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Effects of Air Temperature and Lake Ice on Snowfall on the South Shore of Lake Superior

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Abstract

Lake Superior is a forcing factor for local weather systems, causing substantial amounts of lake effect snow in the winter (particularly on the south shore). This study assesses decreasing ice cover of Lake Superior and its effects upon synoptic weather factors. Data were collected from eleven National Weather Service (NWS) stations located on the south shore of the lake. Rainfall and snowfall amounts from December to May were regressed on percent ice coverage and average monthly temperatures from 1972-2002. Ice coverage and average monthly temperature had a negative relationship with snowfall and rainfall.

Keywords: Lake Superior, lake-effect snow, lake-effect rain events, Great Lakes ice cover

Introduction

Lake Superior is the largest of the Great Lakes and has a profound impact on the surrounding land. It influences economic sustainability for the fishing and tourism industries as well as influencing local weather systems, causing substantial amounts of lake effect snow in the winter (especially on the south shore). The focus of this study is to assess how the current trend of the warming of Lake Superior and the corresponding reduction in ice coverage affects synoptic weather factors by examining the relationship between percent ice coverage and average monthly temperatures and monthly snowfall and rainfall totals.

Approximately 1,000 ma ago, during the Proterozoic Era, a rift valley formed in central North America, extending from Oklahoma to the current location of Lake Superior (Minnesota Sea Grant, 2006). For ~22 ma succeeding this event, magma flowed from various Laurentian volcanoes around the current shoreline, causing the crust to sink, forming the Lake's basin. Offsetting this consistent flow of magma were periods of glacial activity, which further formed the basin, abrading the landscape during periods of recession. The most recent ice sheet to recede was the Wisconsin Ice Sheet, (~12.5 ka); the melt water from this phenomenon is responsible for filling the basin currently containing Lake Superior (Figure 1) (Minnesota Sea Grant, 2006). The southern shoreline of the Lake serves as evidence of the retreating glaciers and lava flow; visible are remnants of the sedimentary cliffs unscathed by the retreating glaciers. These cliffs overlook the lake, some as high as 200 ft (60 m) (National Park Service, 2002).

Figure 1: Map of Lake Superior

The local Chippewa Indian tribe called the Lake Kitchie-Gummi, meaning *Great Water*. Lake Superior is the second largest lake in the world (by surface area), fourth largest overall holding 2,935 cubic miles (12,232 cubic km) of water, covering 31,700 square miles (82,097 square km), and forming a shoreline that extends 2730 miles (4393 km) (Great Lakes Environmental Research Laboratory, GLERL, 2004) (Figure 1). The water in the lake (as of 2006) averages 40°F (4.4°C), reaching its peak in August at 64°F (18°C) (University of Missouri, Kansas-City, 2008). August is the only month of the year which swimming and other various forms of water sports can be enjoyed without the imminent dangers cold water can have on the human body, though long-term exposure even at this time of the year still produces a risk of hypothermia (Dawson, 1987). The lake is also characterized by its clear water, which is due mainly to the inability of certain types of algae to thrive, a direct consequence of the water temperatures (Great Lakes Information Network, 2008).

Lake Dynamics and Warming Trends

There has been recent concern over the warming of Lake Superior, and the related economic and ecological effects. This trend extends back to the early 1900s (U.S. Army Corps of Engineers, USACE, 2006), though most of these studies focus on the last 30-40 years, for which more reliable data are available. This warming is hypothesized by researchers to be an effect of global climate change, evident in an earlier start to the summer stratification season, which allows the lake surface to accumulate much more heat from shortwave radiation, causing a positive ice-albedo feedback (as the radiation warms the water, there is a decrease in ice coverage) in the winter months (Austin and Coleman, 2006). Stratification is a vital part of the lake's dynamics; in the winter and spring months the water is isothermic, but as the top warms in the late spring and summer months, the water column separates into layers. The turnover occurs in the fall, when solar insolation is decreased due to seasonal change causing the surface waters to decrease in temperature, therefore diminishing the density difference between layers. Stronger winds essentially mix the lake at substantial depths until the bottom waters reach the same density as the surface waters. Lake turnover is the driving factor for the redistribution of oxygen and nutrients (GLERL, 2008). According to the Minnesota Sea Grant, Lake Superior turnover has recently been occurring in early December, later than in previous years.

Lake ice is a direct indicator of climate change (Assel, 2005), and it is evident that surface temperatures around Lake Superior are indeed increasing. Jay Austin and Steven Coleman (2007) conducted the first conclusive study of this warming phenomenon and the

role of ice as a determining factor of surface air temperature, wind speed, and shortwave absorption. Austin and Coleman acquired data from 3 open water buoys in Lake Superior, maintained by the National Oceanographic and Atmospheric Administration (NOAA). The authors established evidence of lake warming from 1979-2006, averaging 0.198ºF/yr (0.11ºC/yr), which was correlated with higher than average wind speeds at the buoy sites. The increased wind speeds directly affect the mixed layer depth (causing it to extend much deeper) and therefore the timing of stratification, which again, has been turning over in early December, later than in previous years. They implied that the amount of heat being absorbed by the lake is greater than the amount being released (Austin and Coleman, 2007).

