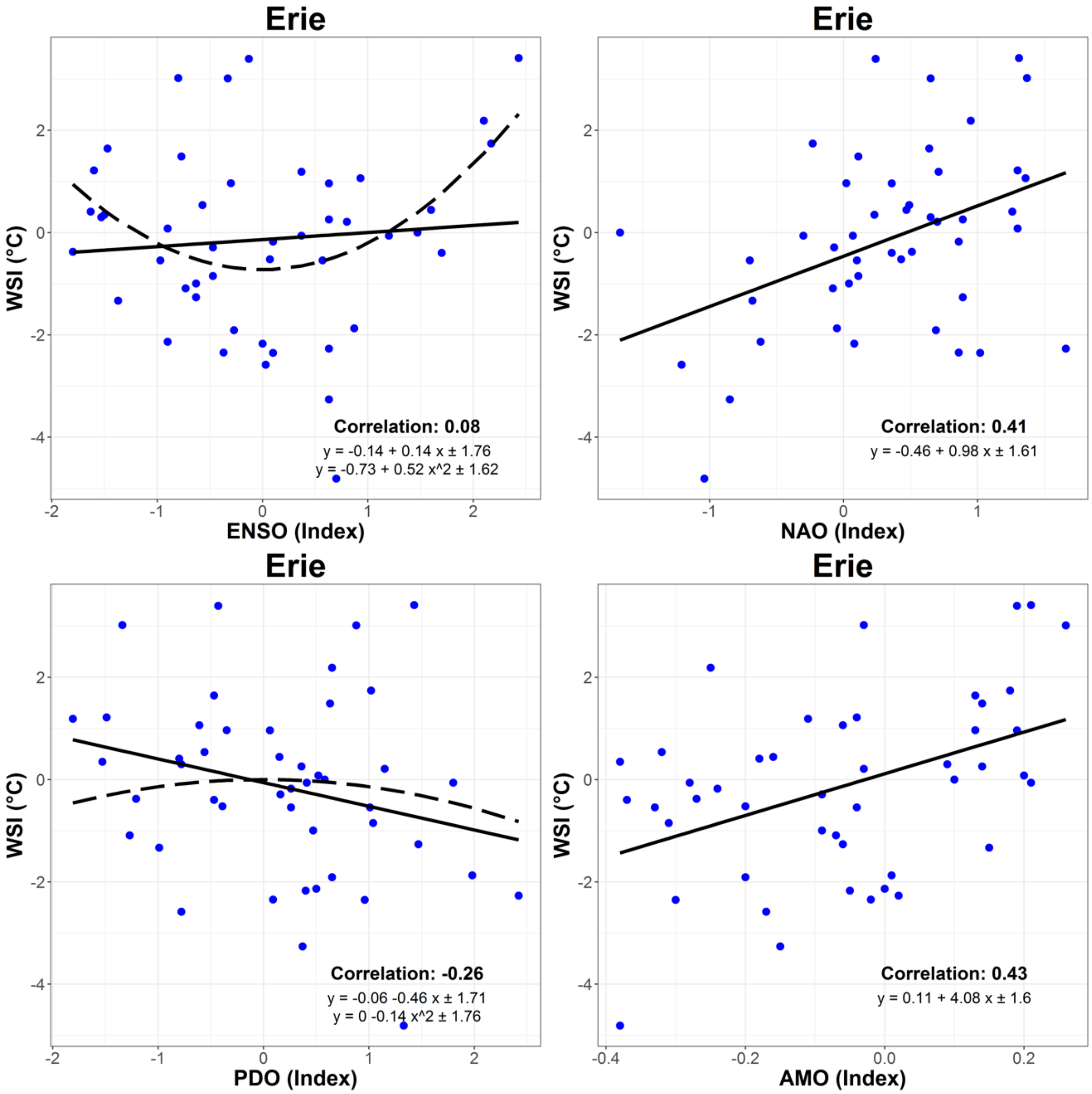

Fig. 15. Comparison between WSI and atmospheric teleconnection patterns [Erie].

[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

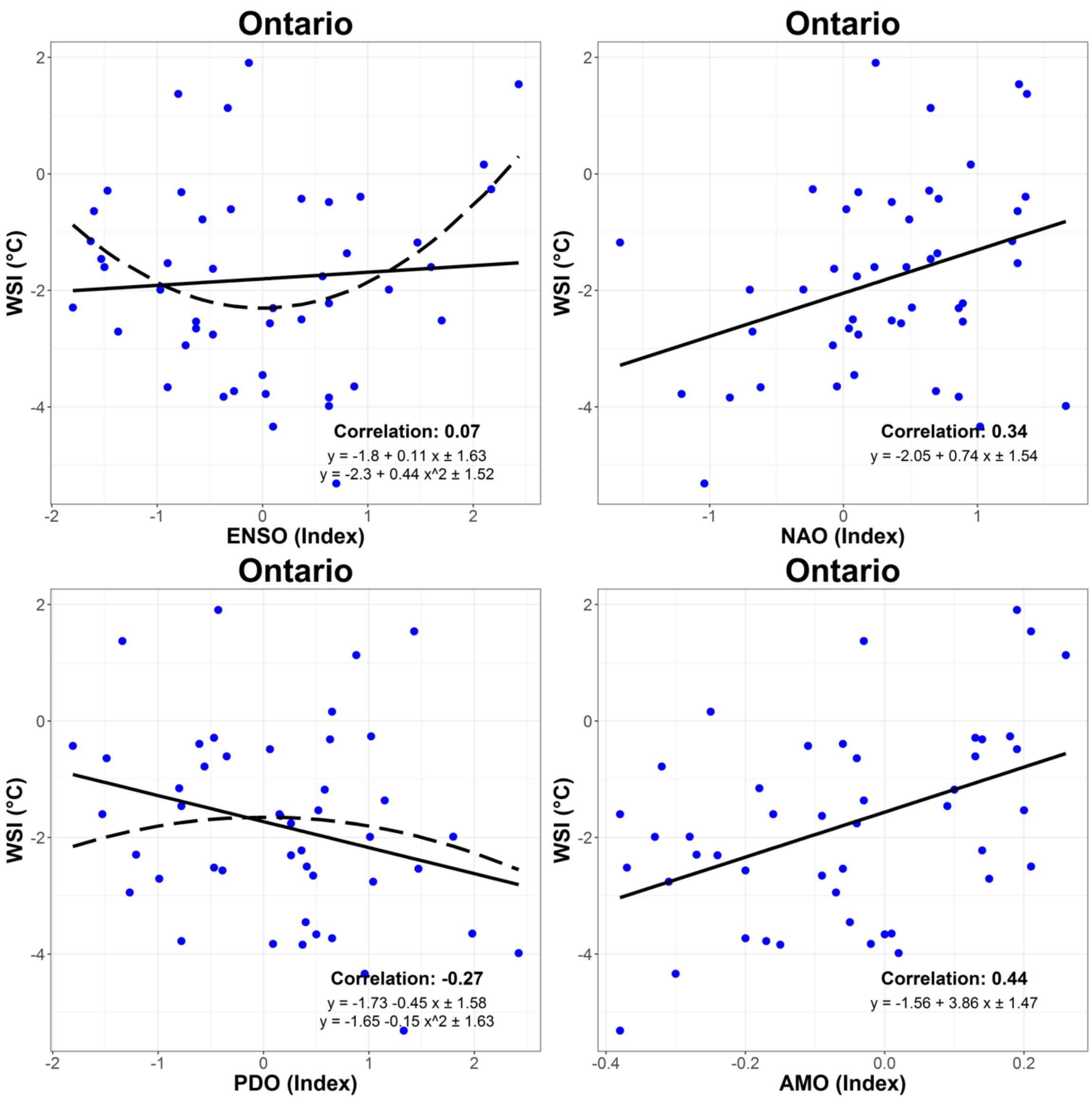

Fig. 16. Comparison between WSI and atmospheric teleconnection patterns [Ontario].

[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

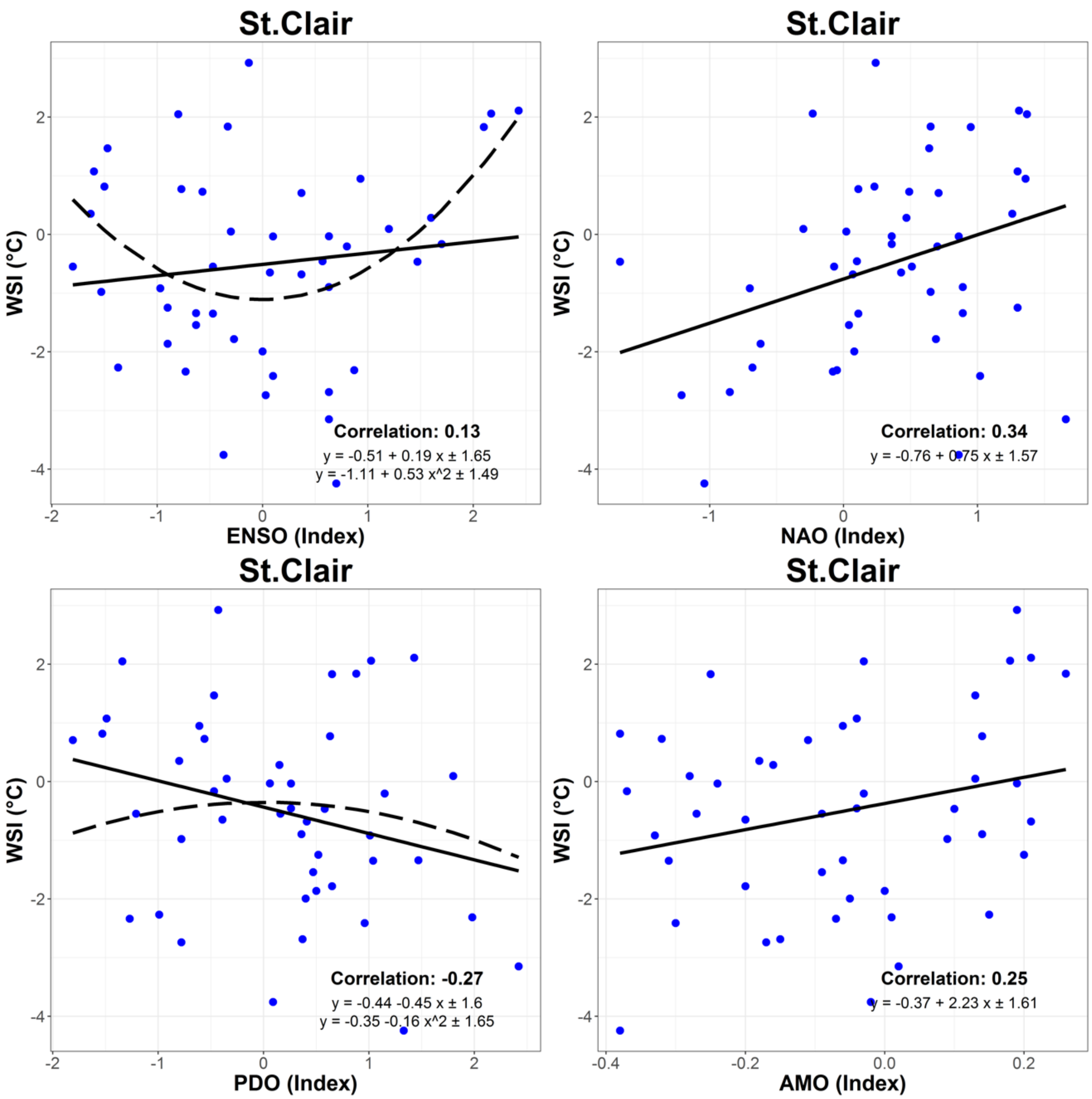

Fig. 17. Comparison between WSI and atmospheric teleconnection patterns [St. Clair].

[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

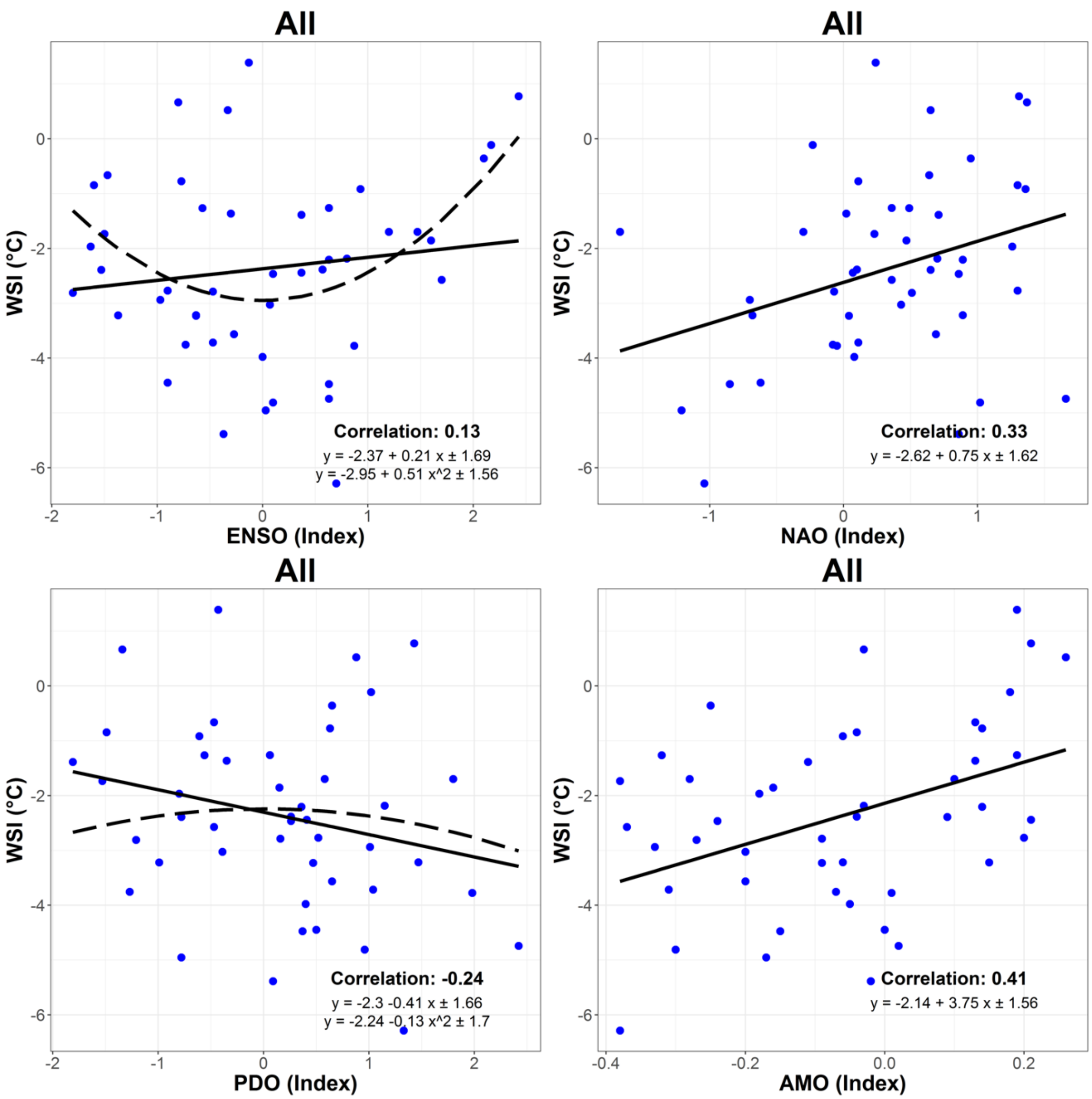

Fig. 18. Comparison between WSI and atmospheric teleconnection patterns [Great Lakes].
[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

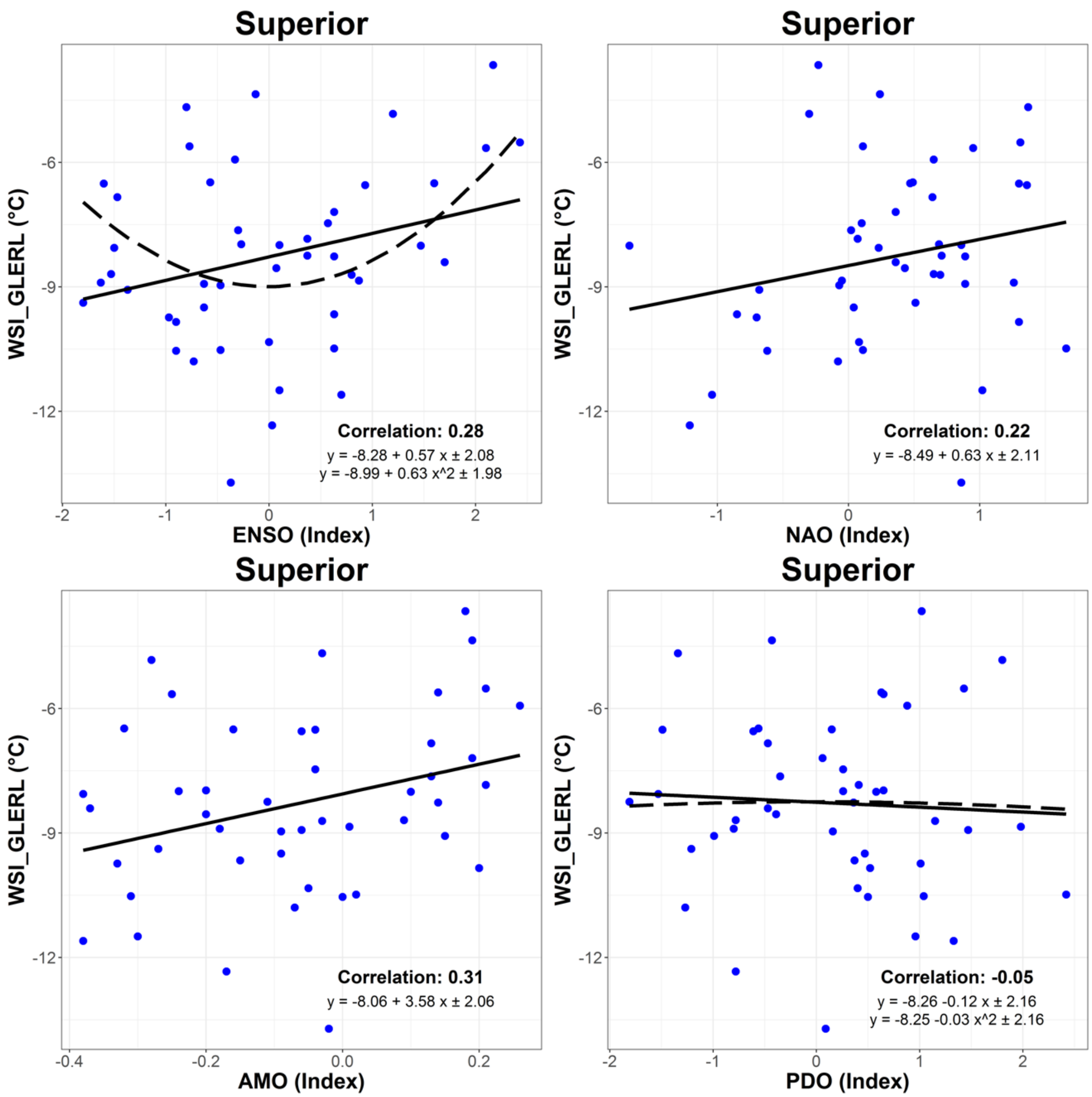

Fig. 19. Comparison between WSI_GLERL and atmospheric teleconnection patterns [Superior]. [95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