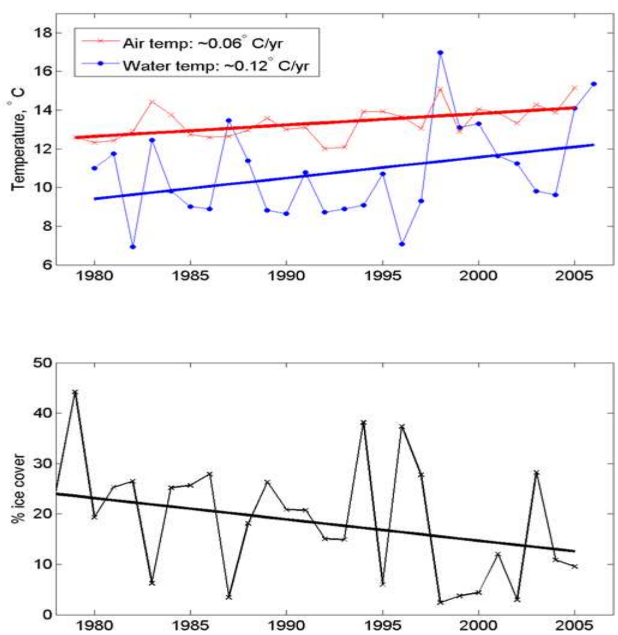
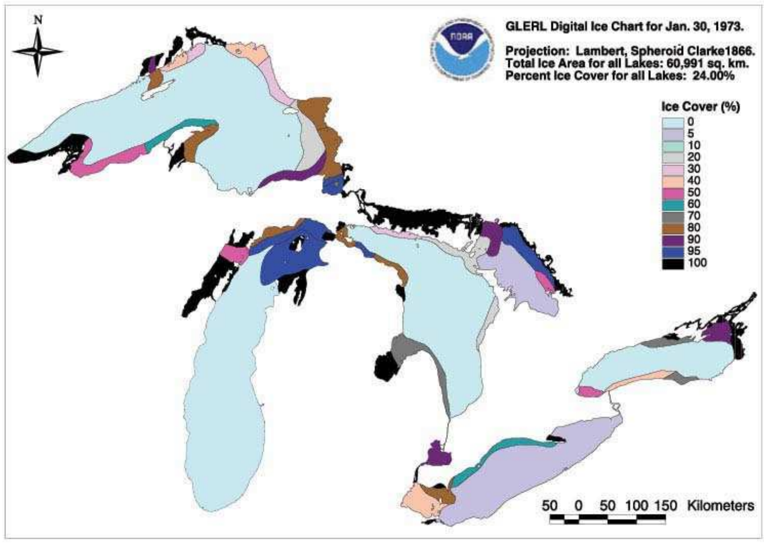
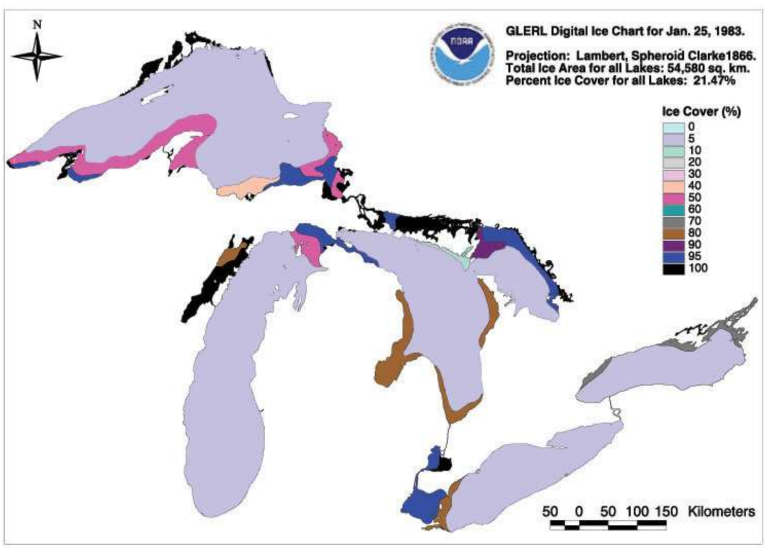


Figure 2: (a: top) Air temperature and water temperature records from 1978- 2006.
(b: bottom) Percent ice coverage
Source: Austin and Coleman, 2007.

The cause of Lake Superior's decreased ice formation is uncertain, but is attributed to rising regional temperatures (Crowley, 2006) (Figure 2 a & b). Assel (2005) studied ice

cover of all of the Great Lakes (from 1972-2002) through remote sensing techniques and found that ice cover decreased from an average of 44% in 1979 to 1.4% in 2002. This was coupled with a decrease in the span of days in which there was continuous ice coverage (136 days in 1979 to 59 days in 2002, with mild variability in between) (Figure 3). This diminishing ice coverage adversely affects evaporation of lake water due to the ability of wind to penetrate more surface area of the lake throughout the year. The lake level has consistently shown a downward trend since 1978 of ~0.39 in. (10mm) per year, raising concerns that snowfall has abated, possibly prohibiting the amount of run-off, therefore affecting the water budget (NOAA, 2007). A recognized potential outcome of reduced ice coverage and warming of the lake surface is the rise in lake-effect snowfall rates on the southern shore of the lake, specifically to the Upper Peninsula of Michigan and northern Wisconsin. There areas currently receive large amounts of lake-effect snow, on average 98-138 inches (249-350 cm) per year. The increase in lake temperature and lack of ice coverage in the winter causes greater evaporation by winds, and therefore could produce extreme lake-effect snowfall rates (Lofgren, 2004).





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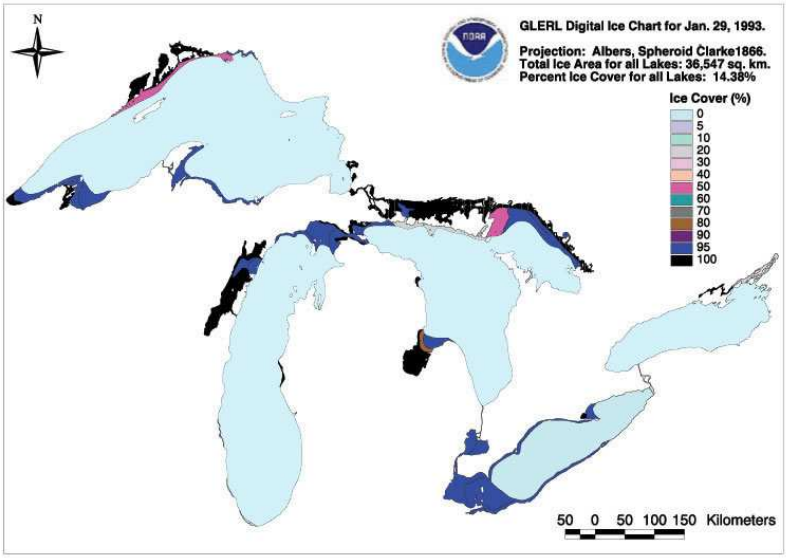