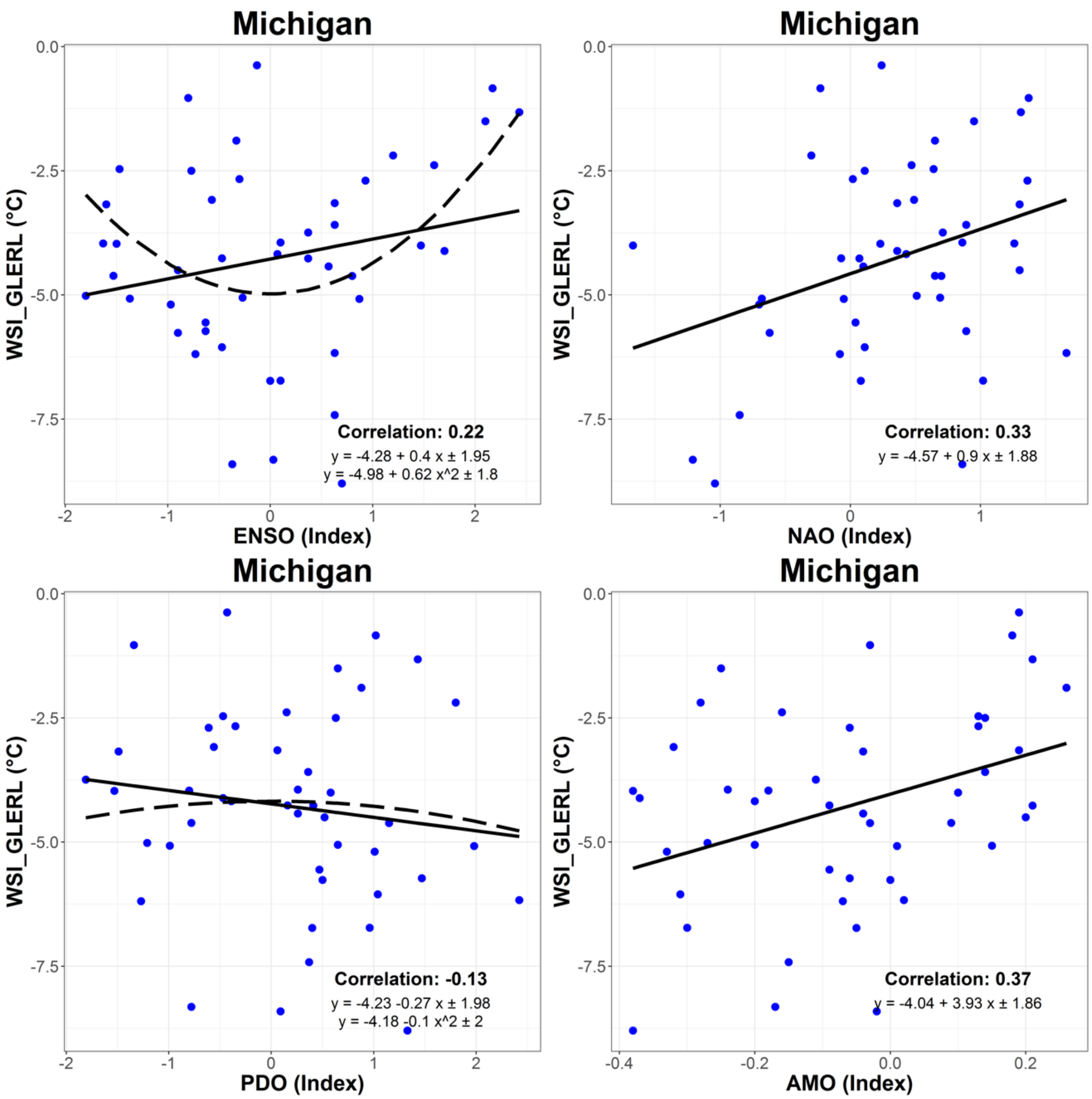

Fig. 20. Comparison between WSI_GLERL and atmospheric teleconnection patterns [Michigan]. [95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

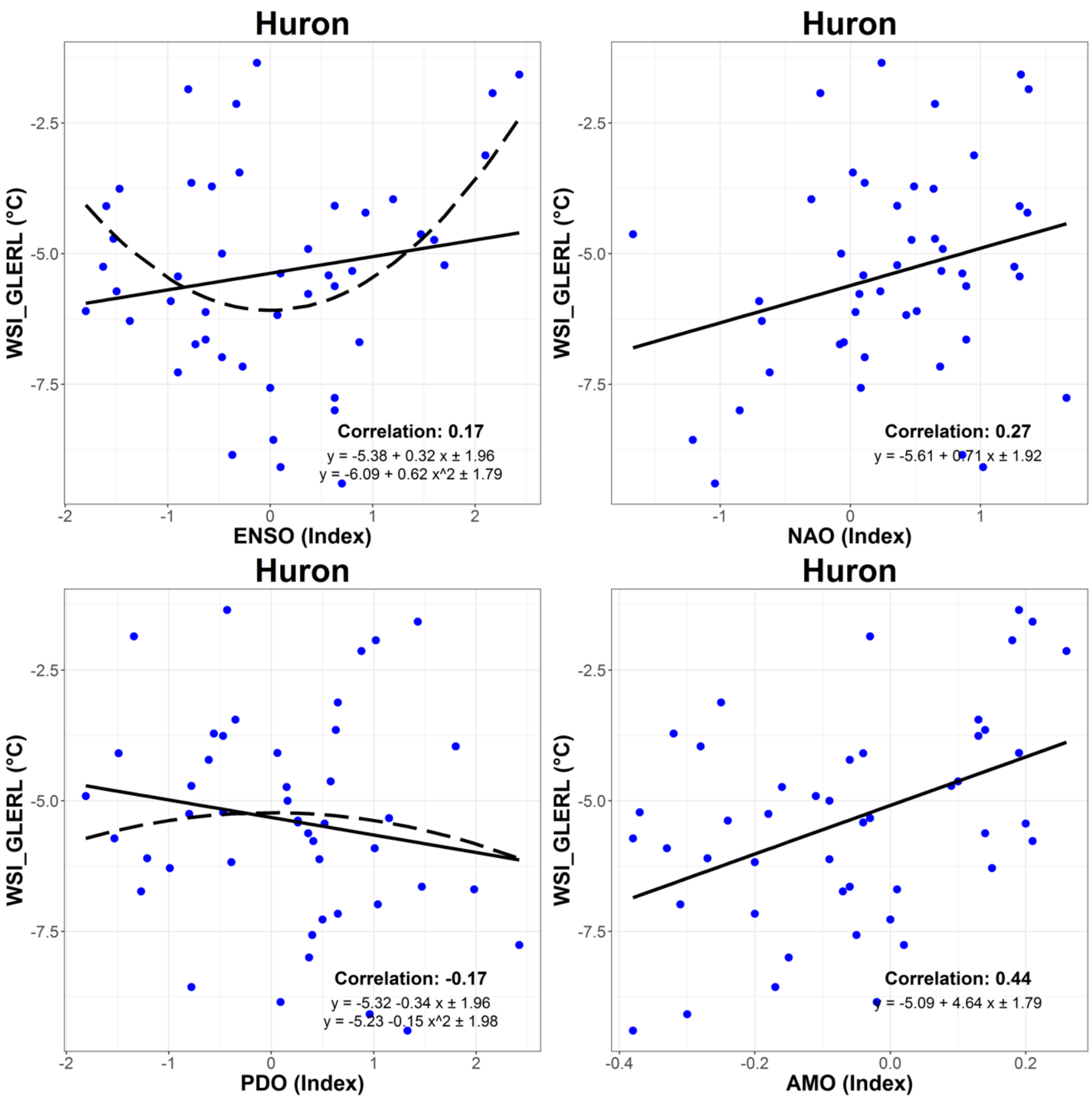

Fig. 21. Comparison between WSI_GLERL and atmospheric teleconnection patterns [Huron]. [95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

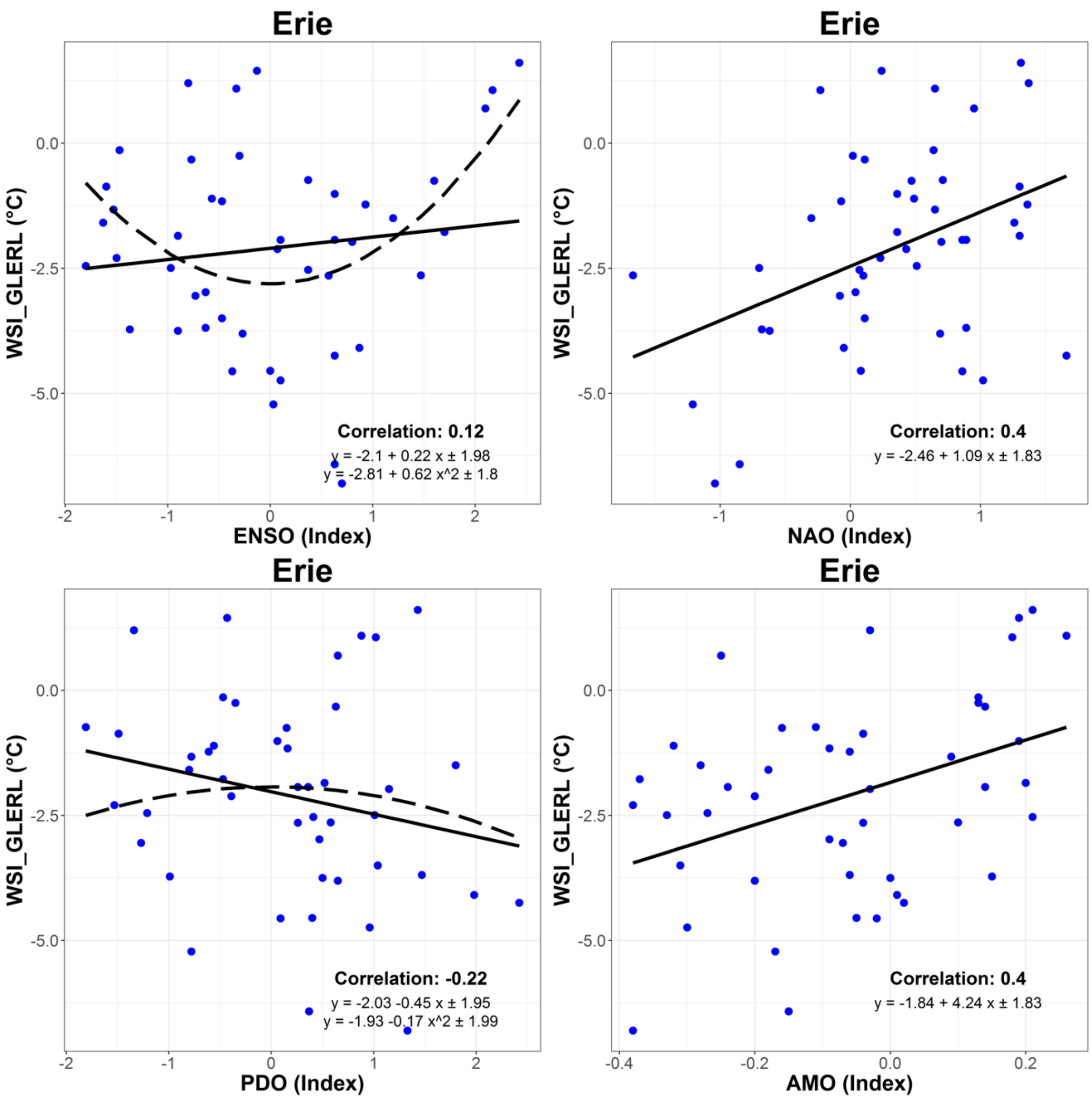

Fig. 22. Comparison between WSI_GLERL and atmospheric teleconnection patterns [Erie].
[95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

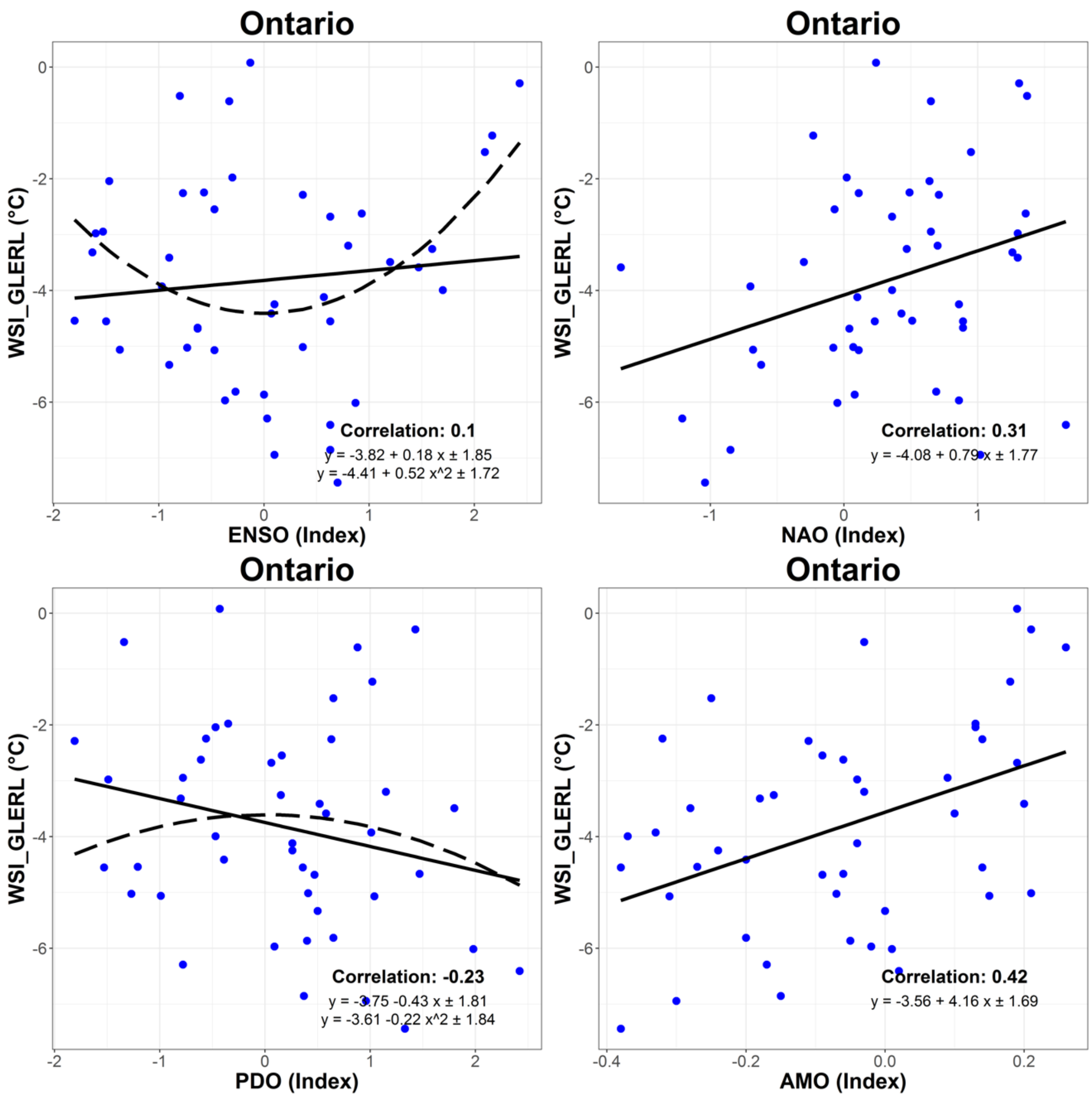

Fig. 23. Comparison between WSI_GLERL and atmospheric teleconnection patterns [Ontario]. [95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

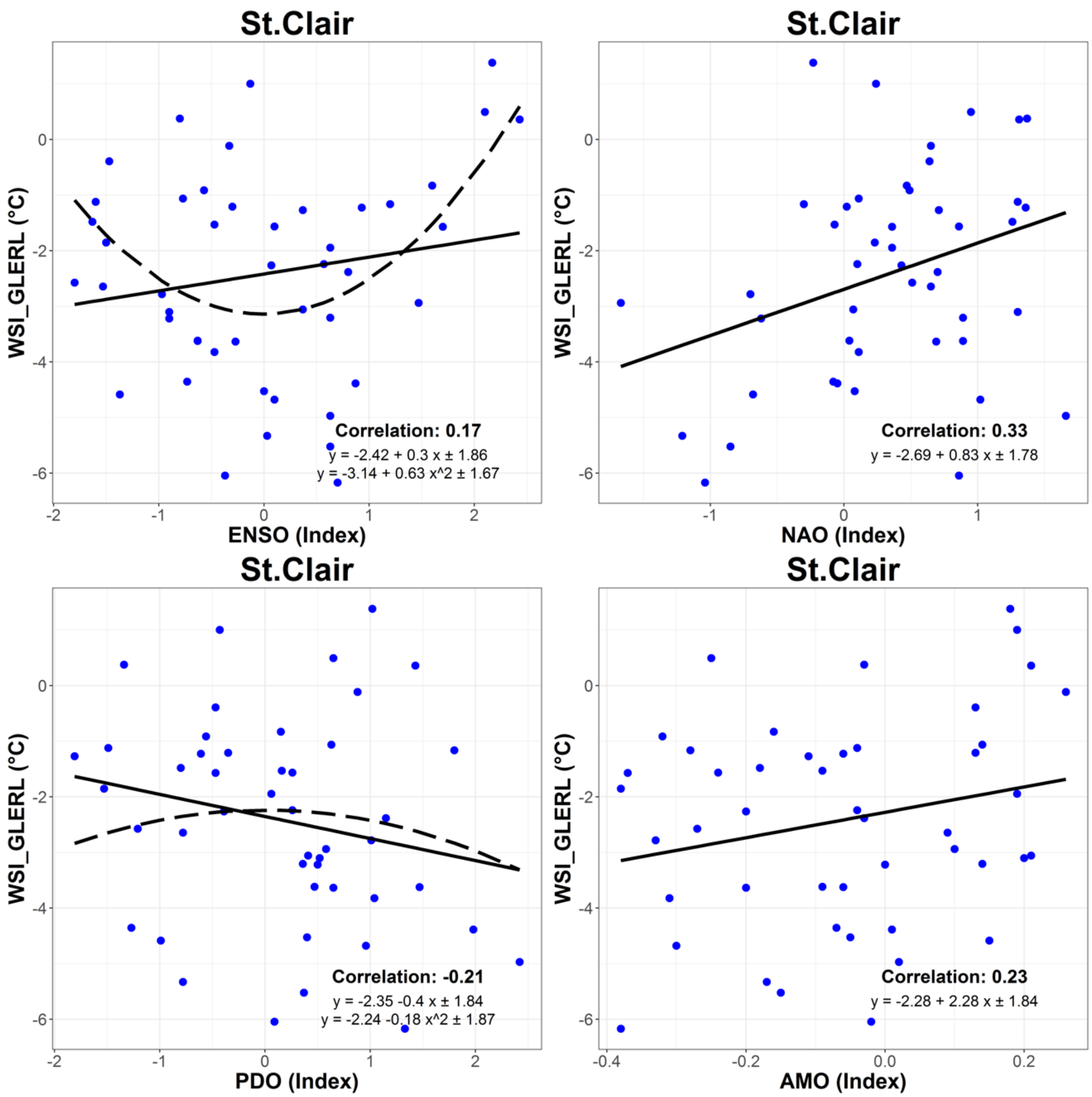

Fig. 24. Comparison between WSI_GLERL and atmospheric teleconnection patterns [St. Clair]. [95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

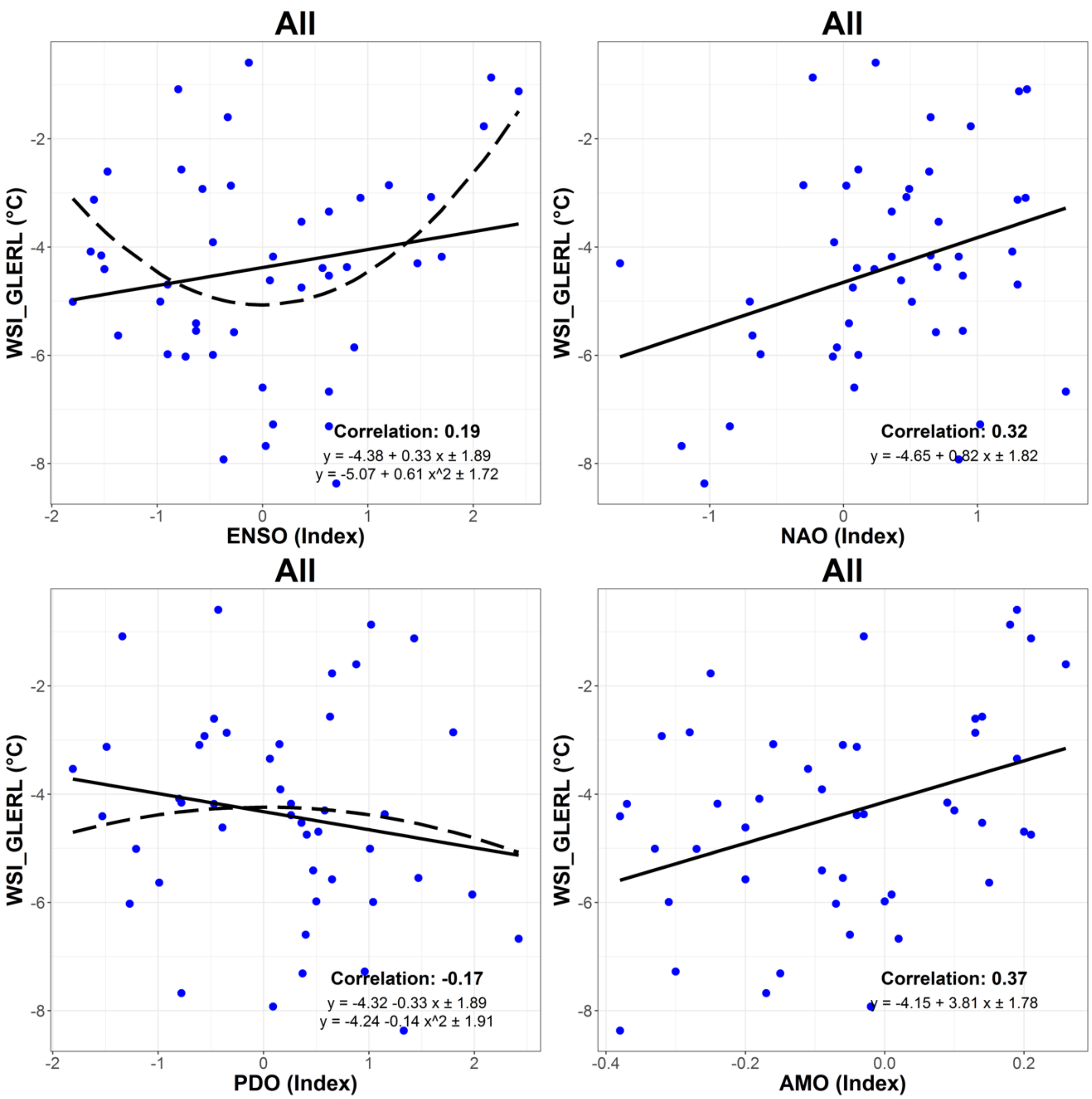

Fig. 25. Comparison between WSI_GLERL and atmospheric teleconnection patterns [Great Lakes]. [95% critical values for Pearson's correlation coefficient (DoF=44): ±0.29].

4.5 AMIC vs. atmosphere (circulation) teleconnection patterns

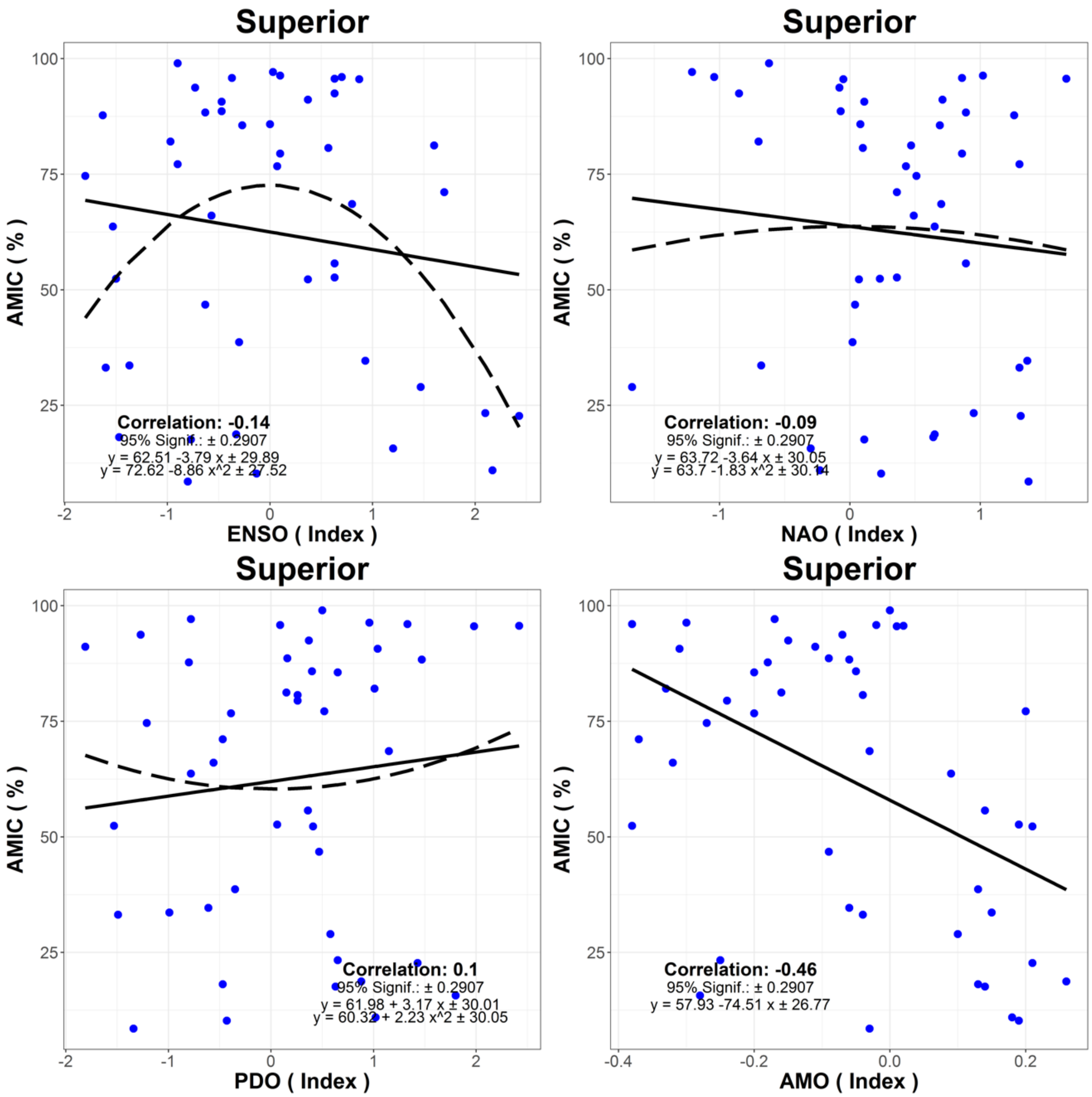

Fig. 26. Comparison between AMIC and atmospheric teleconnection patterns [Superior].

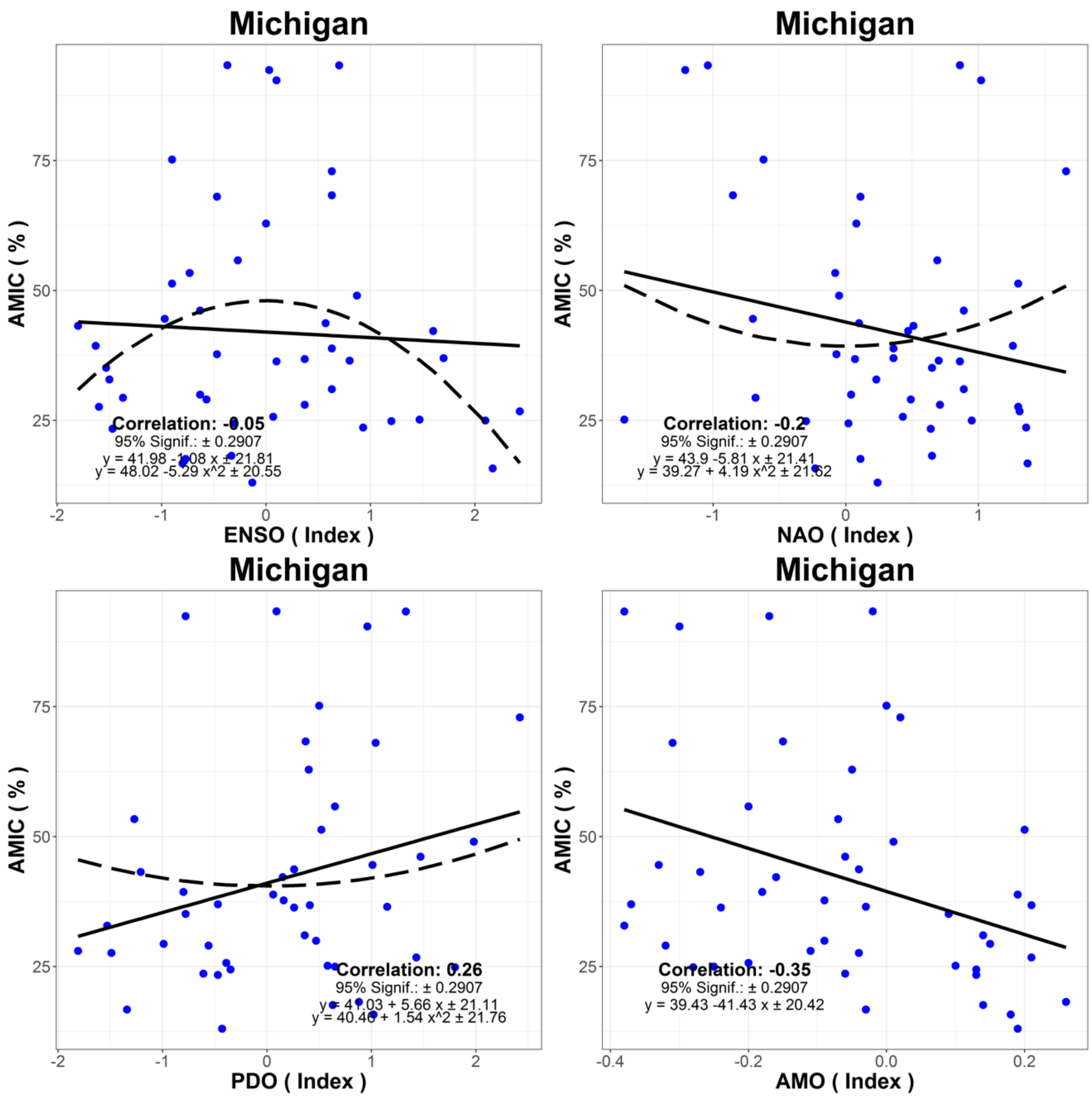

Fig. 27. Comparison between AMIC and atmospheric teleconnection patterns [Michigan].

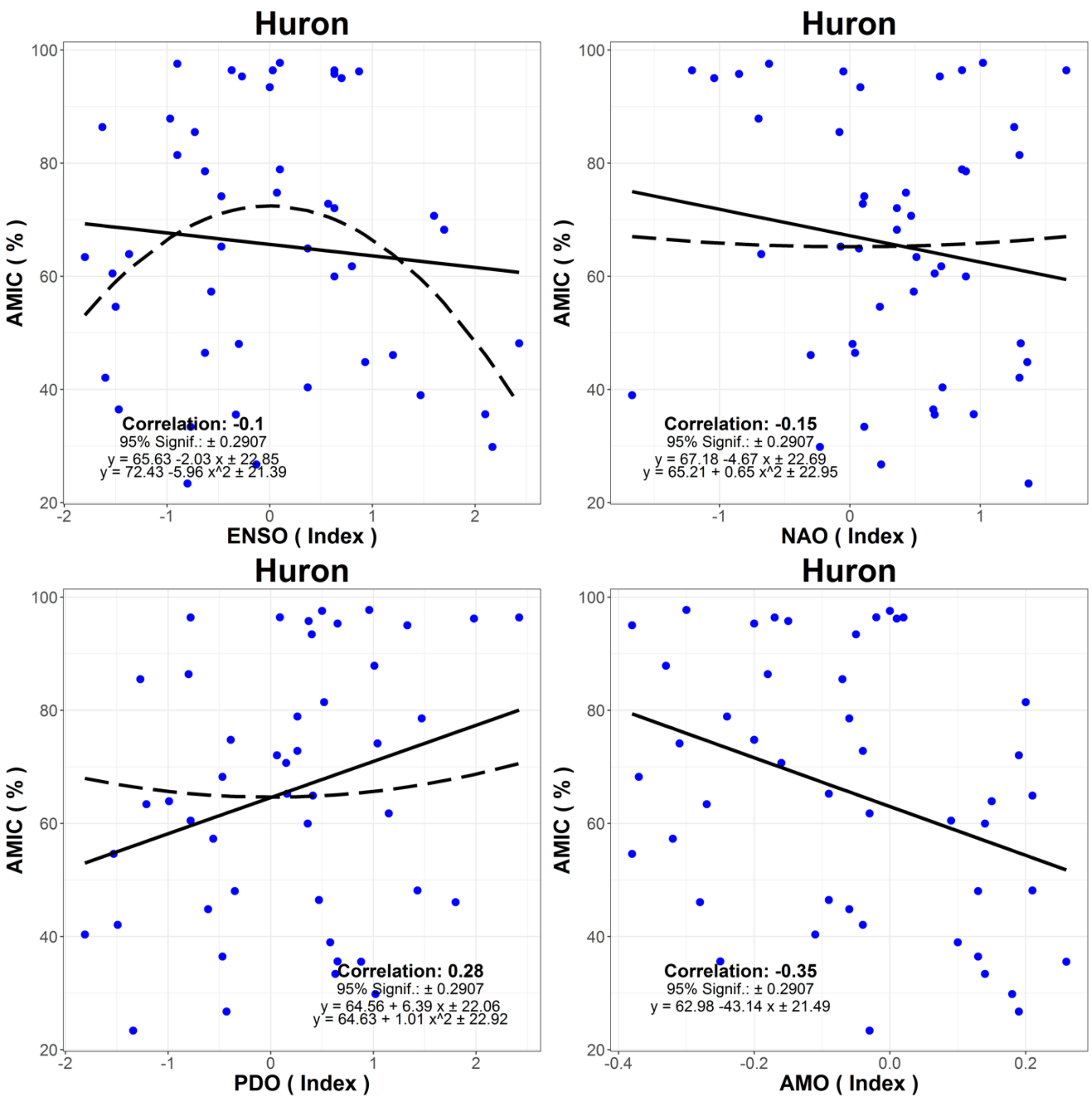

Fig. 28. Comparison between AMIC and atmospheric teleconnection patterns [Huron].

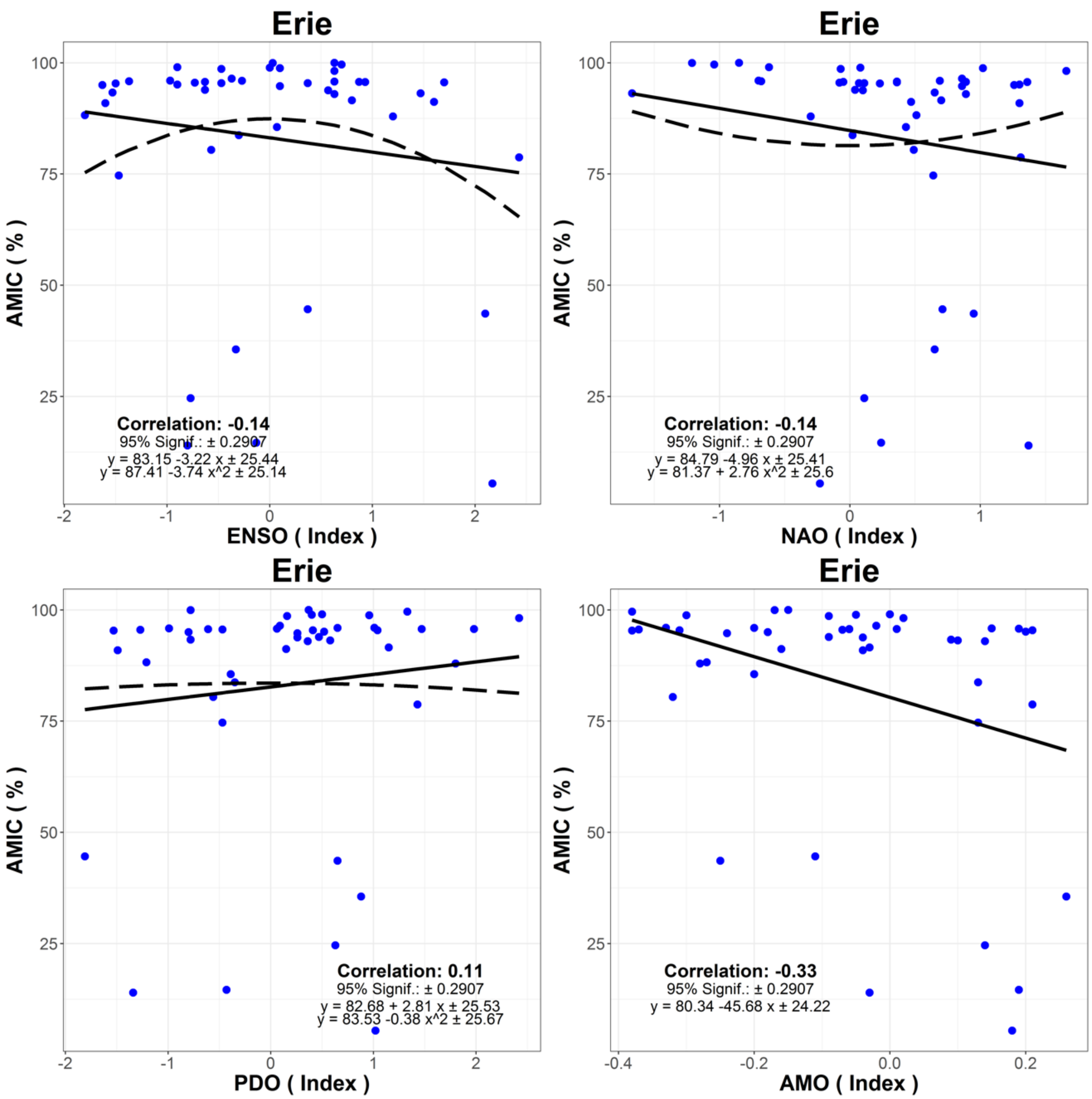

Fig. 29. Comparison between AMIC and atmospheric teleconnection patterns [Erie].

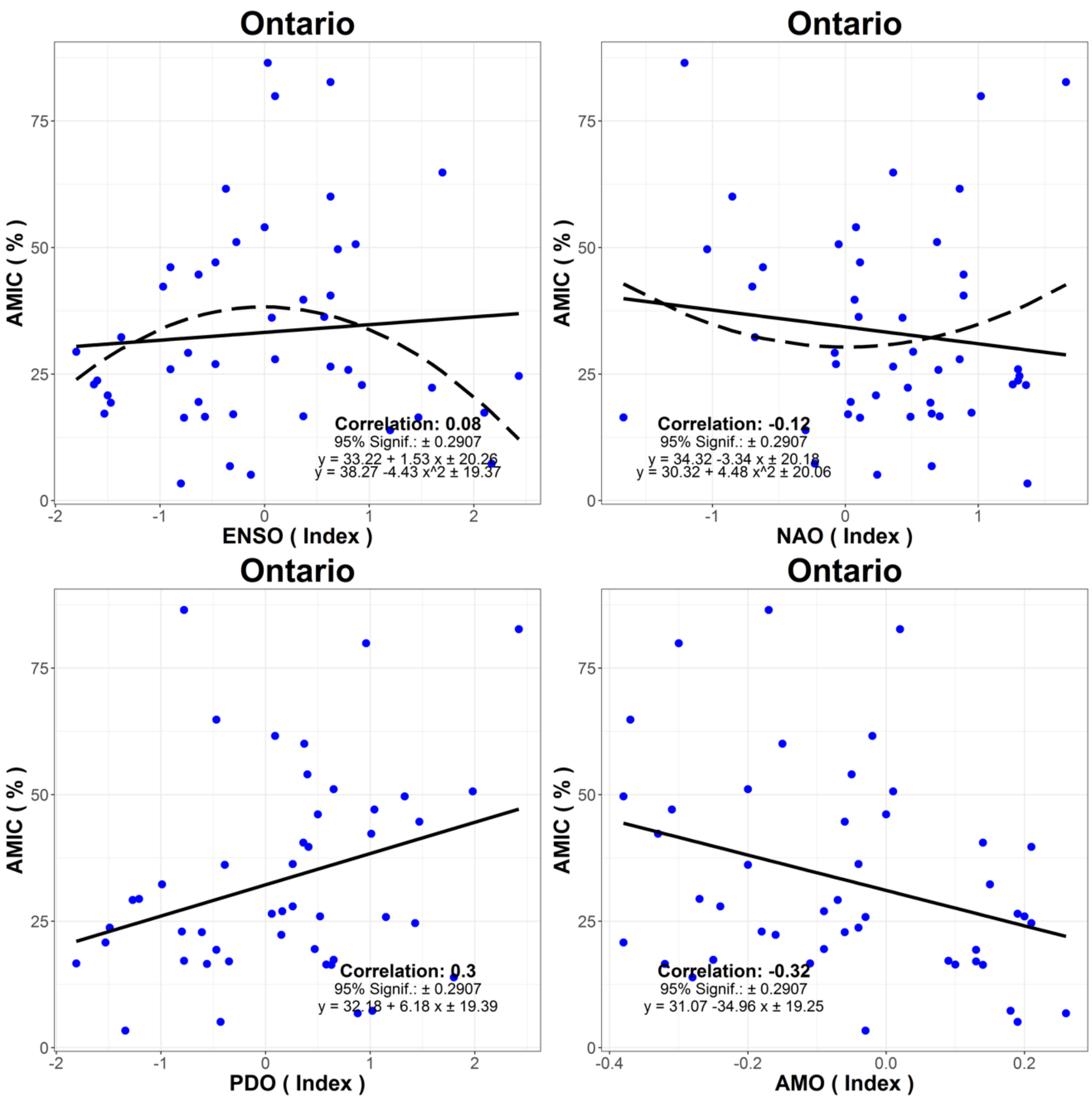

Fig. 30. Comparison between AMIC and atmospheric teleconnection patterns [Ontario].