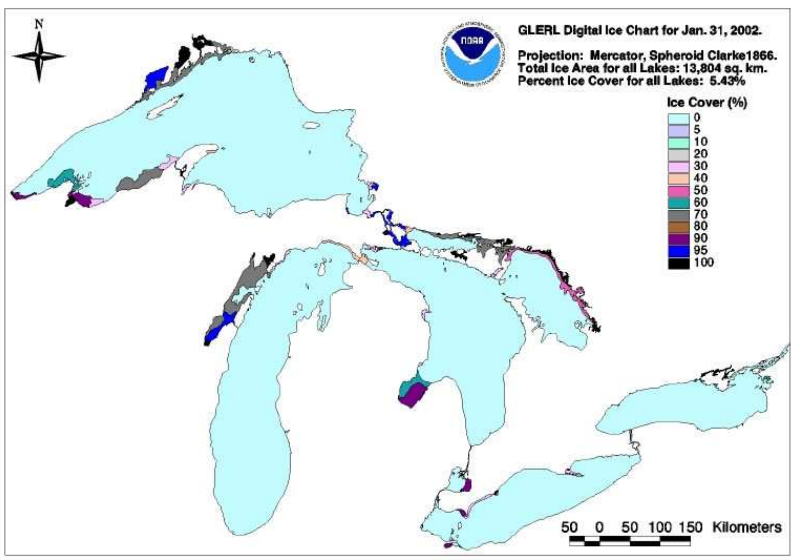

Figure 3: Percent ice cover for January 30, 1973; percent ice cover for January 25, 1983 ; percent ice cover for January 29, 1993; percent ice cover for January 31, 2002
Source: GLERL Ice Atlas

Physical Characteristics of Lake Effect Snow

Lake effect snow (LES) is a common occurrence along the southern shore of Lake Superior during the winter months. Cold Arctic air masses pass over the lake and rapidly warm and gain moisture, though their temperatures remain cooler than lake temperatures (Kunkel *et al*. 2003). This cooler air above the warmer lake waters causes the air to become unstable and as the air lifts vertically, it tends to cool and condense, forming clouds that, if they rise high enough, can eventually produce LES. The winds in this region during the winter months are predominantly from the north and therefore the LES advects onto the shore, affecting areas as far as 20 miles inland (NOAA, 2007). LES events are also characterized by the intensity of the wind shear near the surface of the lake, defining the convective boundary layer (CBL). A more intense shear at the CBL is associated with higher snowfall accumulations and can control the location of the snowfall (Kristovich *et al.* 2003) which is typically on the leeward side of a lake, or as in the case of Lake Superior, the south shore and leeward shore of Canada (Ahrens, 2007). Lake Superior's warming trends could strengthen the temperature gradient between the open water and the passing cold air masses.

Methodology

Eleven stations were chosen due to their proximity to Lake Superior's south shore, including stations in the Upper Peninsula of Michigan, northern Wisconsin, and one additional point at Duluth, Minnesota (Figure 4). Data were used from December-May each winter season, from 1972-2002.

Figure 4: Locations of National Weather Service stations.

Percent Ice Coverage Data

Daily percent ice coverage data for Lake Superior were downloaded from the Great Lakes Environmental Research Laboratory (GLERL) (2007) for the same months as the weather station data. Daily ice cover percentages were created from a combination of composite ice charts, ships, satellite, shore, and air craft observations (GLERL, NOAA Great Lakes Ice Atlas, 2007).

NOAA National Climatic Data Center Data

The National Climatic Data Center (NCDC) collects data for National Weather Service stations located throughout the United States. Observations of minimum daily temperature, maximum daily temperature, rainfall (including snow melt), and snowfall (including hail and ice) are recorded on a daily basis for each station.

For any month in which data were absent for any date for any category (snow, temp, etc.), such gaps were filled using data from the nearest other site and added/averaged into the total for that month from the next nearest station's measurement for that date. There are some exceptions for accounting for missing data:

- Some dates have missing rain and/or snowfall data included an "accumulation since last measurement" notation in the margin (A). These totals were used when there were two or fewer days of missing data. Otherwise, the measurements for those dates are taken from the nearest station. Some rain and snowfall totals were added in the subsequent measurement. As long as this is noted by the recorder (an "S" in the margin) this was deemed as a legitimate measurement.
- Missing temperature data were figured into that station's monthly average from the next nearest station.
- If an entire month of data was missing, the next nearest stations' data were used as a substitute.
- If a category of data was missing, the next nearest stations' data were used as a substitute.

- In the case of Ashland, WI, the measurements were missing or incomplete from 1994-1998 and again from 2000 until the 2002. This station was discarded.

Results

The data sets were analyzed in the Statistical Analysis Software (SAS) package, version 9.1 (2003). Total monthly snow, rain, and snow/rain ratio amounts were regressed on average monthly temperature and percent ice cover for each individual station. Additionally, total precipitation amounts were regressed on average temperature and percent ice cover for all stations per month.

Snowfall Analysis

Snowfall was regressed on average monthly temperatures and monthly percent ice cover. All station locations had a $p<0.0001$ for both temperature and ice (Table 1), except for Duluth, which reported a $p=0.26$ for percent ice coverage. This could be attributed to the geographic location of Duluth's weather station, which is not downwind of Lake Superior, but situated approximately 6.37 miles to the west of the shoreline. Duluth also received the least amount of snowfall during the 30-year study period (Figure 5).

For these stations, the average air temperature parameter estimate was -1.162. For every 1°F increase in temperature, snowfall across the region would *decrease* on an average of 1.162 inches. For a hypothetical 4.5°F increase in temperature, 5.229 *less* inches of snowfall could be expected. Alternately, for a 25% decrease in ice cover, snowfall across the region would *increase* by 5.465 inches (average parameter estimate for ice cover is -0.2186).