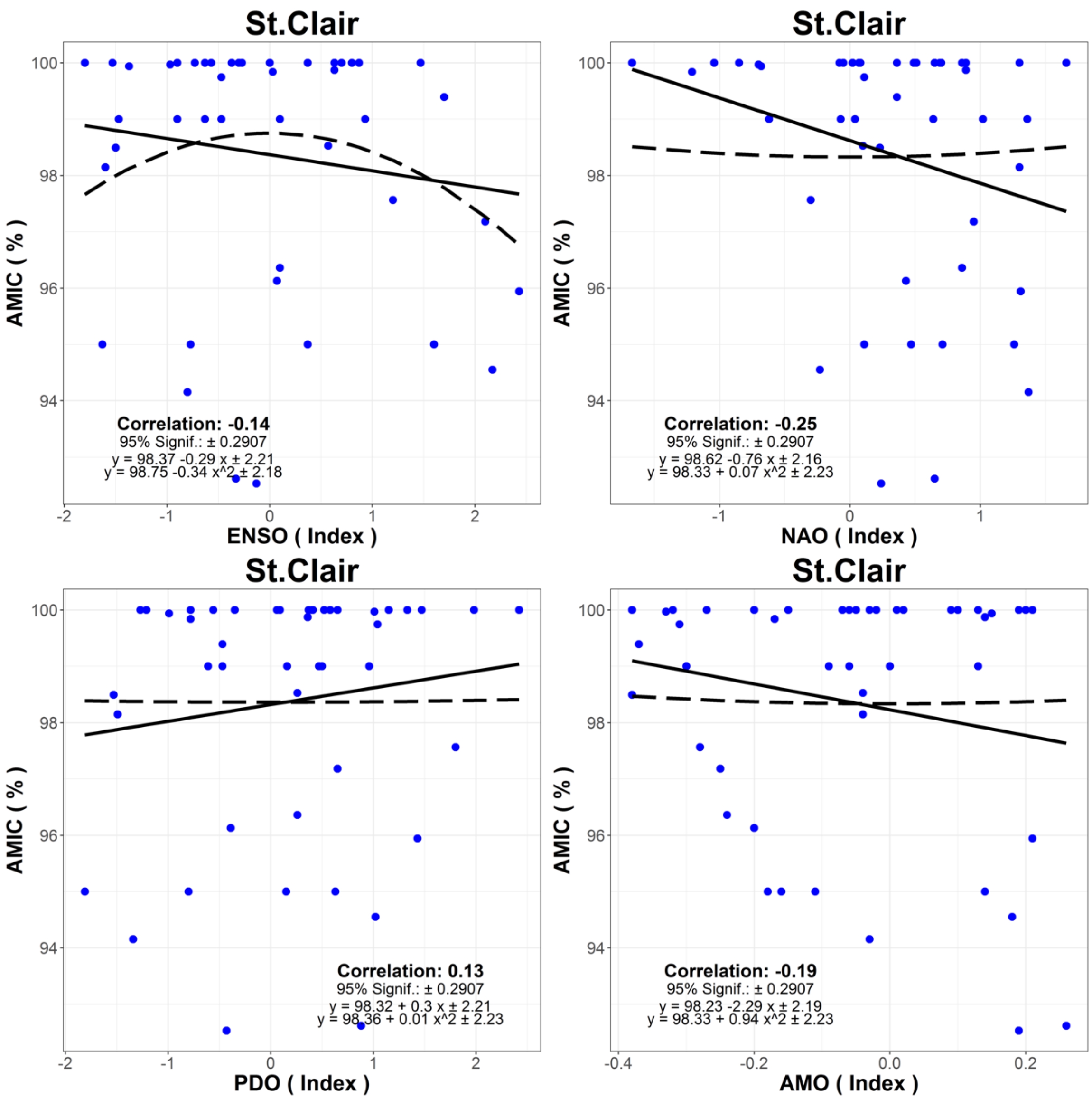

Fig. 31. Comparison between AMIC and atmospheric teleconnection patterns [St. Clair].

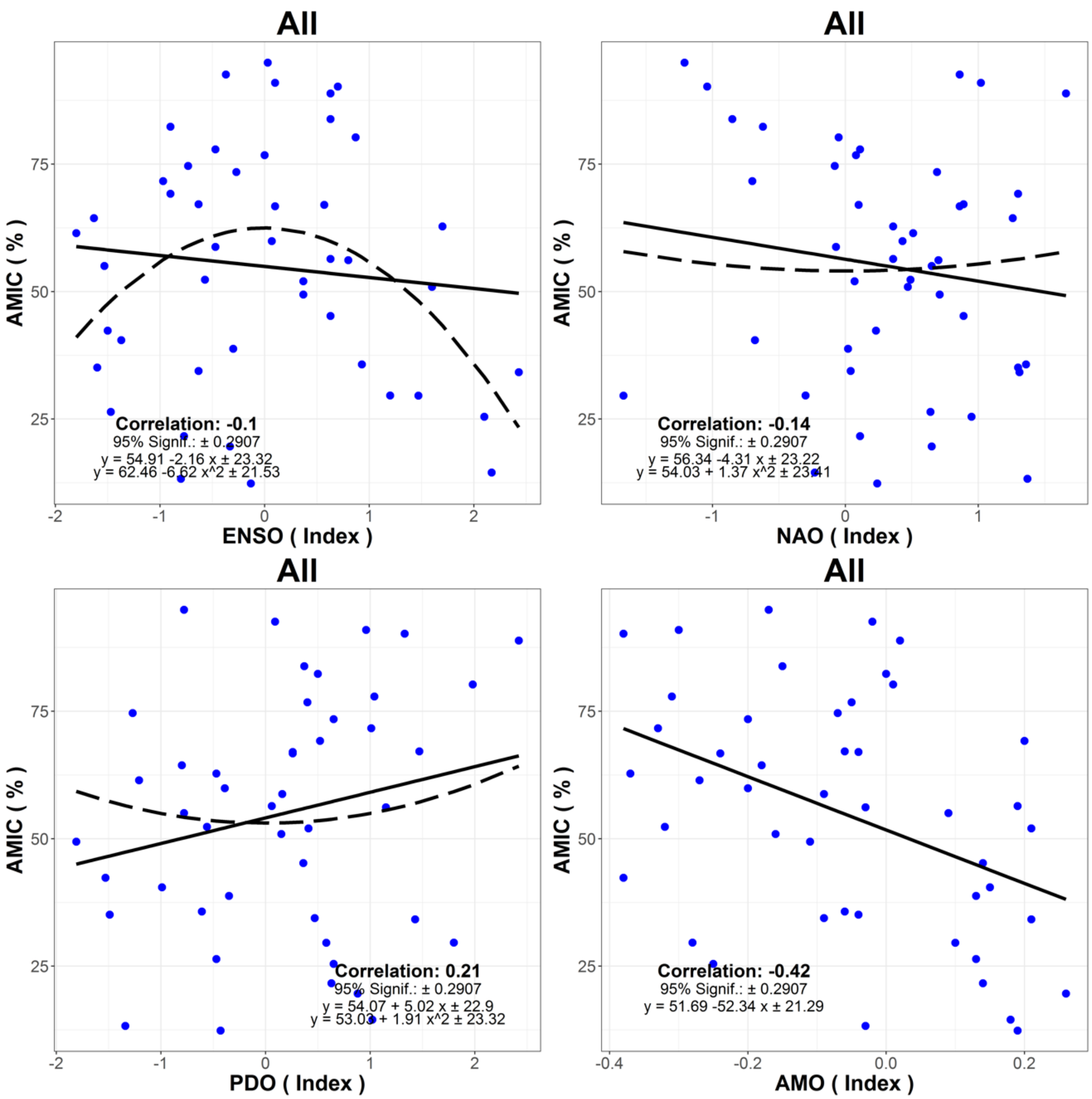

Fig. 32. Comparison between AMIC and atmospheric teleconnection patterns [Great Lakes].

4.6 Duration vs. atmosphere (circulation) teleconnection patterns

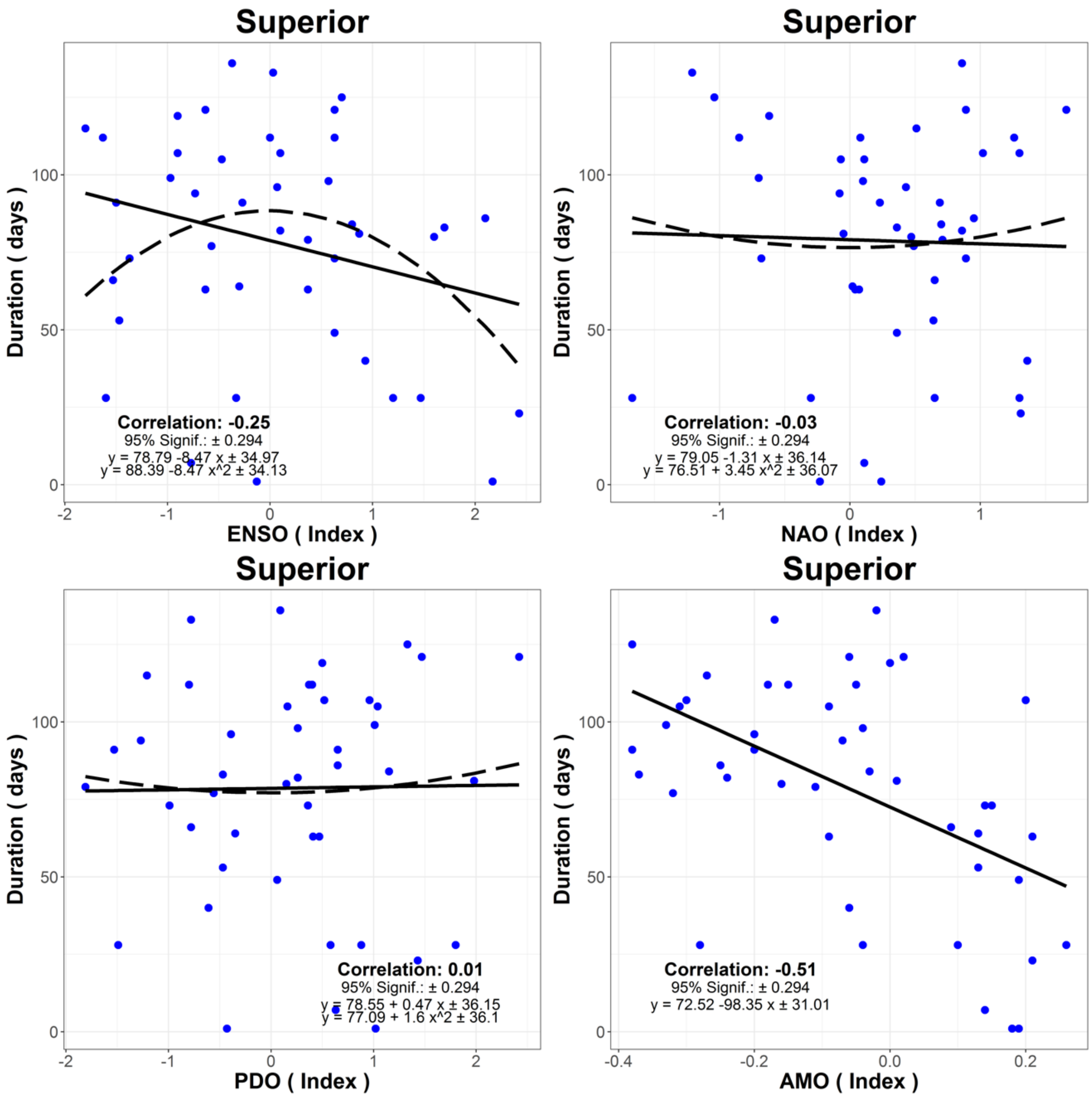

Fig. 33. Comparison between duration and atmospheric teleconnection patterns [Superior].

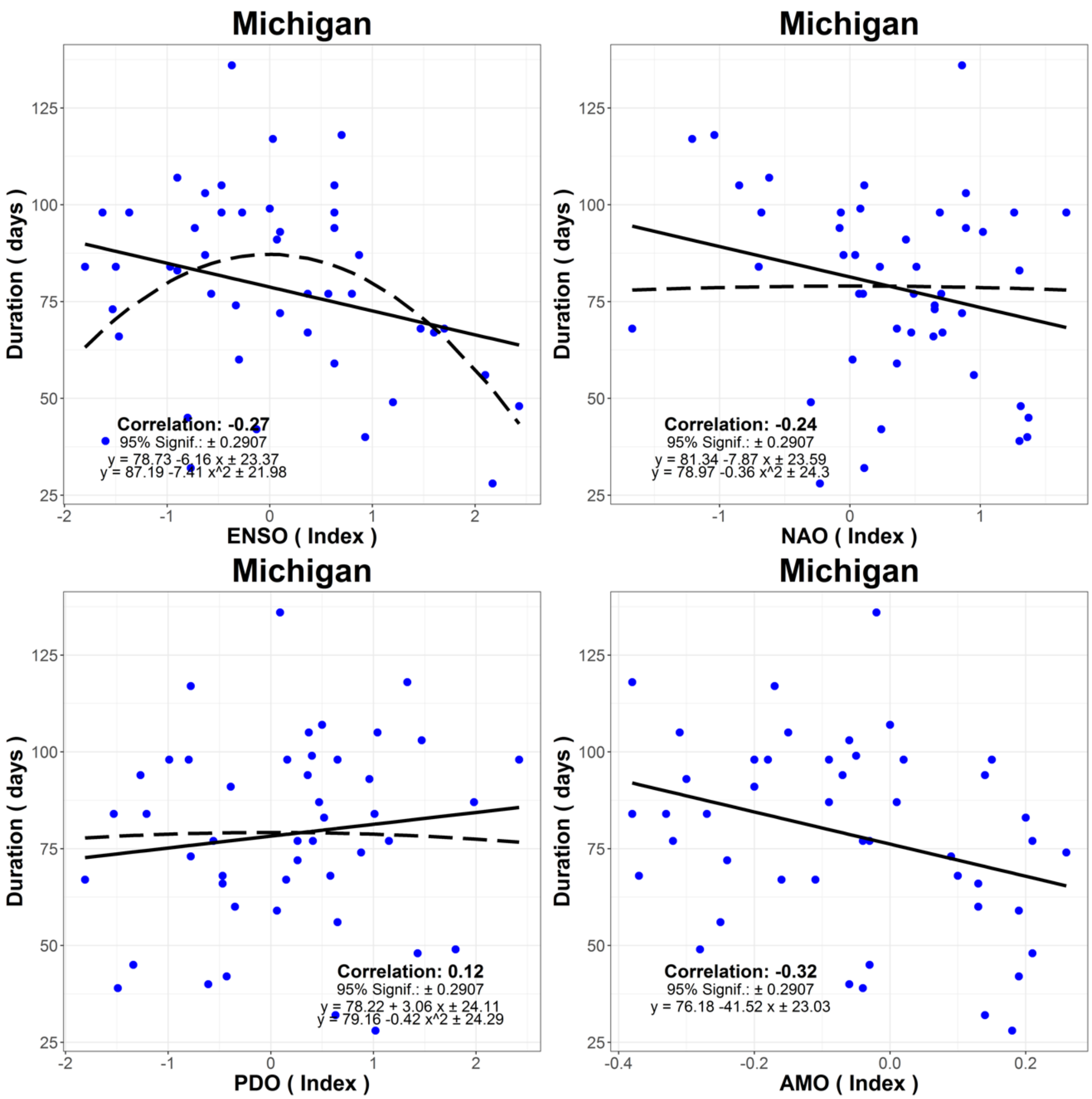

Fig. 34. Comparison between duration and atmospheric teleconnection patterns [Michigan].

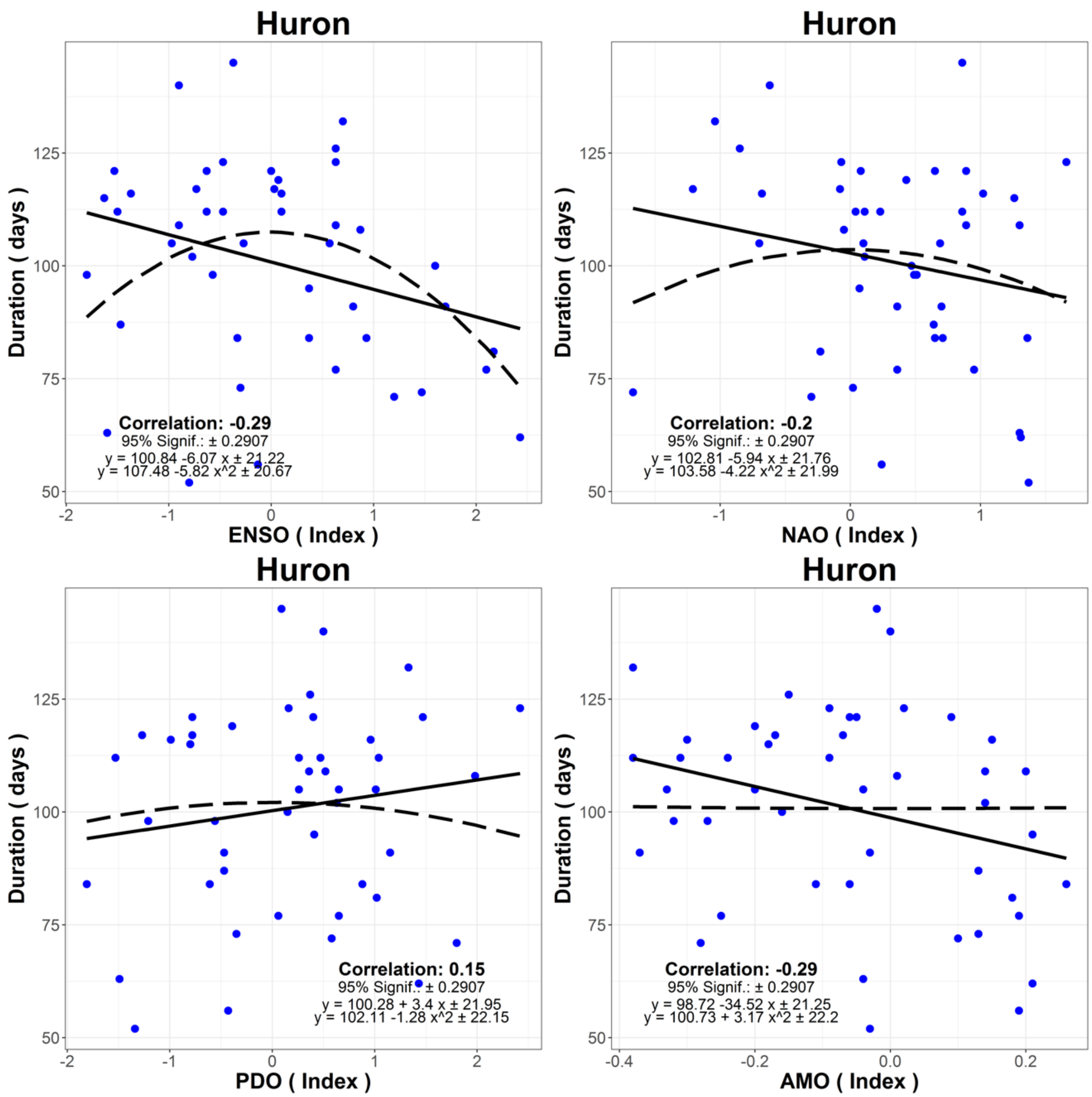

Fig. 35. Comparison between duration and atmospheric teleconnection patterns [Huron].

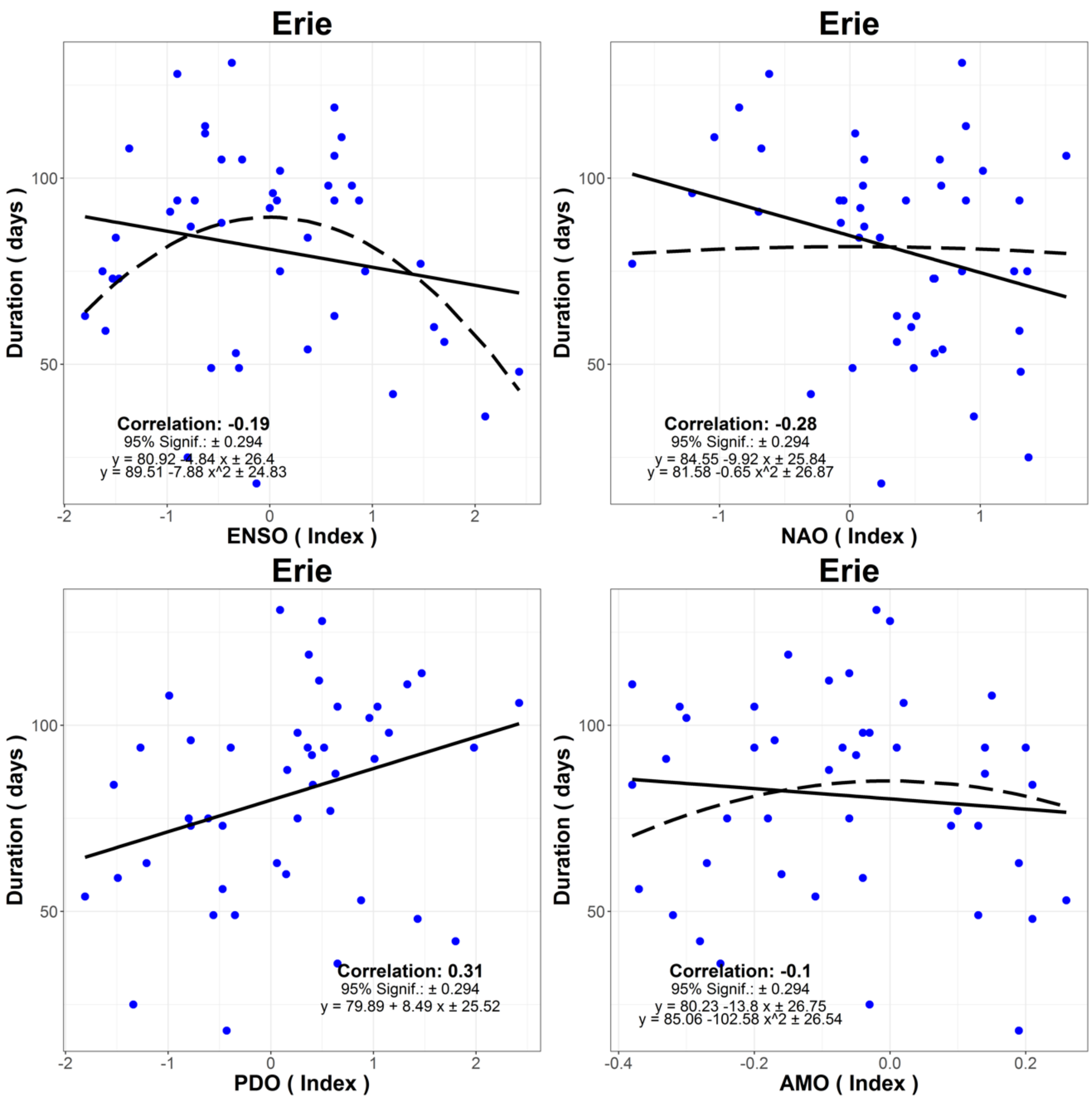

Fig. 36. Comparison between duration and atmospheric teleconnection patterns [Erie].