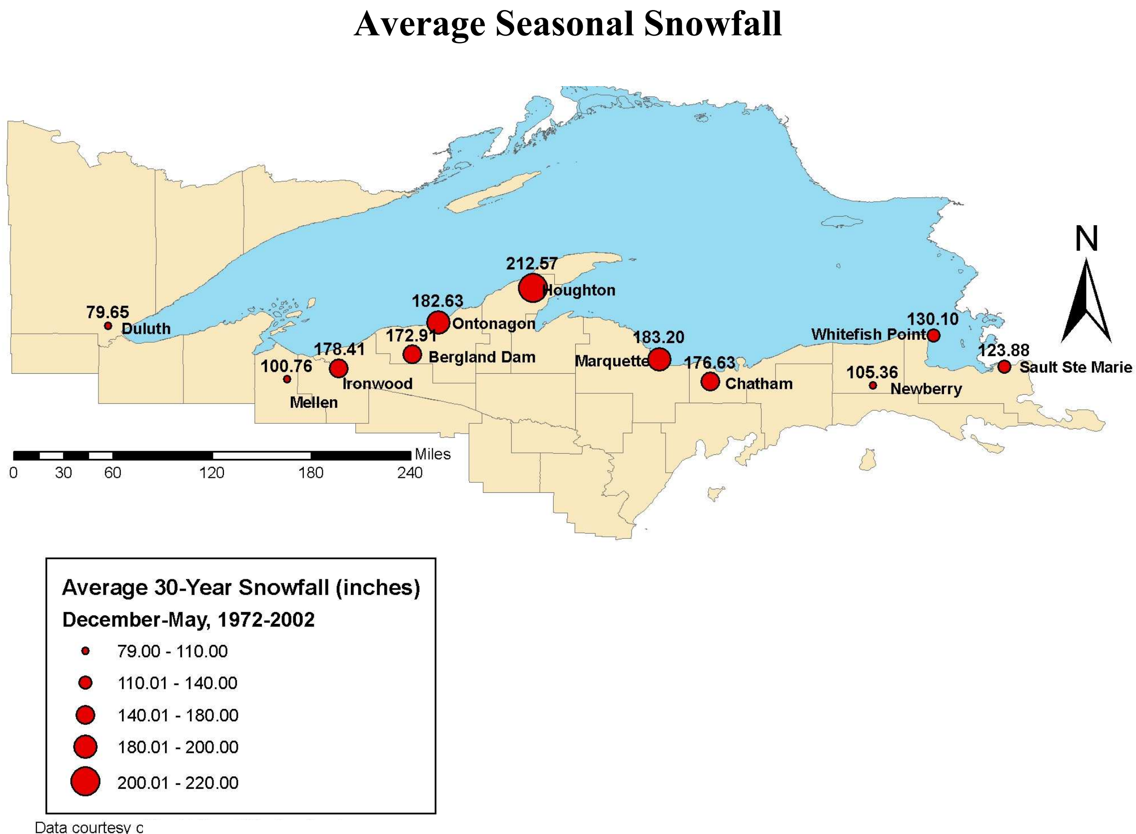

Figure 5: Average seasonal snowfall.

The R^2 values for each station were slightly varied, with Ontonagon yielding the highest value of 0.7075 and Duluth with the lowest value, 0.4467. This is explained by the proximity of the Ontonagon station to the lakeshore (0.76 miles inland) and the fact that the location is directly downwind of the lake. Bergland, Chatham, Houghton, Ironwood, and Whitefish were similar in these values (R^2=0.6133, R^2=0.6152, R^2=0.6595, R^2=0.6241, and R^2=0.6314, respectively) which is consistent with their near-shore locations. Sault Ste. Marie and Duluth are at the western and eastern extremities of the study area. While Duluth's station is west of the shoreline, Sault Ste. Marie (R^2=0.5517) is at the east end of Whitefish Bay, which feeds the St. Mary's River, and therefore may lose lake effect conditions as the air masses pass over the surrounding land. Marquette, Mellen, and Newberry yielded the lowest R^2 values (R^2=0.4768,

R^2=0.4569, and R^2=0.4856, respectively). Mellen and Newberry are the two stations that are furthest inland (15.41 and 24.13 miles south of the shore, respectively). This could explain why their values are lower as lake effects are stronger near shore. Marquette, which is situated on the shoreline, is geographically located in a bay setting and therefore may be more susceptible to rising air temperatures than LES as the cold air masses are susceptible to both water and land influences, the latter prohibiting the formation of LES.

Dependent Variable: SNOW					
		Temperature		Ice Cover	
Station	R^2	Parameter Estimate	*p*	Parameter Estimate	*P*
Bergland	0.6133	-1.1179	*<0.0001*	-0.2251	*<0.0001*
Chatham	0.6152	-1.4992	*<0.0001*	-0.2474	*<0.0001*
Duluth	0.4467	-0.3969	*<0.0001*	-0.0256	0.2552
Houghton	0.6595	-2.0074	*<0.0001*	-0.4151	*<0.0001*
Ironwood	0.6241	-1.1144	*<0.0001*	-0.2578	*<0.0001*
Marquette	0.4768	-1.1600	*<0.0001*	-0.1644	*0.0024*
Mellen	0.4569	-0.5671	*<0.0001*	-0.0840	*0.0082*
Newberry	0.4856	-0.8362	*<0.0001*	-0.0947	*0.0103*
Ontonagon	0.7075	-1.6427	*<0.0001*	-0.4217	*<0.0001*
Sault Ste. Marie	0.5517	-0.9582	*<0.0001*	-0.1850	*<0.0001*
Whitefish	0.6314	-1.4840	*<0.0001*	-0.2844	*<0.0001*

Table 1. Results of regression of snowfall on surface air temperature and lake ice coverage.

Rainfall Analysis

Seasonal rainfall was regressed on average monthly temperature and percent ice cover (Table 2). The parameter estimates for ice coverage are all negative, so as ice cover increases, rainfall decreases. Of these, the stations with significant *p*-values were Bergland, Ontonagon, and Whitefish, suggesting that the proximity of these shoreline stations to open water could affect the conditions conducive to winter rain events (Figure 6). Houghton, Ontonagon, and Whitefish were found to have a negative parameter estimate against average monthly temperature, while

the other stations remained positive, though Ontonagon was non-significant (p=0.2965). Six of the stations had significant p-values: Chatham, Duluth, Houghton, Ironwood, Mellen, and Whitefish.