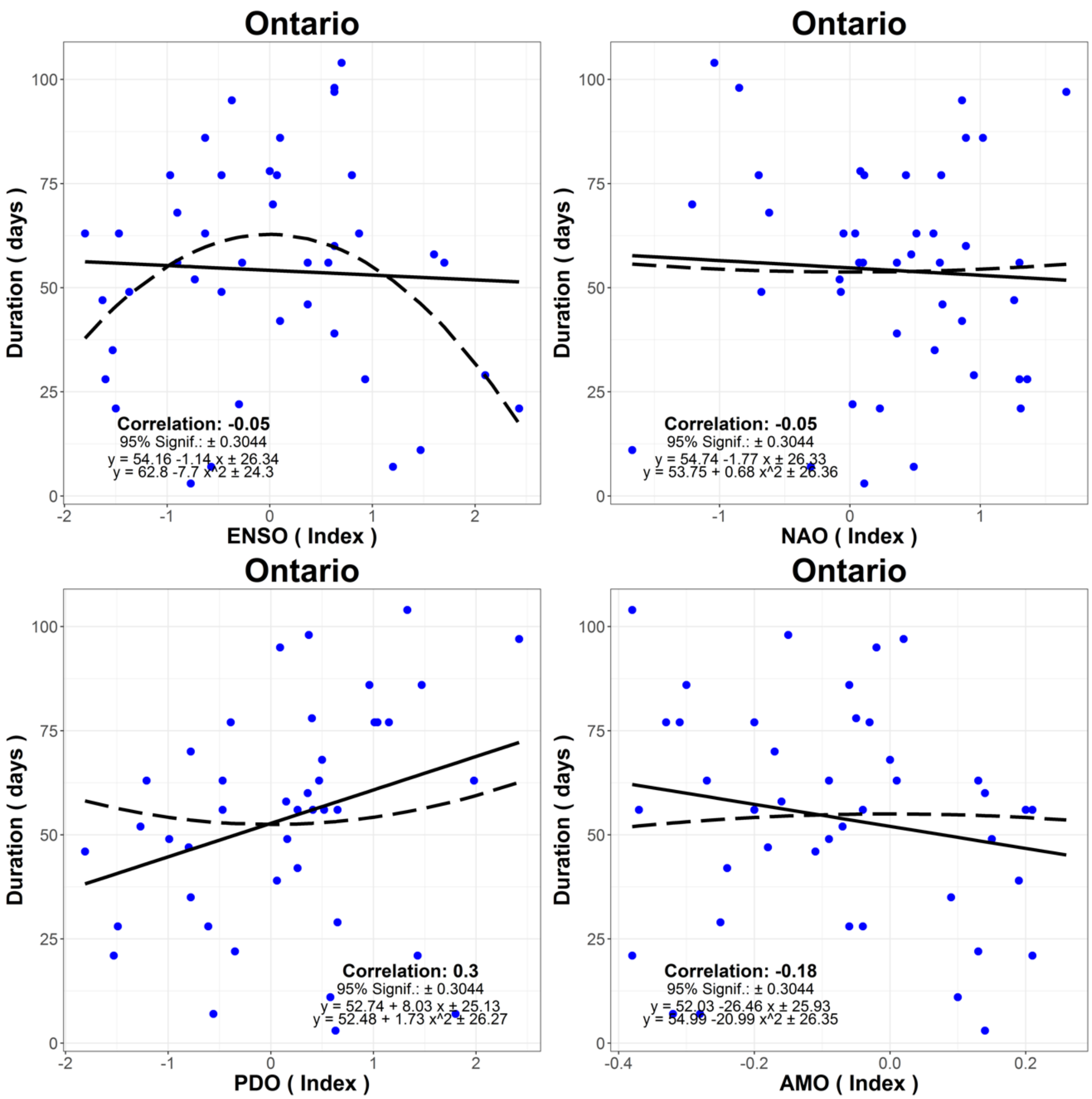

Fig. 37. Comparison between duration and atmospheric teleconnection patterns [Ontario].

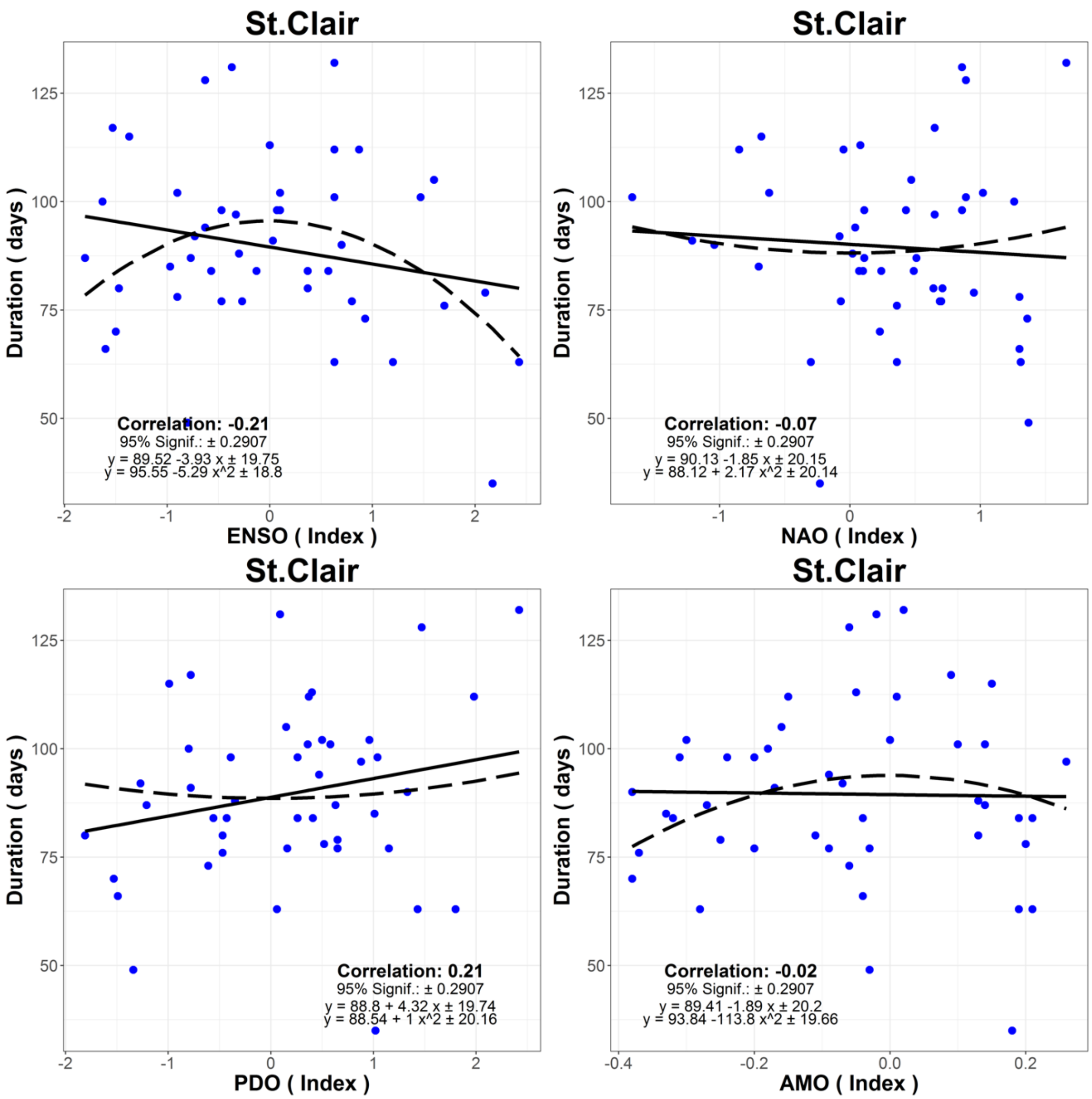

Fig. 38. Comparison between duration and atmospheric teleconnection patterns [St. Clair].

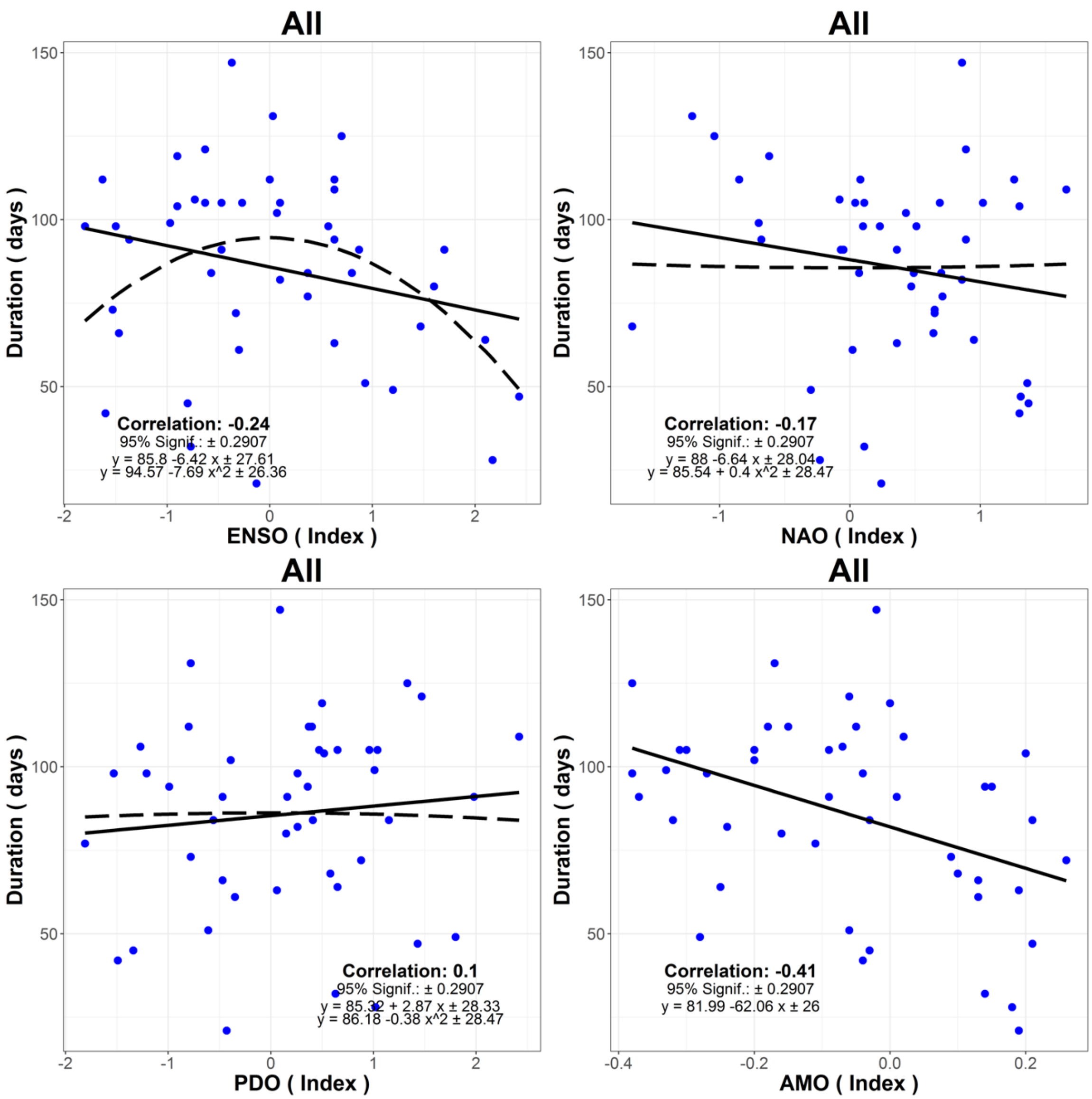

Fig. 39. Comparison between duration and atmospheric teleconnection patterns [Great Lakes].

4.7 AMIC vs. FDD and AMIC vs. WSI/WSI_GLERL

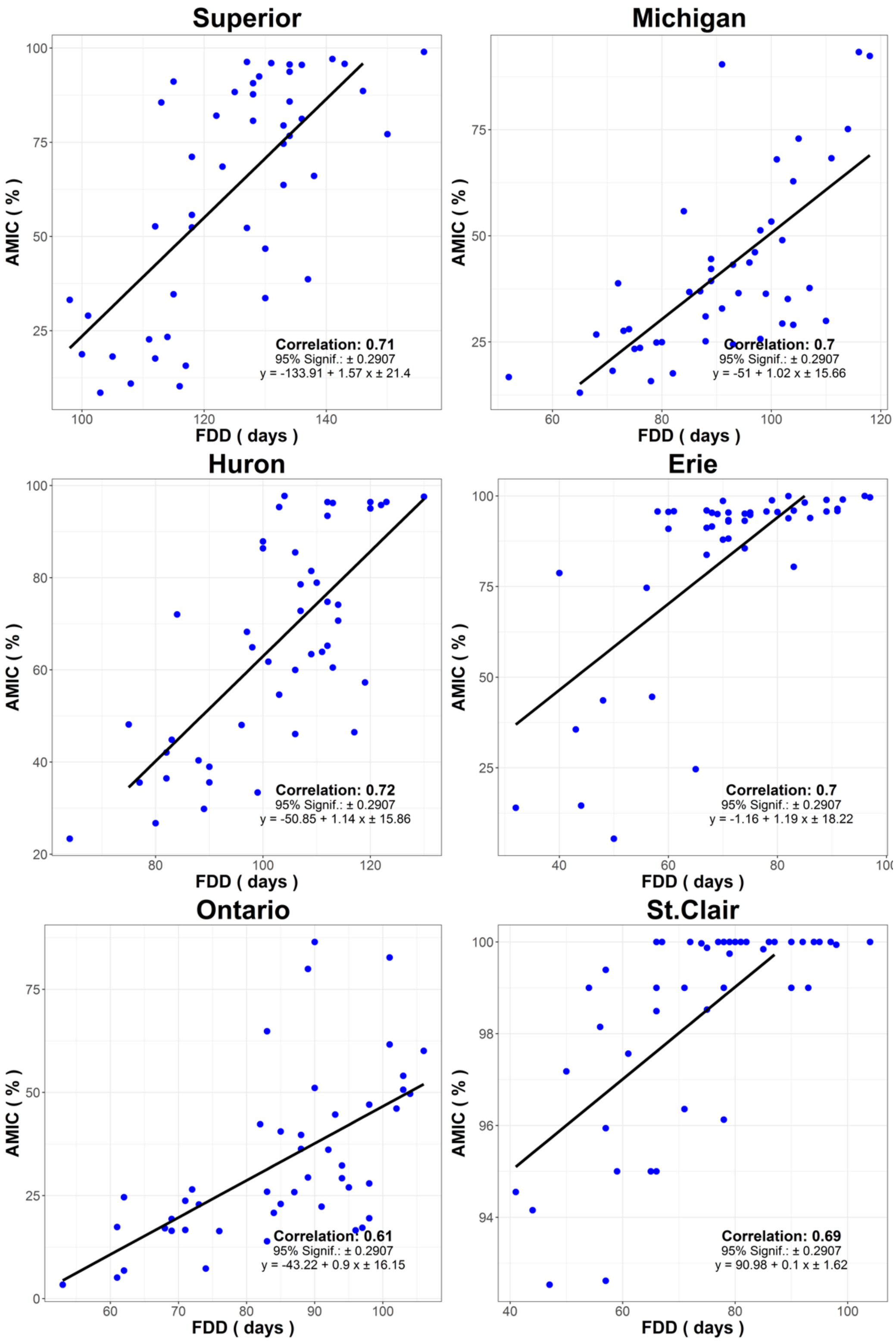

Fig. 40. Comparison between AMIC and FDD – (1).

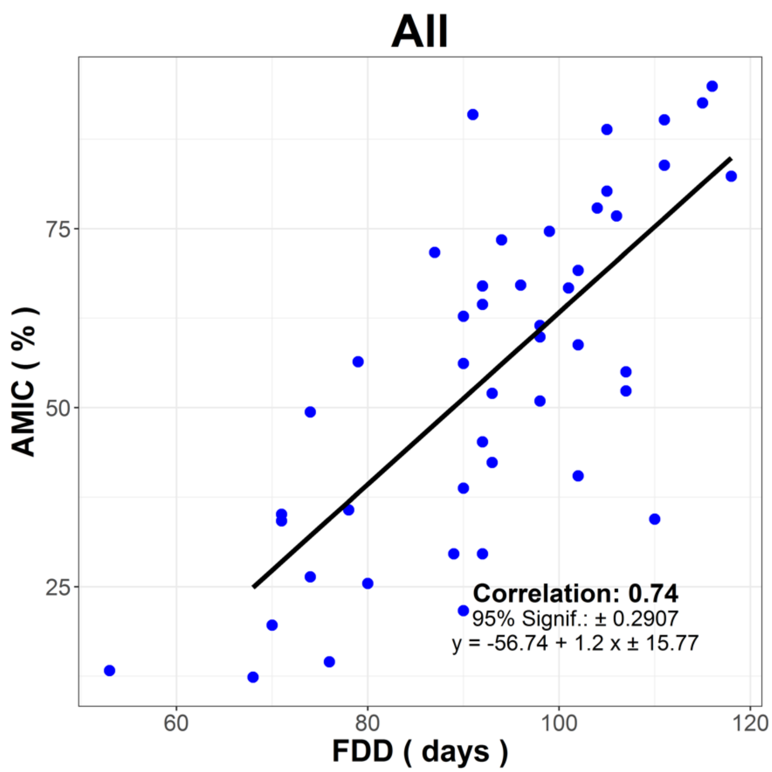

Fig. 41. Comparison between AMIC and FDD – (2).

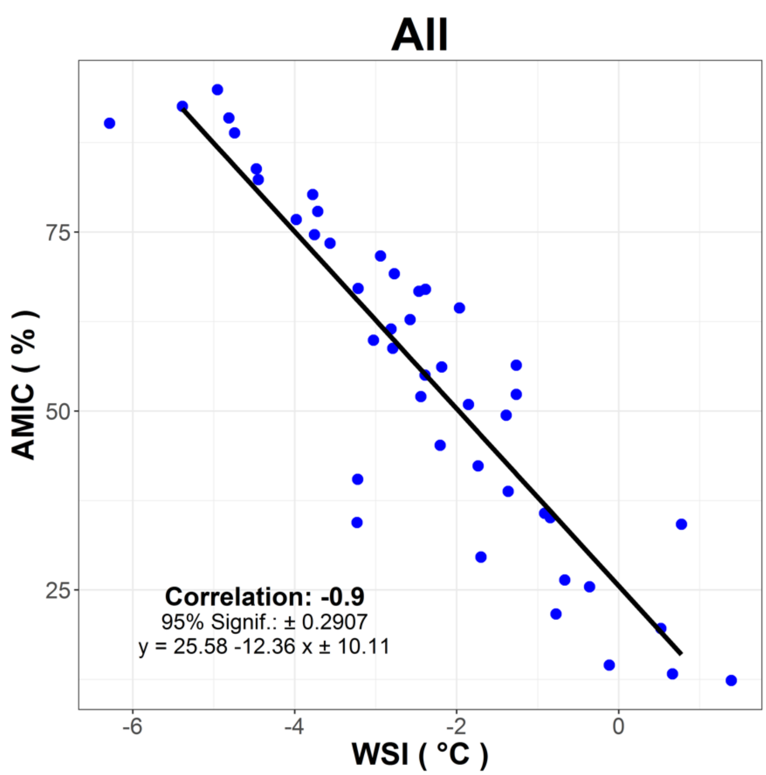

Fig. 42. Comparison between AMIC and WSI – (1).

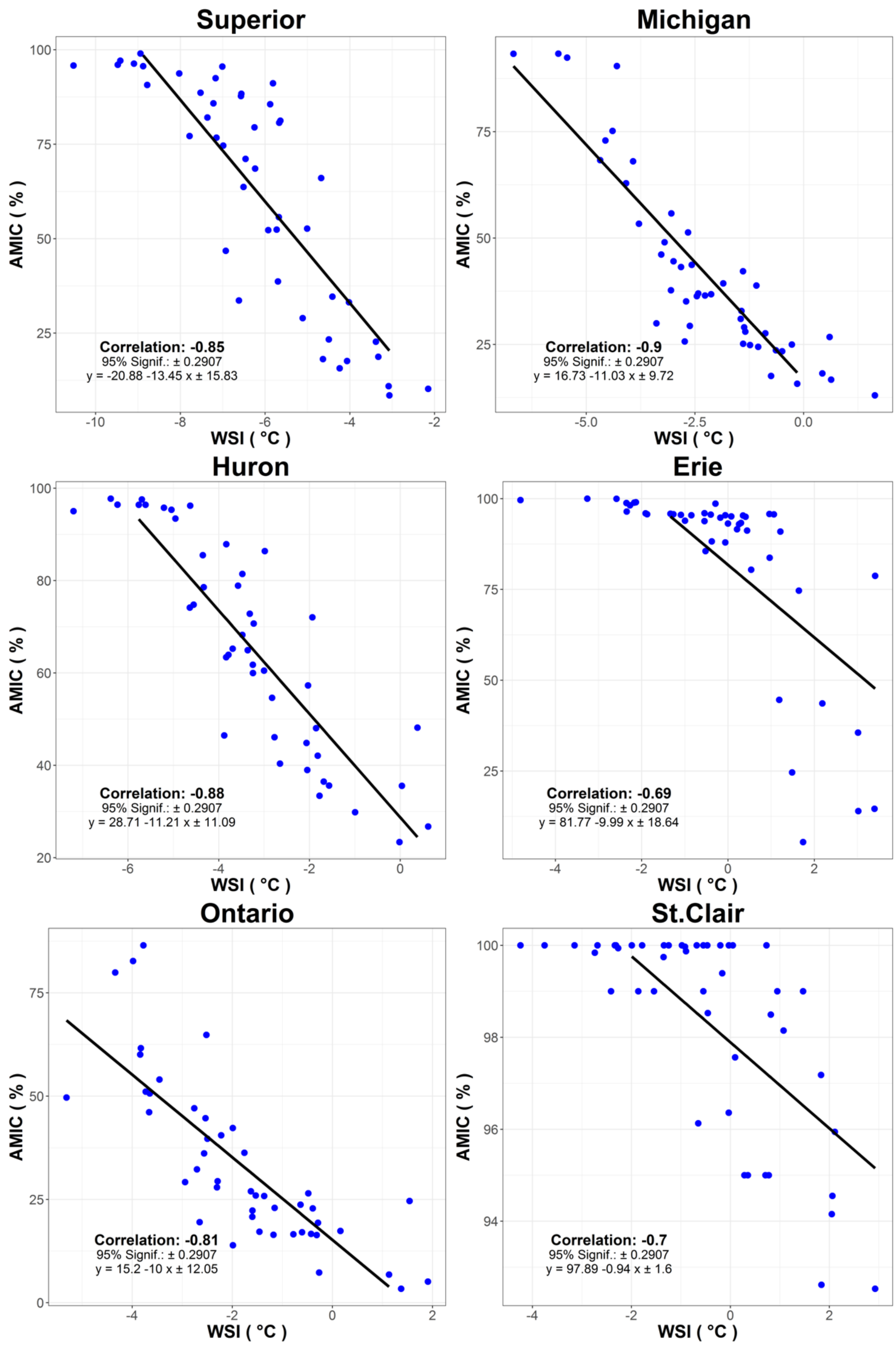

Fig. 43. Comparison between AMIC and WSI – (2).

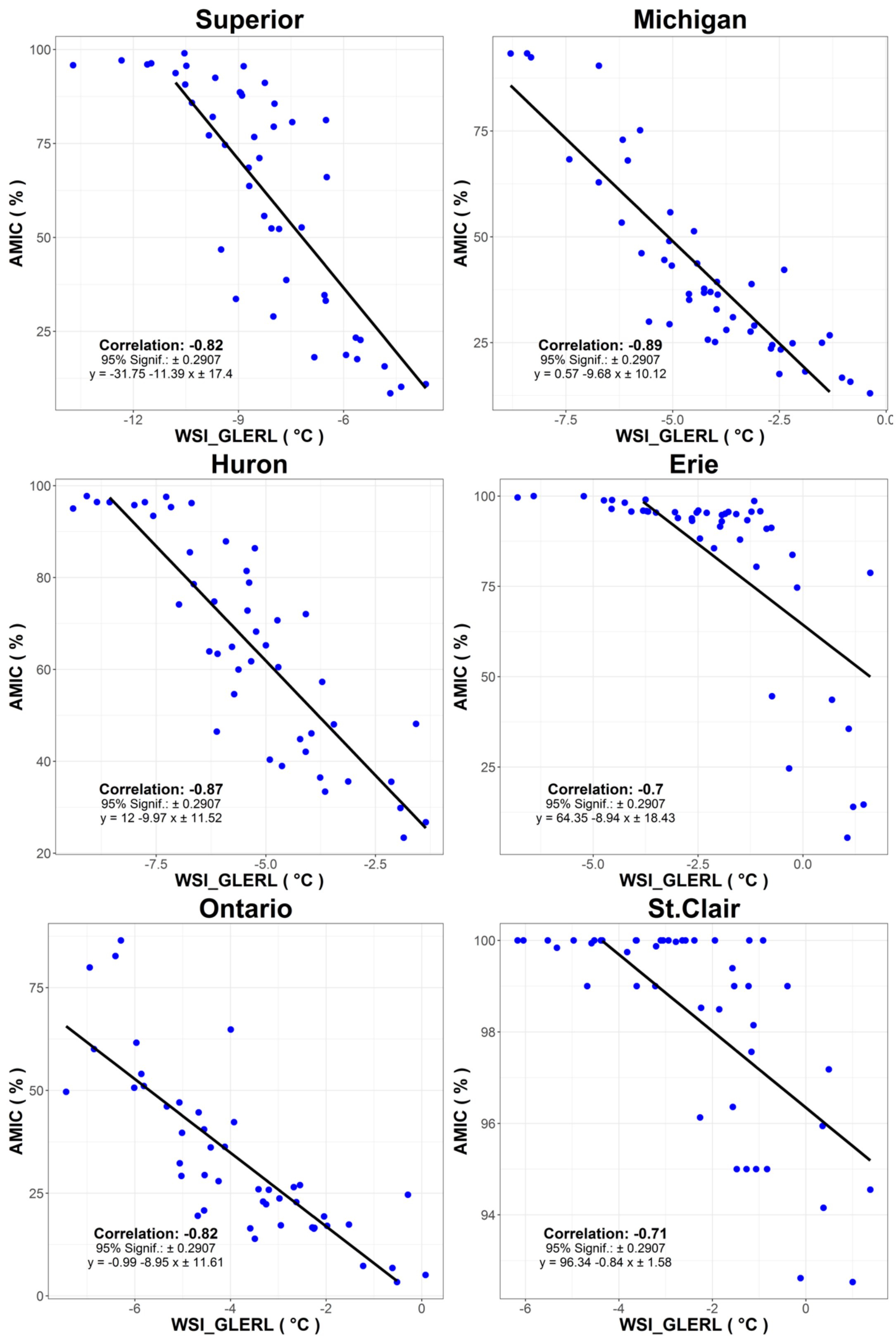

Fig. 44. Comparison between AMIC and WSI_CLERL – (1).

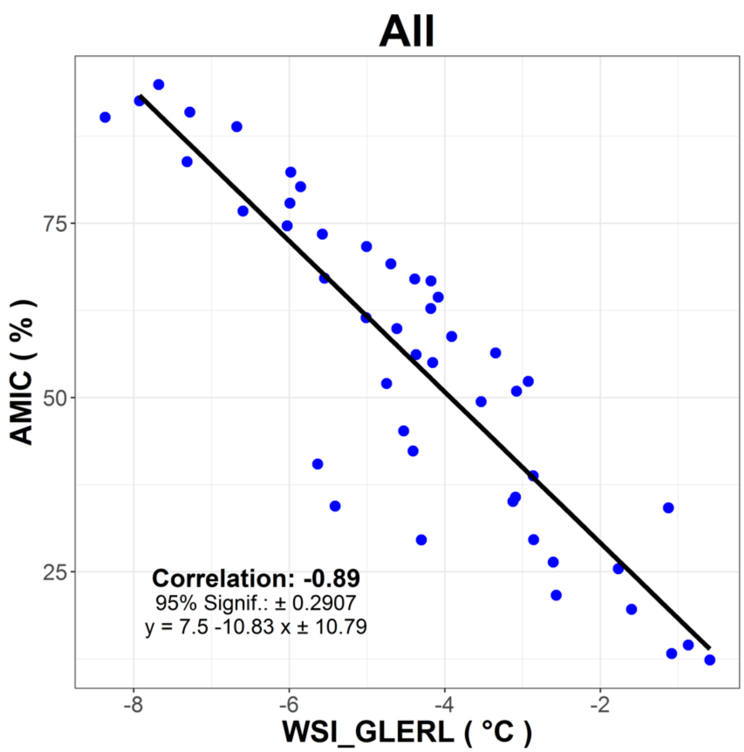

Fig. 45. Comparison between AMIC and WSI_CLERL – (2).

4.8 Duration vs. AMIC, duration vs. FDD and duration vs. WSI/WSI_GLERL

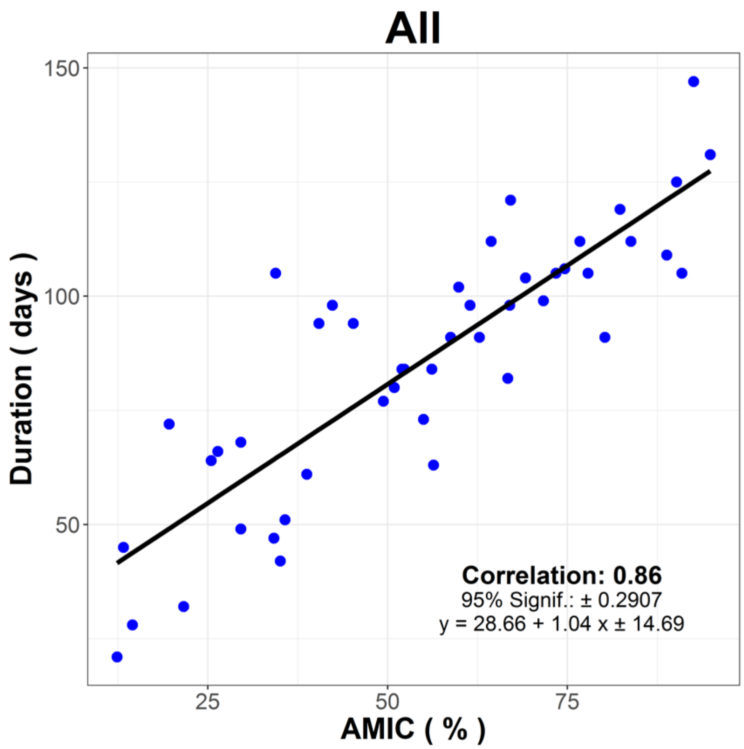

Fig. 46. Comparison between duration and AMIC – (1).

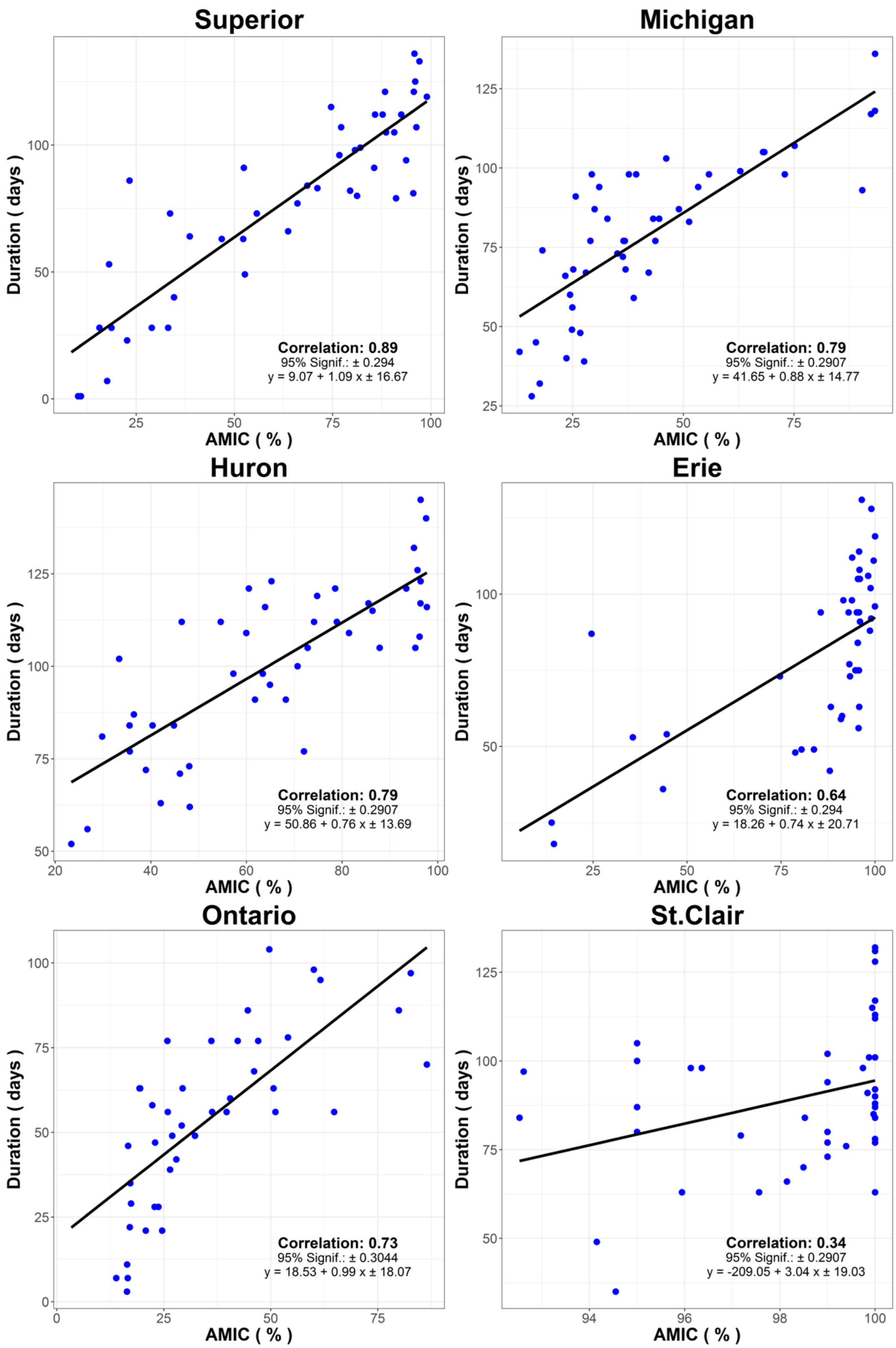

Fig. 47. Comparison between duration and AMIC – (2).

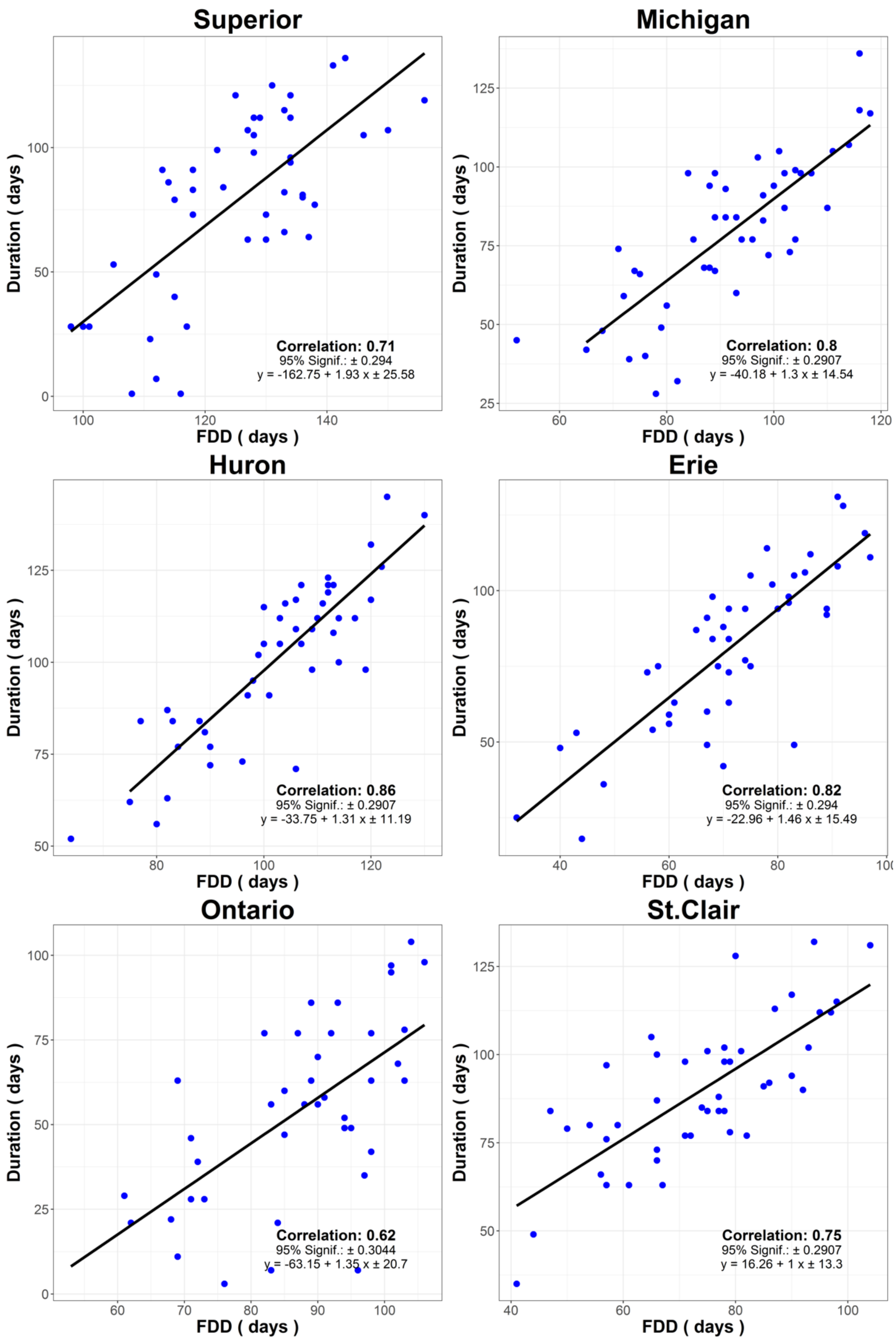

Fig. 48. Comparison between duration and FDD – (1).

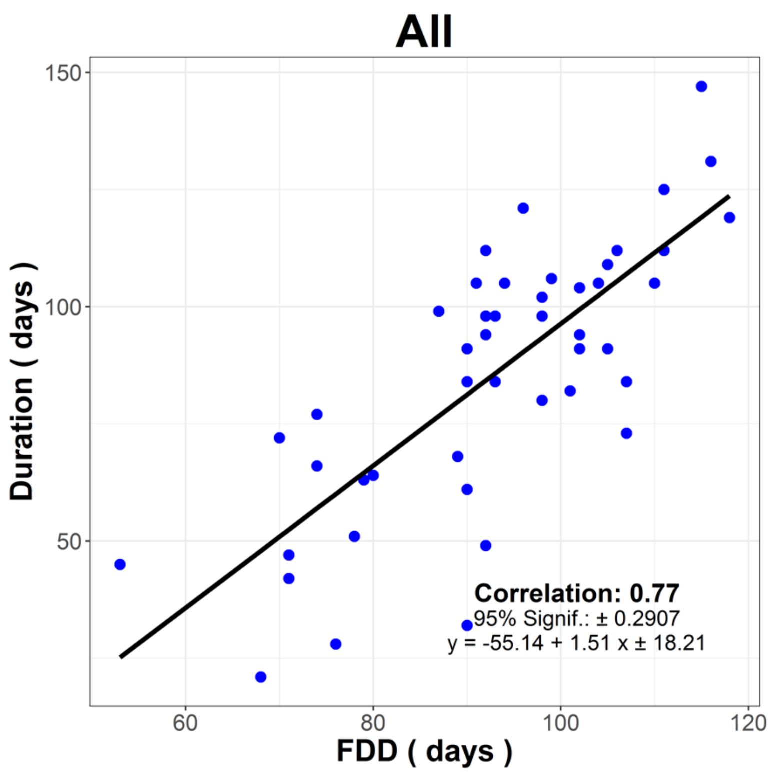

Fig. 49. Comparison between duration and FDD – (2).

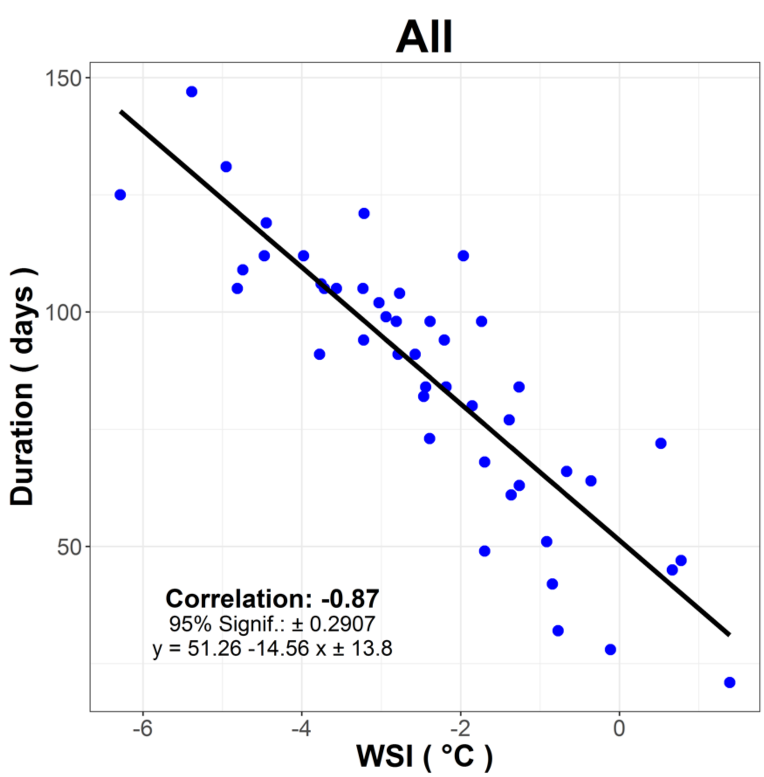

Fig. 50. Comparison between duration and WSI – (1).