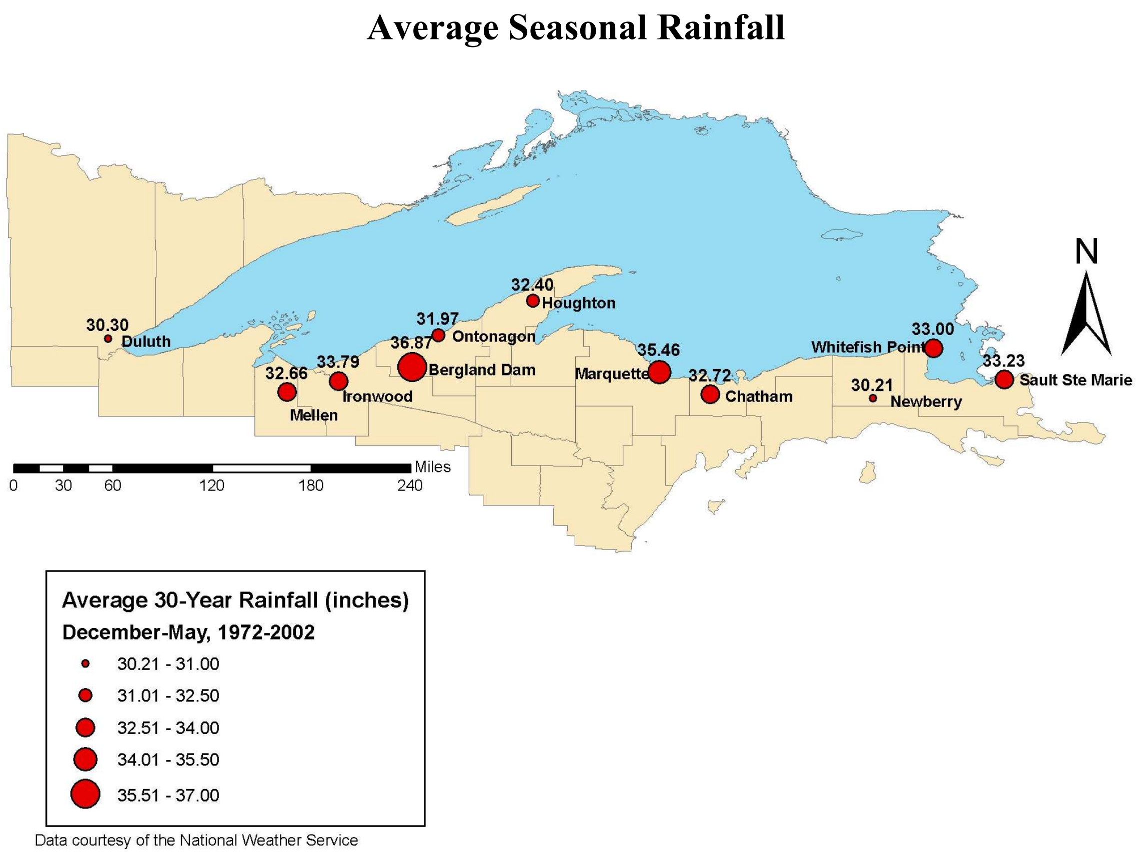

Figure 6: Average seasonal rainfall.

The R^2 values for eight of the eleven stations were below 0.10, and all were below 0.32. These values suggest that surface air temperature and ice cover have relatively minor influence on rainfall events. The average parameter estimate across the region for temperature is 0.0069 and ice cover is -0.0079. A 4.5°F temperature increase would yield 0.031 *more* inches of rain and a 25% ice decrease would also yield 0.1975 *more* inches of rainfall.

Dependent Variable: RAIN					
		Temperature		Ice Cover	
Station	R^2	Parameter Estimate	*p*	Parameter Estimate	*p*
Bergland	0.0910	0.0029	0.6793	-0.0157	*0.0004*
Chatham	0.0467	0.0144	0.0505	-0.0047	0.2421
Duluth	0.3174	0.0461	*<0.0001*	-0.0010	0.7750
Houghton	0.0990	-0.0441	*<0.0001*	-0.0102	0.0705
Ironwood	0.1577	0.0184	*0.0007*	-0.0099	*0.0044*
Marquette	0.0277	0.0149	0.0865	-0.0030	0.5508
Mellen	0.2570	0.0354	*<0.0001*	-0.0037	0.2831
Newberry	0.0330	0.0139	0.0711	-0.0032	0.4505
Ontonagon	0.0653	-0.0072	0.2965	-0.0138	*0.0006*
Sault Ste. Marie	0.0281	0.0018	0.7692	-0.0075	0.0576
Whitefish	0.0602	-0.0200	*0.0291*	-0.0141	*0.0011*

Table 2. Results of regression of rainfall on surface air temperature and lake ice coverage.

Snowfall/Rainfall Ratio Analysis

The ratio of snowfall to rainfall (SR) was calculated and regressed on average monthly temperature and percent ice coverage to assess these effects on the form taken by precipitation (Figure 7). For all stations, the SR parameter estimate was negative for average monthly temperature and was significant at the p<0.0001 level. Thus, not surprisingly, a smaller proportion of the precipitation was snow when surface air temperatures were warm. The parameter estimates were negative for all stations except Bergland and Ironwood for percent ice coverage and all stations except Bergland, Chatham, Duluth, Newberry, and Mellen had p<0.05 (Table 3).

30-year SR Ratios

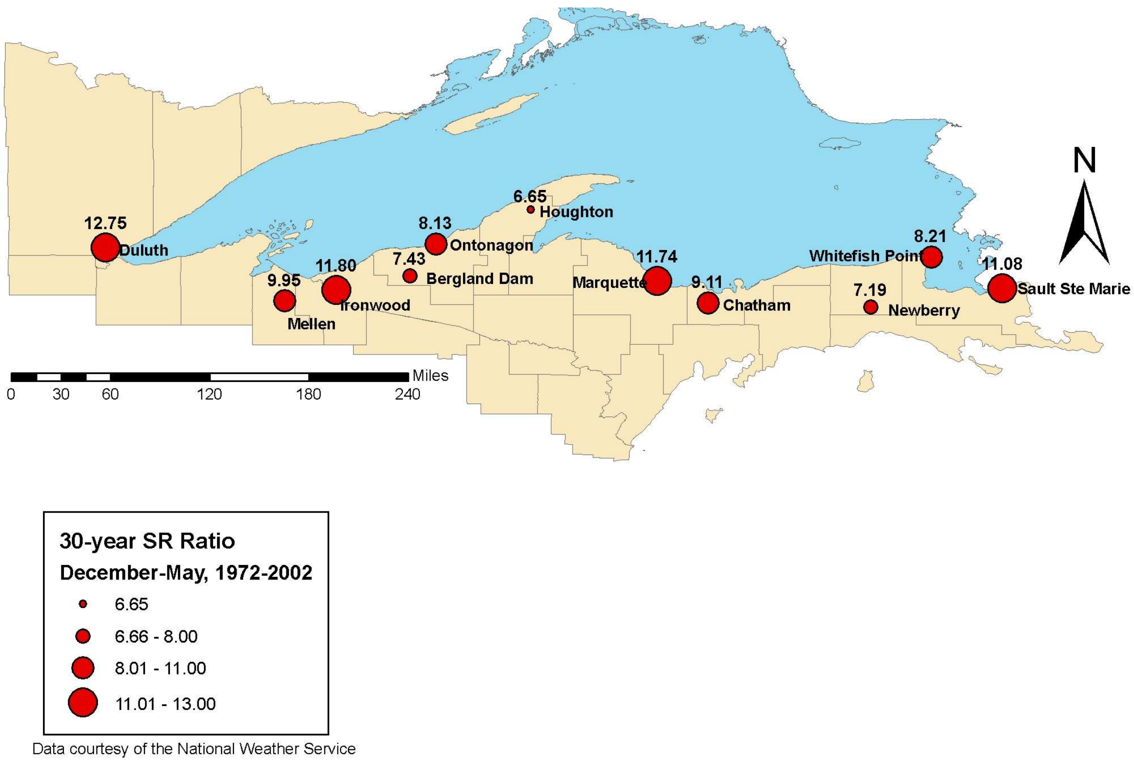

Figure 7: 30-year SR ratios.

Dependent Variable: SNOW/RAIN					
		Temperature		Ice Cover	
Station	R^2	Parameter Estimate	*p*	Parameter Estimate	*P*
Bergland	0.7629	-0.3923	*<0.0001*	0.0044	0.7012
Chatham	0.5163	-0.8269	*<0.0001*	-0.0631	0.0679
Duluth	0.4744	-0.4985	*<0.0001*	-0.0352	0.1872
Houghton	0.3849	-0.6372	*<0.0001*	-0.1409	*<0.0001*
Ironwood	0.1577	-0.6108	*<0.0001*	0.0420	*0.0328*
Marquette	0.7009	-0.5008	*<0.0001*	-0.0313	*0.0369*
Mellen	0.7098	-0.3995	*<0.0001*	-0.0243	0.0699
Newberry	0.3776	-0.4591	*<0.0001*	-0.0086	0.7449
Ontonagon	0.7089	-0.5738	*<0.0001*	-0.0732	*<0.0001*
Sault Ste. Marie	0.7649	-0.3934	*<0.0001*	-0.2534	*0.0106*
Whitefish	0.6575	-0.5357	*<0.0001*	-0.0460	*0.0017*

Table 3. Results of regression of SR ratio on surface air temperature and lake ice coverage.

R^2 values for this analysis were fairly high, stating that much of the variance in the form of precipitation can be attributed to average monthly temperature and percent ice coverage. The low R^2 values at some sites could be attributed to the influence of melt water in precipitation gauges, which the NWS combines with rainfall totals. This could partially explain the low R^2 at Duluth (R^2=0.4744), Sault Ste. Marie (R^2=0.3776), and Houghton (R^2=0.3849). All other stations had R^2 values which ranged from R^2=0.6745 to R^2=0.7873, suggesting that the ratio of snow to rain is predictable from temperature and ice cover. The average parameter estimates for temperature and ice coverage are -0.5289 and -0.0572, respectively, denoting that a 4.5°F temperature increase would yield decrease in the ratio from an average of 9.5:1 to 7:1 and a 25% decrease in ice cover would increase the ratio to 10:1

Snow Water Equivalent Analysis

The snow water equivalent (SWE) is the measure of the amount of water contained within the snowpack if it were to melt (Brodzik, 2004). The present study will invert this to

express all precipitation as inches of snowfall. First, the rainfall data were converted to snowfall amounts (the SWE) through multiplying the rainfall data (per station) by a constant factor of 10 (Dube, 2004) and then adding these results to the snowfall data. Although this method oversimplifies the snow/liquid water relationship, more complicated conversions were not feasible with the monthly values used in the study. These amounts were regressed on temperature and percent ice coverage to assess if total precipitation (in snowfall amounts) was dependent on percent ice coverage and/or average monthly temperatures (Figure 8).