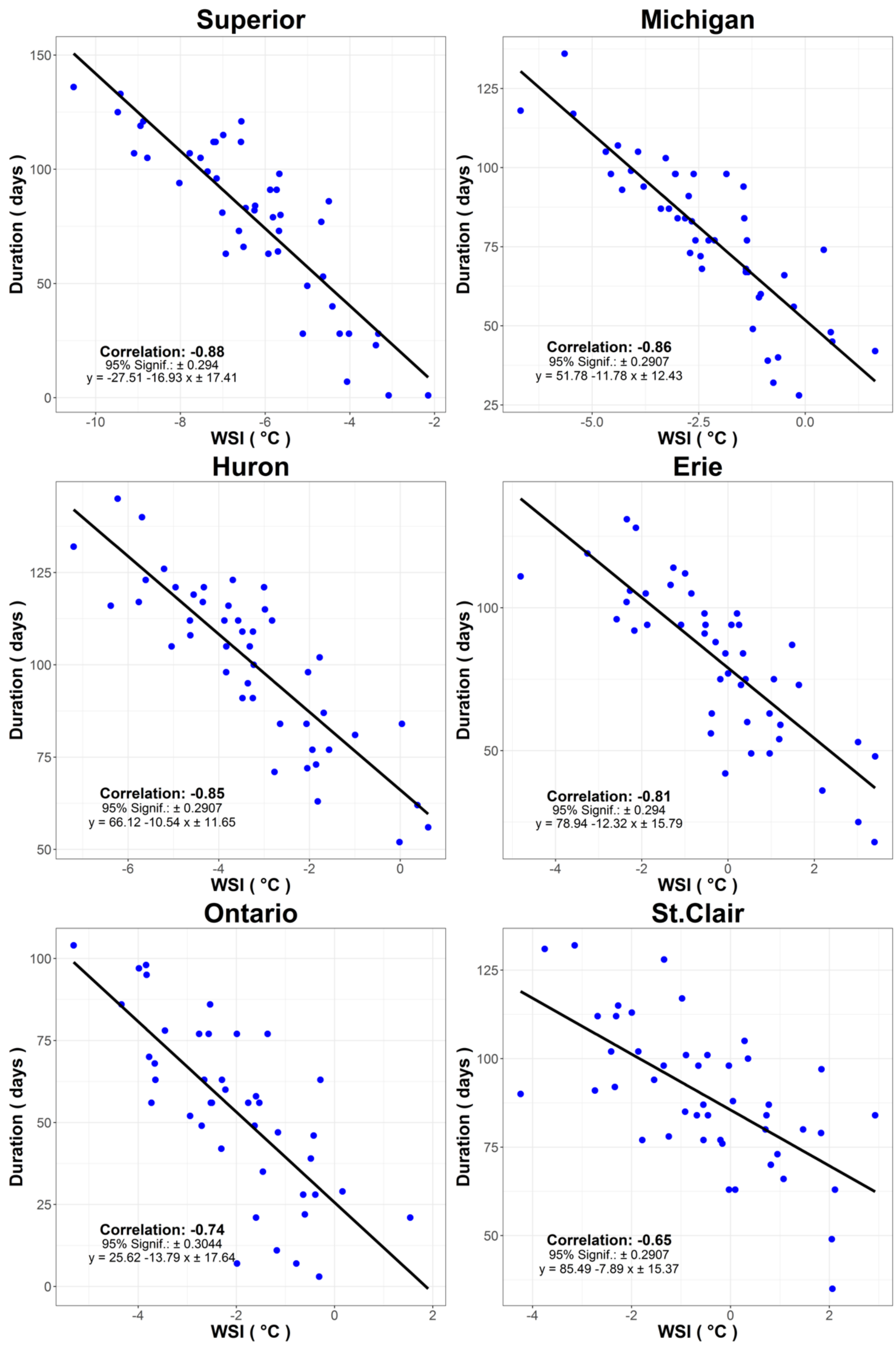

Fig. 51. Comparison between duration and WSI – (2).

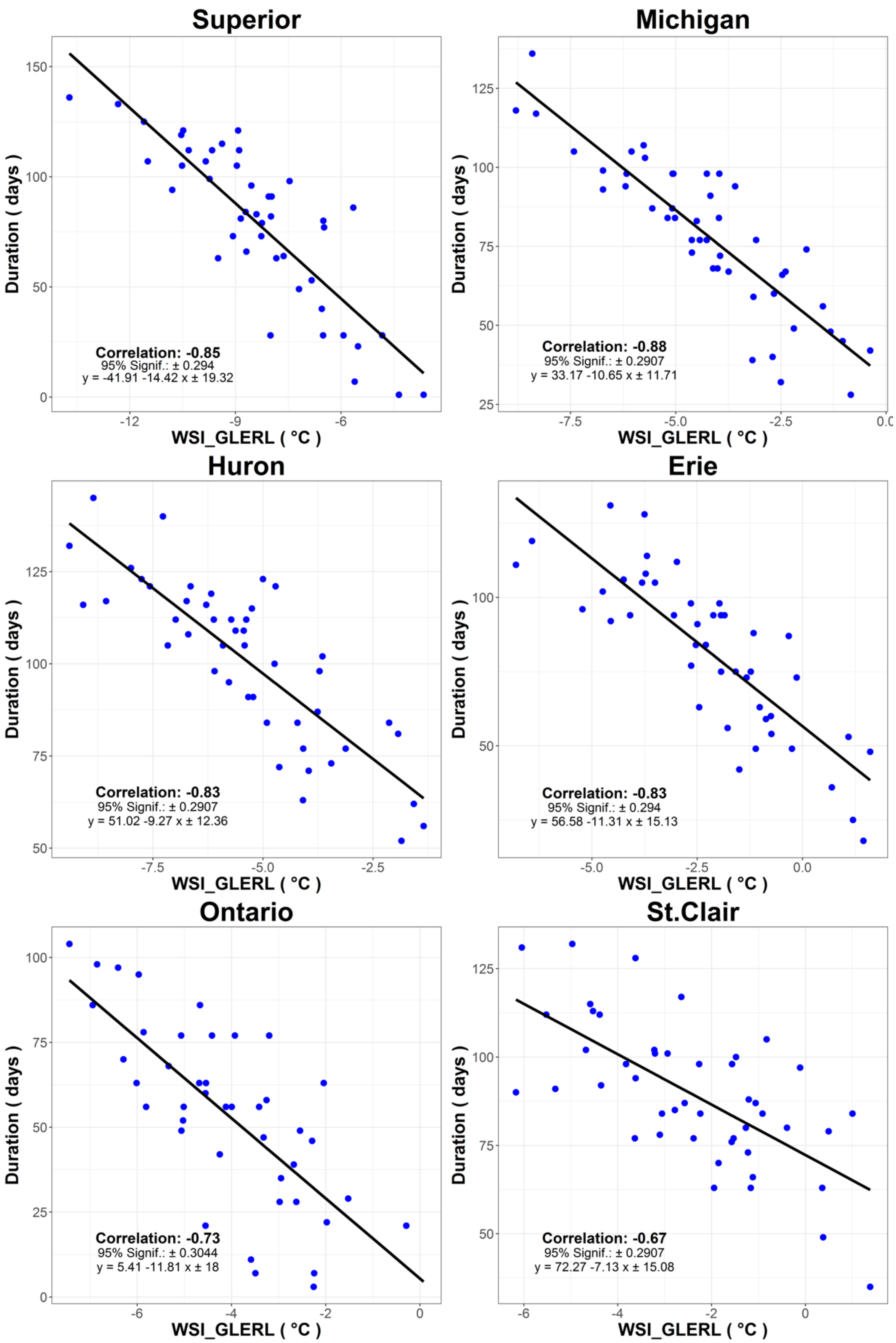

Fig. 52. Comparison between duration and WSI_GLERL – (1).

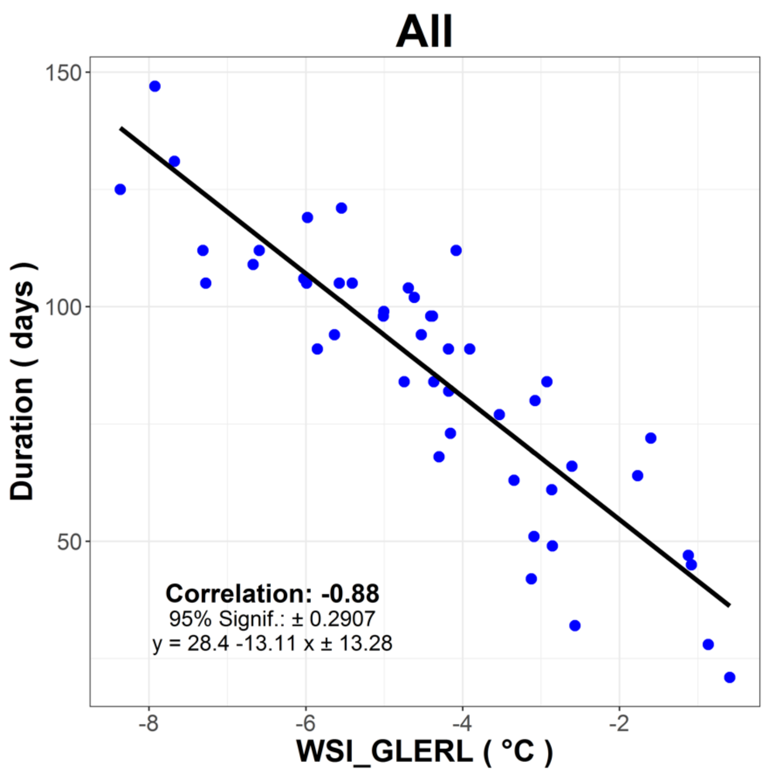

Fig. 53. Comparison between duration and WSI_GLERL – (2).

5.0 Summary

We have investigated in depth Great Lakes ice duration, winter severity index (WSI), cumulative freezing degree days (FDD), and atmospheric teleconnection patterns, 1973 – 2018 for all five individual lakes and the whole Great Lakes. We provided not only their time series, but also the individual linear scatter plots between ice duration/WSI/FDD and major four teleconnection patterns (ENSO, PDO, NAO, and AMO). Furthermore, when a linear relationship is weak, a quadratic (nonlinear) relationship was derived. Both linear correlation coefficients and linear and nonlinear regression models were provided.

Based on these relationships, we can estimate the ice duration using WSI and cumulative FFD using the linear regression equation (model). Furthermore, we can derive multi-variable statistical regression models to hindcast and forecast ice duration using WSI, and cumulative FDD, and using teleconnection patterns indices, which will be conducted in the near future.

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Appendix: Great Lakes environmental parameters

Table 2.Environmental parameters in Lake Superior.

Year	Freezeup (date)	Breakup (date)	Duration (days)	AMIC (%)	FDD (days)	WSI (°C)	WSI_GLERL (°C)
1973	1972-12-20	1973-03-13	83	71.131	118	-6.460	-8.404
1974	1973-12-31	1974-04-25	115	74.617	133	-6.989	-9.382
1975	1975-01-16	1975-04-03	77	66.058	138	-4.675	-6.481
1976	1976-01-06	1976-04-06	91	52.407	118	-5.728	-8.058
1977	1976-12-16	1977-04-20	125	96.036	131	-9.478	-11.600
1978	1977-12-28	1978-04-19	112	92.489	129	-7.169	-9.662
1979	1979-01-01	1979-05-14	133	97.110	141	-9.415	-12.336
1980	1980-01-02	1980-04-09	98	80.700	128	-5.665	-7.464
1981	1981-01-07	1981-04-08	91	85.572	113	-5.881	-7.973
1982	1982-01-04	1982-04-26	112	85.814	134	-7.219	-10.328
1983	1983-01-03	1983-03-30	86	23.317	114	-4.495	-5.653
1984	1983-12-20	1984-04-19	121	88.352	125	-6.561	-8.926
1985	1984-12-28	1985-04-06	99	82.073	122	-7.360	-9.735
1986	1985-12-21	1986-04-05	105	90.698	128	-8.780	-10.519
1987	1987-01-24	1987-02-21	28	15.680	117	-4.241	-4.832
1988	1988-01-10	1988-04-03	84	68.547	123	-6.236	-8.711
1989	1989-01-01	1989-04-23	112	87.734	128	-6.570	-8.896
1990	1989-12-27	1990-04-02	96	76.729	134	-7.147	-8.549
1991	1991-01-09	1991-03-29	79	91.134	115	-5.815	-8.248
1992	1992-01-17	1992-04-06	80	81.223	136	-5.638	-6.503
1993	1993-01-13	1993-04-05	82	79.473	133	-6.251	-7.992
1994	1994-01-03	1994-04-20	107	96.333	127	-9.095	-11.489
1995	1995-02-08	1995-03-20	40	34.657	115	-4.411	-6.548
1996	1996-01-12	1996-05-10	119	99.000	156	-8.943	-10.540
1997	1997-01-14	1997-04-29	105	88.618	146	-7.524	-8.961
1998	1998-01-16	1998-01-16	1	10.946	108	-3.083	-3.655
1999	1999-01-15	1999-03-09	53	18.121	105	-4.633	-6.838
2000	2000-01-28	2000-02-25	28	33.155	98	-4.021	-6.511
2001	2001-02-05	2001-04-09	63	46.774	130	-6.929	-9.494
2002	2002-03-18	2002-03-18	1	10.237	116	-2.150	-4.357
2003	2003-01-23	2003-04-14	81	95.548	136	-7.010	-8.850
2004	2004-01-22	2004-03-25	63	52.260	127	-5.924	-7.841
2005	2005-01-17	2005-03-31	73	55.711	118	-5.675	-8.265
2006	2006-03-02	2006-03-09	7	17.625	112	-4.066	-5.613
2007	2007-02-01	2007-03-22	49	52.680	112	-5.006	-7.196
2008	2008-01-28	2008-04-03	66	63.665	133	-6.511	-8.691
2009	2009-01-12	2009-04-16	94	93.722	134	-8.027	-10.795
2010	2010-02-04	2010-03-04	28	28.975	101	-5.112	-8.006
2011	2011-01-20	2011-04-03	73	33.647	130	-6.618	-9.072
2012	NA	NA	NA	8.510	103	-3.067	-4.668
2013	2013-01-25	2013-03-30	64	38.664	137	-5.698	-7.634
2014	2013-12-31	2014-05-16	136	95.816	143	-10.521	-13.717
2015	2015-01-02	2015-05-03	121	95.653	134	-8.877	-10.485
2016	2016-02-12	2016-03-06	23	22.705	111	-3.386	-5.519
2017	2017-02-17	2017-03-17	28	18.718	100	-3.328	-5.932
2018	2017-12-29	2018-04-15	107	77.172	150	-7.781	-9.844

Table 3. Environmental parameters in Lake Michigan.

Year	Freezeup (date)	Breakup (date)	Duration (days)	AMIC (%)	FDD (days)	WSI (°C)	WSI_GLERL (°C)
1973	1972-12-28	1973-03-06	68	36.960	87	-2.424	-4.114
1974	1974-01-10	1974-04-04	84	43.184	93	-2.819	-5.019
1975	1975-01-16	1975-04-03	77	29.019	104	-1.369	-3.088
1976	1975-12-30	1976-03-23	84	32.869	91	-1.429	-3.972
1977	1976-12-16	1977-04-13	118	93.287	116	-6.678	-8.798
1978	1977-12-28	1978-04-12	105	68.290	111	-4.681	-7.420
1979	1978-12-27	1979-04-23	117	92.395	118	-5.442	-8.318
1980	1980-01-16	1980-04-02	77	43.690	96	-2.575	-4.426
1981	1980-12-24	1981-04-01	98	55.792	84	-3.043	-5.056
1982	1982-01-11	1982-04-20	99	62.866	104	-4.086	-6.731
1983	1983-01-18	1983-03-15	56	24.949	80	-0.270	-1.504
1984	1983-12-27	1984-04-08	103	46.129	97	-3.274	-5.730
1985	1985-01-05	1985-03-30	84	44.541	89	-2.994	-5.195
1986	1985-12-21	1986-04-05	105	68.014	101	-3.923	-6.052
1987	1987-01-24	1987-03-14	49	24.855	79	-1.231	-2.192
1988	1988-01-10	1988-03-27	77	36.489	94	-2.268	-4.620
1989	1989-01-08	1989-04-16	98	39.352	89	-1.848	-3.964
1990	1989-12-18	1990-03-19	91	25.692	98	-2.735	-4.177
1991	1991-01-07	1991-03-15	67	28.008	74	-1.340	-3.744
1992	1992-01-20	1992-03-27	67	42.189	89	-1.395	-2.390
1993	1993-01-13	1993-03-26	72	36.344	99	-2.458	-3.945
1994	1994-01-03	1994-04-06	93	90.418	91	-4.298	-6.728
1995	1995-02-08	1995-03-20	40	23.599	76	-0.637	-2.699
1996	1996-01-03	1996-04-19	107	75.154	114	-4.396	-5.765
1997	1996-12-27	1997-04-04	98	37.711	107	-3.052	-4.263
1998	1998-01-16	1998-02-13	28	15.763	78	-0.148	-0.839
1999	1999-01-05	1999-03-12	66	23.362	75	-0.493	-2.468
2000	2000-01-21	2000-02-29	39	27.608	73	-0.881	-3.177
2001	2000-12-25	2001-03-22	87	29.953	110	-3.386	-5.556
2002	2002-02-11	2002-03-25	42	13.008	65	1.640	-0.378
2003	2003-01-13	2003-04-10	87	48.995	102	-3.198	-5.081
2004	2004-01-12	2004-03-29	77	36.773	85	-2.127	-4.266
2005	2004-12-27	2005-03-31	94	31.007	88	-1.448	-3.590
2006	2006-02-09	2006-03-13	32	17.585	82	-0.749	-2.502
2007	2007-01-22	2007-03-22	59	38.813	72	-1.086	-3.152
2008	2008-01-21	2008-04-03	73	35.115	103	-2.703	-4.615
2009	2008-12-22	2009-03-26	94	53.364	100	-3.790	-6.193
2010	2010-01-05	2010-03-14	68	25.144	88	-1.393	-4.006
2011	2010-12-18	2011-03-26	98	29.335	102	-2.617	-5.075
2012	2012-01-20	2012-03-05	45	16.712	52	0.633	-1.034
2013	2013-01-22	2013-03-23	60	24.423	93	-1.045	-2.667
2014	2013-12-14	2014-04-29	136	93.325	116	-5.644	-8.410
2015	2015-01-02	2015-04-10	98	72.910	105	-4.560	-6.169
2016	2016-01-17	2016-03-05	48	26.735	68	0.599	-1.320
2017	2017-01-06	2017-03-21	74	18.180	71	0.433	-1.894
2018	2017-12-28	2018-03-21	83	51.304	98	-2.660	-4.501

Table 4. Environmental parameters in Lake Huron.

Year	Freezeup (date)	Breakup (date)	Duration (days)	AMIC (%)	FDD (days)	WSI (°C)	WSI_GLERL (°C)
1973	1972-12-20	1973-03-21	91	68.242	97	-3.478	-5.222
1974	1974-01-10	1974-04-18	98	63.407	109	-3.837	-6.100
1975	1975-01-16	1975-04-24	98	57.277	119	-2.031	-3.715
1976	1975-12-23	1976-04-13	112	54.616	103	-2.825	-5.722
1977	1976-12-16	1977-04-27	132	95.031	120	-7.201	-9.397
1978	1977-12-21	1978-04-26	126	95.778	122	-5.208	-8.000
1979	1978-12-27	1979-04-23	117	96.409	120	-5.763	-8.563
1980	1980-01-02	1980-04-16	105	72.814	107	-3.317	-5.417
1981	1980-12-24	1981-04-08	105	95.326	103	-5.042	-7.163
1982	1982-01-04	1982-05-05	121	93.427	112	-4.955	-7.568
1983	1983-01-18	1983-04-05	77	35.588	90	-1.567	-3.121
1984	1983-12-20	1984-04-19	121	78.552	107	-4.330	-6.645
1985	1985-01-05	1985-04-20	105	87.868	100	-3.834	-5.909
1986	1985-12-21	1986-04-12	112	74.139	114	-4.637	-6.982
1987	1987-01-24	1987-04-05	71	46.083	106	-2.771	-3.961
1988	1988-01-10	1988-04-10	91	61.772	101	-3.249	-5.333
1989	1988-12-30	1989-04-24	115	86.376	100	-2.983	-5.251
1990	1989-12-15	1990-04-13	119	74.775	112	-4.554	-6.176
1991	1991-01-07	1991-04-01	84	40.358	88	-2.649	-4.909
1992	1992-01-13	1992-04-22	100	70.684	114	-3.230	-4.736
1993	1992-12-28	1993-04-19	112	78.903	110	-3.574	-5.381
1994	1993-12-27	1994-04-22	116	97.746	104	-6.381	-9.083
1995	1995-01-06	1995-03-31	84	44.828	83	-2.065	-4.217
1996	1995-12-11	1996-04-29	140	97.578	130	-5.694	-7.271
1997	1996-12-27	1997-04-29	123	65.242	112	-3.691	-5.000
1998	1998-01-02	1998-03-24	81	29.822	89	-0.993	-1.931
1999	1999-01-05	1999-04-02	87	36.451	82	-1.686	-3.760
2000	2000-01-14	2000-03-17	63	42.070	82	-1.819	-4.091
2001	2000-12-21	2001-04-12	112	46.453	117	-3.877	-6.118
2002	2002-02-04	2002-04-01	56	26.735	80	0.618	-1.350
2003	2003-01-06	2003-04-24	108	96.208	113	-4.629	-6.695
2004	2004-01-08	2004-04-12	95	64.913	98	-3.361	-5.772
2005	2004-12-23	2005-04-11	109	59.973	106	-3.246	-5.624
2006	2005-12-22	2006-04-03	102	33.387	99	-1.777	-3.647
2007	2007-01-18	2007-04-05	77	72.031	84	-1.935	-4.086
2008	2007-12-17	2008-04-16	121	60.504	113	-3.002	-4.715
2009	2008-12-18	2009-04-14	117	85.503	106	-4.352	-6.733
2010	2010-01-05	2010-03-18	72	38.972	90	-2.049	-4.631
2011	2010-12-16	2011-04-11	116	63.907	111	-3.787	-6.288
2012	2012-01-16	2012-03-08	52	23.370	64	-0.016	-1.855
2013	2013-01-18	2013-04-01	73	48.028	96	-1.855	-3.448
2014	2013-12-12	2014-05-06	145	96.431	123	-6.232	-8.851
2015	2014-12-20	2015-04-22	123	96.416	112	-5.613	-7.758
2016	2016-01-13	2016-03-15	62	48.144	75	0.382	-1.573
2017	2017-01-06	2017-03-31	84	35.549	77	0.038	-2.136
2018	2017-12-16	2018-04-04	109	81.452	109	-3.480	-5.438

Table 5. Environmental parameters in Lake Erie.