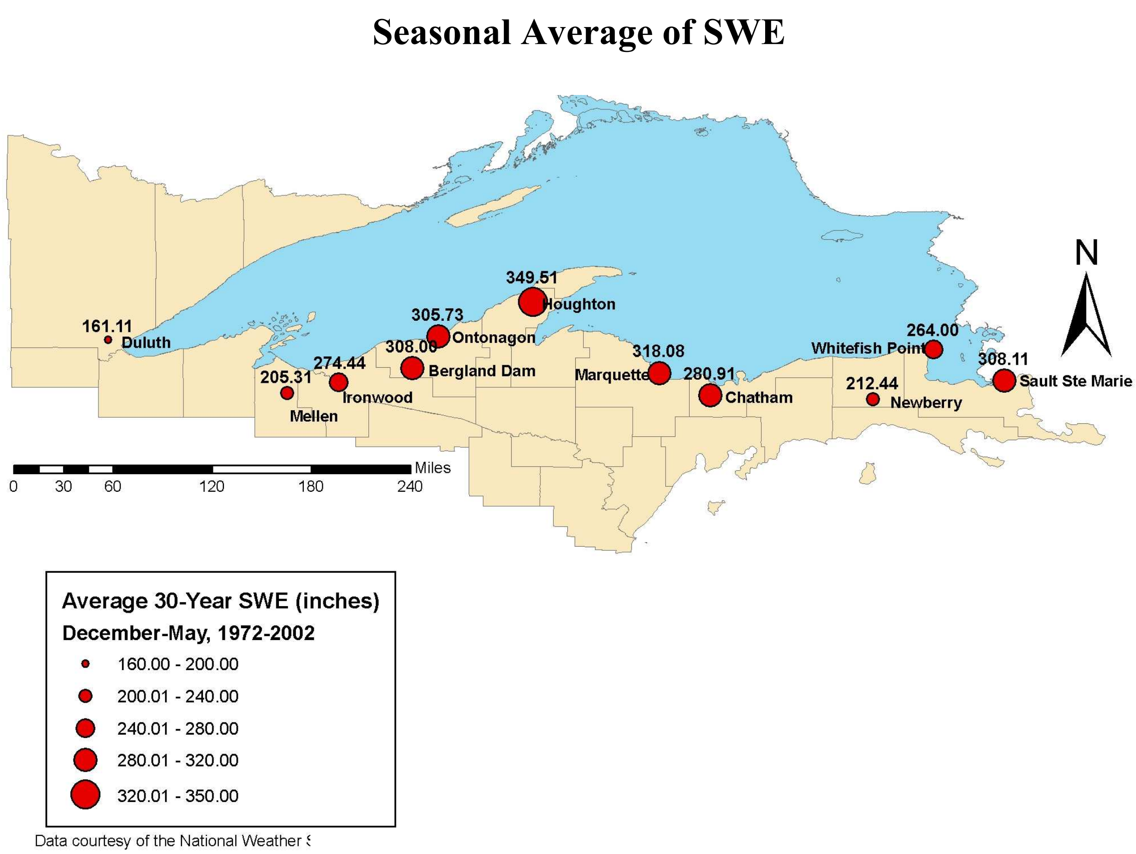

Figure 8: Seasonal average of SWE.

Dependent Variable: SWE					
		Temperature		Ice Cover	
Station	R^2	Parameter Estimate	*p*	Parameter Estimate	*p*
Bergland	0.3095	-1.0893	*<0.0001*	-0.3815	*<0.0001*
Chatham	0.3800	-1.3554	*<0.0001*	-0.2941	*<0.0001*
Duluth	0.0108	0.0640	0.3940	-0.0352	0.4645
Houghton	0.4817	-2.4487	*<0.0001*	-0.5168	*<0.0001*
Ironwood	0.1577	-0.9303	*<0.0001*	-0.3565	*<0.0001*
Marquette	0.1785	-1.0155	*<0.0001*	-0.1941	*0.0402*
Mellen	0.0402	-0.2133	*0.0147*	-0.1211	*0.0376*
Newberry	0.1533	-0.6973	*<0.0001*	-0.1265	0.0646
Ontonagon	0.4831	-1.7143	*<0.0001*	-0.5594	*<0.0001*
Sault Ste. Marie	0.2576	-0.9405	*<0.0001*	-0.2596	*0.0002*
Whitefish	0.3799	-1.6842	*<0.0001*	-0.4250	*<0.0001*

Table 4. Results of regression of SWE on surface air temperature and lake ice coverage.

All stations except for Duluth had significant relationships of SWE with average monthly temperature and percent ice cover (Table 4). Newberry had a *p*-value of 0.0646 against percent ice cover and this value could be attributed to its inland location. The absence of influence at Duluth is attributable to location of the station to the west of the lake and therefore, not downwind and unable to have the effects of air mass movements over the lake. All stations had negative parameter estimates for both variables except for Duluth, which had a positive relationship of SWE with average monthly temperature. Thus, total precipitation increased with colder temperatures, and with less ice cover on Lake Superior. Six locations (Bergland, Chatham, Houghton, Ironwood, Ontonagon, and Whitefish) had moderately high R^2 values, ranging from 0.3095 (Bergland) to 0.4831 (Ontonagon). For total precipitation (SWE), a reasonable scenario of 4.5°F increase in temperature would yield 4.919 *less* inches of precipitation whereas a 25% decrease in ice cover would yield 7.430 *more* inches of precipitation (parameter estimates were -1.0932 and -0.2972, respectively).

Conclusions

The present study suggests that a 4.5°F increase in air temperature and a 25% decrease in ice cover would result in minimal change in snowfall, a less that 1.0” increase. The snowfall regression model would predict an increase of only 0.25” of snow. The SWE model predicts total precipitation (in snow equivalent units) to increase by roughly 2.5”, but the SR model predicts that the SR ratio of this would only be ~7.5:1, or contain roughly 1.0” of snow. This represents a small increase relative to the 100-200” of snow presently recorded by most of the stations.

Snowfall		Decrease in ice cover (%)											
Increase in temperature (F)		**0.00**	**-10.00**	**-20.00**	**-25.00**	**-30.00**	**-40.00**	**-50.00**	**-60.00**	**-70.00**	**-80.00**	**-90.00**	**-100.00**
	1	-1.162	1.024	3.211	4.304	5.397	7.583	9.770	11.956	14.143	16.329	18.515	20.702
	2	-2.324	-0.138	2.048	3.142	4.235	6.421	8.608	10.794	12.980	15.167	17.353	19.540
	3	-3.487	-1.300	0.886	1.979	3.073	5.259	7.445	9.632	11.818	14.005	16.191	18.377
	4	-4.649	-2.462	-0.276	0.817	1.910	4.097	6.283	8.470	10.656	12.842	15.029	17.215
	4.5	-5.230	-3.043	-0.857	0.236	1.329	3.516	5.702	7.889	10.075	12.261	14.448	16.634
	5	-5.811	-3.625	-1.438	-0.345	0.748	2.935	5.121	7.308	9.494	11.680	13.867	16.053
	6	-6.973	-4.787	-2.600	-1.507	-0.414	1.773	3.959	6.145	8.332	10.518	12.705	14.891
	7	-8.135	-5.949	-3.762	-2.669	-1.576	0.610	2.797	4.983	7.170	9.356	11.542	13.729
	8	-9.297	-7.111	-4.925	-3.831	-2.738	-0.552	1.635	3.821	6.007	8.194	10.380	12.567
	9	-10.460	-8.273	-6.087	-4.994	-3.900	-1.714	0.472	2.659	4.845	7.032	9.218	11.404
	10	-11.622	-9.435	-7.249	-6.156	-5.063	-2.876	-0.690	1.497	3.683	5.869	8.056	10.242

TABLE 5: Snowfall expectancies from increase in temperature and decrease in ice cover.