Year	Freezeup (date)	Breakup (date)	Duration (days)	AMIC (%)	FDD (days)	WSI (°C)	WSI_GLERL (°C)
1973	1973-01-09	1973-03-06	56	95.590	60	-0.398	-1.777
1974	1974-01-10	1974-03-14	63	88.219	71	-0.375	-2.453
1975	1975-01-23	1975-03-13	49	80.444	83	0.537	-1.108
1976	1975-12-23	1976-03-16	84	95.369	68	0.348	-2.295
1977	1976-12-16	1977-04-06	111	99.595	97	-4.810	-6.803
1978	1977-12-21	1978-04-19	119	100.000	96	-3.261	-6.420
1979	1978-12-27	1979-04-02	96	99.958	82	-2.583	-5.223
1980	1980-01-02	1980-04-09	98	93.828	82	-0.545	-2.649
1981	1980-12-24	1981-04-08	105	95.938	83	-1.909	-3.809
1982	1982-01-11	1982-04-13	92	98.920	89	-2.172	-4.550
1983	1983-01-18	1983-02-23	36	43.605	48	2.188	0.695
1984	1983-12-27	1984-04-19	114	95.720	78	-1.266	-3.692
1985	1985-01-05	1985-04-06	91	95.990	67	-0.543	-2.494
1986	1985-12-21	1986-04-05	105	95.416	75	-0.849	-3.502
1987	1987-01-24	1987-03-07	42	87.932	70	-0.063	-1.500
1988	1988-01-03	1988-04-10	98	91.562	68	0.210	-1.972
1989	1989-01-08	1989-03-24	75	95.000	69	0.408	-1.588
1990	1989-12-15	1990-03-19	94	85.541	74	-0.522	-2.118
1991	1991-01-11	1991-03-06	54	44.589	57	1.189	-0.737
1992	1992-01-20	1992-03-20	60	91.216	67	0.444	-0.751
1993	1993-01-20	1993-04-05	75	94.762	75	-0.178	-1.932
1994	1994-01-03	1994-04-15	102	98.811	79	-2.353	-4.742
1995	1995-01-06	1995-03-22	75	95.688	58	1.063	-1.227
1996	1995-12-11	1996-04-17	128	99.000	92	-2.135	-3.751
1997	1996-12-27	1997-03-25	88	98.613	70	-0.289	-1.161
1998	NA	NA	NA	5.445	50	1.742	1.060
1999	1999-01-05	1999-03-19	73	74.672	56	1.642	-0.139
2000	2000-01-04	2000-03-03	59	90.920	60	1.214	-0.867
2001	2000-12-21	2001-04-12	112	93.915	86	-0.996	-2.980
2002	2002-01-03	2002-01-21	18	14.583	44	3.398	1.447
2003	2002-12-30	2003-04-03	94	95.717	89	-1.873	-4.091
2004	2004-01-08	2004-04-01	84	95.409	71	-0.061	-2.532
2005	2004-12-27	2005-03-31	94	92.960	71	0.257	-1.934
2006	2005-12-12	2006-03-09	87	24.603	65	1.487	-0.328
2007	2007-01-29	2007-04-02	63	95.762	61	0.962	-1.015
2008	2008-01-21	2008-04-03	73	93.332	71	0.301	-1.327
2009	2008-12-22	2009-03-26	94	95.549	80	-1.091	-3.050
2010	2009-12-31	2010-03-18	77	93.138	74	0.001	-2.643
2011	2010-12-16	2011-04-03	108	95.835	91	-1.333	-3.723
2012	2012-01-21	2012-02-15	25	13.978	32	3.020	1.200
2013	2013-01-22	2013-03-12	49	83.747	67	0.966	-0.251
2014	2013-12-12	2014-04-22	131	96.456	91	-2.346	-4.561
2015	2015-01-02	2015-04-18	106	98.150	85	-2.271	-4.247
2016	2016-01-18	2016-03-06	48	78.749	40	3.412	1.608
2017	2016-12-17	2017-02-08	53	35.570	43	3.016	1.093
2018	2017-12-27	2018-03-31	94	95.125	74	0.078	-1.852

Table 6. Environmental parameters in Lake Ontario.

Year	Freezeup (date)	Breakup (date)	Duration (days)	AMIC (%)	FDD (days)	WSI (°C)	WSI_GLERL (°C)
1973	1973-01-09	1973-03-06	56	64.828	83	-2.518	-3.995
1974	1974-01-10	1974-03-14	63	29.391	89	-2.294	-4.541
1975	1975-02-06	1975-02-13	7	16.573	96	-0.780	-2.245
1976	1976-01-27	1976-02-17	21	20.801	84	-1.601	-4.552
1977	1976-12-30	1977-04-13	104	49.672	104	-5.313	-7.440
1978	1977-12-28	1978-04-05	98	60.072	106	-3.839	-6.854
1979	1979-01-15	1979-03-26	70	86.498	90	-3.777	-6.293
1980	1980-01-30	1980-03-26	56	36.303	88	-1.757	-4.119
1981	1981-01-07	1981-03-04	56	51.091	90	-3.730	-5.813
1982	1982-01-18	1982-04-06	78	54.014	103	-3.454	-5.866
1983	1983-01-25	1983-02-23	29	17.364	61	0.161	-1.522
1984	1984-01-03	1984-03-29	86	44.642	93	-2.535	-4.667
1985	1985-01-05	1985-03-23	77	42.285	82	-1.989	-3.926
1986	1986-01-04	1986-03-22	77	47.059	98	-2.758	-5.069
1987	1987-02-14	1987-02-21	7	13.895	83	-1.986	-3.491
1988	1988-01-10	1988-03-27	77	25.830	87	-1.364	-3.199
1989	1989-02-05	1989-03-24	47	22.959	85	-1.154	-3.319
1990	1989-12-27	1990-03-14	77	36.122	92	-2.564	-4.414
1991	1991-01-14	1991-03-01	46	16.660	71	-0.427	-2.289
1992	1992-01-29	1992-03-27	58	22.313	91	-1.599	-3.256
1993	1993-02-10	1993-03-24	42	27.931	98	-2.305	-4.250
1994	1994-01-10	1994-04-06	86	79.930	89	-4.338	-6.945
1995	1995-02-08	1995-03-08	28	22.839	73	-0.393	-2.624
1996	1996-01-12	1996-03-20	68	46.103	102	-3.661	-5.333
1997	1997-01-21	1997-03-11	49	26.973	95	-1.629	-2.546
1998	NA	NA	NA	7.308	74	-0.264	-1.226
1999	1999-01-05	1999-03-09	63	19.329	69	-0.288	-2.042
2000	2000-01-21	2000-02-18	28	23.734	71	-0.638	-2.977
2001	2001-01-08	2001-03-12	63	19.484	98	-2.653	-4.685
2002	NA	NA	NA	5.095	61	1.907	0.079
2003	2003-01-23	2003-03-27	63	50.654	103	-3.647	-6.015
2004	2004-01-15	2004-03-11	56	39.688	88	-2.497	-5.013
2005	2005-01-20	2005-03-21	60	40.521	85	-2.222	-4.552
2006	2006-02-27	2006-03-02	3	16.384	76	-0.314	-2.256
2007	2007-02-01	2007-03-12	39	26.478	72	-0.483	-2.678
2008	2008-02-11	2008-03-17	35	17.173	97	-1.459	-2.948
2009	2009-01-12	2009-03-05	52	29.199	94	-2.943	-5.027
2010	2010-02-04	2010-02-15	11	16.427	69	-1.178	-3.587
2011	2011-01-18	2011-03-08	49	32.287	94	-2.706	-5.062
2012	NA	NA	NA	3.389	53	1.372	-0.518
2013	2013-02-09	2013-03-03	22	17.067	68	-0.606	-1.979
2014	2014-01-03	2014-04-08	95	61.613	101	-3.826	-5.970
2015	2015-01-02	2015-04-09	97	82.709	101	-3.983	-6.407
2016	2016-02-14	2016-03-06	21	24.609	62	1.539	-0.290
2017	NA	NA	NA	6.799	62	1.132	-0.613
2018	2017-12-29	2018-02-23	56	25.934	83	-1.532	-3.414

Table 7. Environmental parameters in Lake St. Clair.

Year	Freezeup (date)	Breakup (date)	Duration (days)	AMIC (%)	FDD (days)	WSI (°C)	WSI_GLERL (°C)
1973	1972-12-20	1973-03-06	76	99.391	57	-0.165	-1.571
1974	1973-12-31	1974-03-28	87	100.000	66	-0.548	-2.574
1975	1975-01-16	1975-04-10	84	100.000	77	0.728	-0.915
1976	1975-12-23	1976-03-02	70	98.494	66	0.815	-1.853
1977	1976-12-16	1977-03-16	90	100.000	92	-4.244	-6.169
1978	1977-12-21	1978-04-12	112	100.000	97	-2.687	-5.521
1979	1978-12-18	1979-03-19	91	99.840	85	-2.740	-5.328
1980	1980-01-02	1980-03-26	84	98.526	75	-0.457	-2.240
1981	1980-12-24	1981-03-11	77	100.000	82	-1.785	-3.636
1982	1981-12-21	1982-04-13	113	100.000	87	-1.994	-4.525
1983	1983-01-03	1983-03-23	79	97.179	50	1.831	0.493
1984	1983-12-20	1984-04-26	128	100.000	80	-1.343	-3.622
1985	1984-12-28	1985-03-23	85	99.968	74	-0.918	-2.782
1986	1985-12-14	1986-03-22	98	99.744	79	-1.350	-3.823
1987	1987-01-17	1987-03-21	63	97.564	61	0.095	-1.165
1988	1988-01-03	1988-03-20	77	100.000	72	-0.203	-2.385
1989	1988-12-14	1989-03-24	100	95.000	66	0.353	-1.480
1990	1989-12-13	1990-03-21	98	96.128	78	-0.649	-2.264
1991	1990-12-28	1991-03-18	80	95.000	59	0.707	-1.270
1992	1991-12-20	1992-04-03	105	95.000	65	0.283	-0.829
1993	1992-12-28	1993-04-05	98	96.359	71	-0.034	-1.564
1994	1993-12-27	1994-04-08	102	99.000	78	-2.414	-4.679
1995	1995-01-06	1995-03-20	73	99.000	66	0.948	-1.225
1996	1995-12-11	1996-03-22	102	99.000	93	-1.863	-3.220
1997	1996-12-20	1997-03-07	77	99.000	71	-0.547	-1.532
1998	1998-01-02	1998-02-06	35	94.551	41	2.060	1.380
1999	1998-12-29	1999-03-19	80	99.000	54	1.468	-0.394
2000	1999-12-28	2000-03-03	66	98.147	56	1.073	-1.121
2001	2000-12-11	2001-03-15	94	99.000	90	-1.544	-3.619
2002	2001-12-31	2002-03-25	84	92.532	47	2.925	1.003
2003	2002-12-05	2003-03-27	112	100.000	95	-2.313	-4.386
2004	2003-12-15	2004-03-08	84	100.000	78	-0.680	-3.056
2005	2004-12-20	2005-03-31	101	99.872	75	-0.898	-3.205
2006	2005-12-12	2006-03-09	87	95.000	66	0.774	-1.062
2007	2007-01-18	2007-03-22	63	100.000	67	-0.031	-1.946
2008	2007-12-06	2008-04-01	117	100.000	90	-0.979	-2.644
2009	2008-12-08	2009-03-10	92	100.000	86	-2.337	-4.356
2010	2009-12-14	2010-03-25	101	100.000	81	-0.466	-2.938
2011	2010-12-09	2011-04-03	115	99.939	98	-2.270	-4.586
2012	2012-01-04	2012-02-22	49	94.154	44	2.048	0.377
2013	2012-12-27	2013-03-25	88	100.000	77	0.048	-1.209
2014	2013-11-29	2014-04-09	131	100.000	104	-3.757	-6.043
2015	2014-11-23	2015-04-04	132	100.000	94	-3.150	-4.969
2016	2016-01-05	2016-03-08	63	95.942	57	2.111	0.358
2017	2016-12-16	2017-03-23	97	92.618	57	1.839	-0.114
2018	2017-12-14	2018-03-02	78	100.000	79	-1.248	-3.103

Table 8. Environmental parameters in Great Lakes.

Year	Freezeup (date)	Breakup (date)	Duration (days)	AMIC (%)	FDD (days)	WSI (°C)	WSI_GLERL (°C)
1973	1972-12-20	1973-03-21	91	62.759	90	-2.574	-4.180
1974	1974-01-10	1974-04-18	98	61.457	98	-2.810	-5.012
1975	1975-01-16	1975-04-10	84	52.324	107	-1.265	-2.925
1976	1975-12-23	1976-03-30	98	42.328	93	-1.737	-4.409
1977	1976-12-16	1977-04-20	125	90.197	111	-6.287	-8.368
1978	1977-12-28	1978-04-19	112	83.832	111	-4.474	-7.313
1979	1978-12-27	1979-05-07	131	94.885	116	-4.953	-7.677
1980	1980-01-02	1980-04-09	98	66.987	92	-2.386	-4.386
1981	1980-12-24	1981-04-08	105	73.422	94	-3.565	-5.575
1982	1982-01-04	1982-04-26	112	76.753	106	-3.980	-6.595
1983	1983-01-18	1983-03-23	64	25.455	80	-0.359	-1.769
1984	1983-12-20	1984-04-19	121	67.106	96	-3.218	-5.547
1985	1984-12-28	1985-04-06	99	71.666	87	-2.940	-5.007
1986	1985-12-21	1986-04-05	105	77.868	104	-3.716	-5.991
1987	1987-01-24	1987-03-14	49	29.595	92	-1.699	-2.857
1988	1988-01-10	1988-04-03	84	56.153	90	-2.185	-4.370
1989	1989-01-01	1989-04-23	112	64.405	92	-1.966	-4.083
1990	1989-12-18	1990-03-30	102	59.872	98	-3.028	-4.616
1991	1991-01-07	1991-03-25	77	49.397	74	-1.389	-3.533
1992	1992-01-17	1992-04-06	80	50.921	98	-1.856	-3.077
1993	1993-01-13	1993-04-05	82	66.704	101	-2.466	-4.177
1994	1994-01-03	1994-04-18	105	90.914	91	-4.813	-7.278
1995	1995-01-30	1995-03-22	51	35.718	78	-0.916	-3.090
1996	1995-12-29	1996-04-26	119	82.306	118	-4.449	-5.980
1997	1997-01-14	1997-04-15	91	58.756	102	-2.789	-3.910
1998	1998-01-16	1998-02-13	28	14.506	76	-0.114	-0.868
1999	1999-01-05	1999-03-12	66	26.379	74	-0.665	-2.607
2000	2000-01-18	2000-02-29	42	35.090	71	-0.845	-3.124
2001	2000-12-25	2001-04-09	105	34.422	110	-3.231	-5.409
2002	2002-03-04	2002-03-25	21	12.373	68	1.390	-0.593
2003	2003-01-13	2003-04-14	91	80.222	105	-3.778	-5.853
2004	2004-01-08	2004-04-01	84	52.000	93	-2.442	-4.747
2005	2004-12-27	2005-03-31	94	45.215	92	-2.205	-4.528
2006	2006-02-09	2006-03-13	32	21.644	90	-0.774	-2.568
2007	2007-01-25	2007-03-29	63	56.398	79	-1.263	-3.345
2008	2008-01-21	2008-04-03	73	55.002	107	-2.392	-4.157
2009	2008-12-22	2009-04-07	106	74.631	99	-3.757	-6.026
2010	2010-01-05	2010-03-14	68	29.576	89	-1.699	-4.302
2011	2010-12-30	2011-04-03	94	40.455	102	-3.222	-5.634
2012	2012-01-20	2012-03-05	45	13.279	53	0.665	-1.083
2013	2013-01-22	2013-03-24	61	38.763	90	-1.365	-2.864
2014	2013-12-14	2014-05-10	147	92.562	115	-5.388	-7.925
2015	2015-01-02	2015-04-21	109	88.833	105	-4.742	-6.673
2016	2016-01-19	2016-03-06	47	34.174	71	0.776	-1.123
2017	2017-01-07	2017-03-20	72	19.614	70	0.521	-1.599
2018	2017-12-28	2018-04-11	104	69.172	102	-2.771	-4.692

Table 9. Atmospheric teleconnection indices.

Year	ENSO (°C)	NAO	AMO (°C)	PDO (°C)
1951	-0.70	-0.08	0.07	-1.12
1952	0.57	0.47	0.18	-1.38
1953	0.37	-0.20	0.27	-0.20
1954	0.70	0.21	0.20	-0.95
1955	-0.67	-0.76	0.02	-0.61
1956	-1.13	-0.39	0.18	-2.66
1957	-0.17	0.42	-0.05	-1.26
1958	1.73	-0.49	0.11	0.11
1959	0.60	-0.30	0.15	0.37
1960	-0.07	-0.91	0.17	0.29
1961	0.03	0.31	0.09	0.59
1962	-0.20	-0.11	0.17	-1.71
1963	-0.33	-1.47	0.17	-0.48
1964	1.00	-1.43	-0.04	-0.43
1965	-0.57	-0.61	-0.17	-1.31
1966	1.43	-0.59	-0.06	-0.26
1967	-0.40	0.01	0.08	-0.23
1968	-0.57	-0.54	-0.20	-0.58
1969	1.07	-1.26	-0.03	-1.16
1970	0.47	-0.38	-0.03	0.81
1971	-1.30	-0.70	-0.25	-1.54
1972	-0.67	0.40	-0.34	-1.90
1973	1.70	0.36	-0.37	-0.47
1974	-1.80	0.51	-0.27	-1.21
1975	-0.57	0.49	-0.32	-0.56
1976	-1.50	0.23	-0.38	-1.53
1977	0.70	-1.04	-0.38	1.33
1978	0.63	-0.85	-0.15	0.37
1979	0.03	-1.21	-0.17	-0.78
1980	0.57	0.10	-0.04	0.26
1981	-0.27	0.69	-0.20	0.65
1982	0.00	0.08	-0.05	0.40
1983	2.10	0.95	-0.25	0.65
1984	-0.63	0.89	-0.06	1.47

Year	ENSO (°C)	NAO	AMO (°C)	PDO (°C)
1985	-0.97	-0.70	-0.33	1.01
1986	-0.47	0.11	-0.31	1.04
1987	1.20	-0.30	-0.28	1.80
1988	0.80	0.70	-0.03	1.15
1989	-1.63	1.26	-0.18	-0.80
1990	0.07	0.43	-0.20	-0.39
1991	0.37	0.71	-0.11	-1.81
1992	1.60	0.47	-0.16	0.15
1993	0.10	0.86	-0.24	0.26
1994	0.10	1.02	-0.30	0.96
1995	0.93	1.36	-0.06	-0.61
1996	-0.90	-0.62	0.00	0.50
1997	-0.47	-0.07	-0.09	0.16
1998	2.17	-0.23	0.18	1.02
1999	-1.47	0.64	0.13	-0.47
2000	-1.60	1.30	-0.04	-1.49
2001	-0.63	0.04	-0.09	0.47
2002	-0.13	0.24	0.19	-0.43
2003	0.87	-0.05	0.01	1.98
2004	0.37	0.07	0.21	0.41
2005	0.63	0.89	0.14	0.36
2006	-0.77	0.11	0.14	0.63
2007	0.63	0.36	0.19	0.06
2008	-1.53	0.65	0.09	-0.78
2009	-0.73	-0.08	-0.07	-1.27
2010	1.47	-1.67	0.10	0.58
2011	-1.37	-0.68	0.15	-0.99
2012	-0.80	1.37	-0.03	-1.34
2013	-0.30	0.02	0.13	-0.35
2014	-0.37	0.86	-0.02	0.09
2015	0.63	1.66	0.02	2.42
2016	2.43	1.31	0.21	1.43
2017	-0.33	0.65	0.26	0.88
2018	-0.90	1.30	0.20	0.52