	SWE	Decrease in ice cover (%)											
Increase in temperature (F)		**0.00**	**-10.00**	**-20.00**	**-25.00**	**-30.00**	**-40.00**	**-50.00**	**-60.00**	**-70.00**	**-80.00**	**-90.00**	**-100.00**
	1	-1.093	1.879	4.851	6.337	7.823	10.795	13.767	16.739	19.711	22.683	25.655	28.627
	2	-2.186	0.786	3.758	5.244	6.730	9.702	12.674	15.646	18.618	21.590	24.562	27.534
	3	-3.280	-0.308	2.664	4.150	5.636	8.608	11.580	14.552	17.524	20.496	23.468	26.440
	4	-4.373	-1.401	1.571	3.057	4.543	7.515	10.487	13.459	16.431	19.403	22.375	25.347
	4.5	-4.919	-1.947	1.025	2.511	3.997	6.969	9.941	12.913	15.885	18.857	21.829	24.801
	5	-5.466	-2.494	0.478	1.964	3.450	6.422	9.394	12.366	15.338	18.310	21.282	24.254
	6	-6.559	-3.587	-0.615	0.871	2.357	5.329	8.301	11.273	14.245	17.217	20.189	23.161
	7	-7.652	-4.680	-1.708	-0.222	1.264	4.236	7.208	10.180	13.152	16.124	19.096	22.068
	8	-8.746	-5.774	-2.802	-1.316	0.170	3.142	6.114	9.086	12.058	15.030	18.002	20.974
	9	-9.839	-6.867	-3.895	-2.409	-0.923	2.049	5.021	7.993	10.965	13.937	16.909	19.881
	10	-10.932	-7.960	-4.988	-3.502	-2.016	0.956	3.928	6.900	9.872	12.844	15.816	18.788

TABLE 6: SWE expectancies from increase in temperature and decrease in ice cover.

All stations showed a negative relationship with ice cover, corroborating previous research conducted by Assel (2003) and Austin and Coleman (2007): as lake temperatures are warming, ice cover is diminishing and therefore providing conditions conducive to production of LES occurrences. The lake's temperatures are warming and ice coverage is diminishing, allowing for more ice-free surface area for cold air masses to pass over. This increases the environmental lapse rate and reduces the stability of the air, while additionally increasing evaporation. This is counteracted by the effect of rising air temperatures, which appear likely to melt sufficient snow and cause a portion of the precipitation increase to occur as rain. The balance of these factors, and the consequent ability of regional warming to change snowfall, appear dependent on the relative amount of air temperature warming and ice cover reduction that occur. The hypothetical scenario of a 4.5°F warming and a 25% reduction in ice would result in a minor change, less than that 1.0" of SNOW. This scenario is a simple doubling of recently reported (~30 year) trends of air temperature and ice cover (Austin and Coleman, 2007). If somehow ice cover were to decline more rapidly than this with subsequent warming, different outcomes would be possible (Tables 5 & 6). For instance, a 3°F warming and 50% ice cover reduction would produce a 7-8" increase in snowfall.

Limitations/Discussions

Limitations

The availability of data was a limitation in this study. There are 25 NWS stations located in the study area, though only 11 have adequate data. Many of the other stations (i.e. Munising, MI; Copper Harbor, MI; and Ashland, WI) are primary lake-front stations whose data were inconsistent or frequently missing months and even years of measurements and could not have been accounted for with the next nearest station's data as it would have skewed the datasets. Water temperature data are reported from Lake Superior through the National Data Buoy Center (NDBC), but are collected only after the last ice melts and before the first ice sets (approximately May-November). These data could not be analyzed with the data sets in this discussion. The NDBC buoys were removed after first ice and therefore could not be used to assess lake surface temperatures during the winter snowfall season.

Snowfall meltwater is classified into rainfall through the NWS stations. It is inconclusive to state which amounts of rainfall during the season are attributed to actual rainfall precipitation and what percentage/amount is melt water from snowfall. These amounts were not great, but introduce some noise to the snowfall and rainfall. Additionally, the 10:1 conversion method used in the present study to convert liquid precipitation to snowfall was a simple limitation through the use of monthly rainfall amounts. The effects of air temperature and ice cover on the SWE could have been more accurately predicted through a snow-rain algorithm, though factors such as depth and temperature of the snow pack would have to have been introduced.

Discussion: Implications of Decreasing Ice Cover, Rising Air Temperatures, and Snowfall Rates on Industry, Tourism, and Ecology

There is inadequate research on the effects that warming air temperatures, lake warming, LES rates, and decreasing ice coverage have on the ecology, industry, and tourism sectors of the Great Lakes region. The National Wildlife Federation (NWF) recently published a report regarding the effects of lake warming and the concurrent decreasing ice coverage (among all of the Great Lakes), identifying the effects on the water quality, fisheries, and wildlife (NWF, 2007). These effects on the water supply have been identified as a significant risk, as sediment bacteria increase in metabolic rates, augmenting the consumption of oxygen in the water. Accompanying this phenomenon is the increase in biological productivity, which will further lessen the amount of oxygen in the water, as there will be greater decomposition of bottom matter (NWF, 2007). Oxygen depletion is central to studying ecological impacts in Lake Erie, and though that specific depletion was due to human impact, the effects would be much the same for Lake Superior under the spectre of lake warming (Environmental Protection Agency, 2006). The visual effects of a decline of oxygen are to cause a lake's water to turn a murky, greenish-brown color and to leave beaches with a dark green algal film. Oxygen deficiencies cause species that require less oxygen, i.e. carp and sludge worms, to thrive. The carp (*Cyprinus carpio*) is not native to North America and is considered a pest species as it agitates bottom-lying sediments which increase turbidity and siltation that is harmful to native species (Gulf States Marine Fisheries Commission, 2005). The sludge worm (*Tubifex tubifex*) causes intestinal disruptions and septicemia in fish, causing them to be unfit for human consumption (Ward, 2005).

The Great Lakes are vulnerable to threatening non-native species that arrive through the shipping industry, via the St. Lawrence Seaway. Lake warming will render an influx of invasive species from those already established in the warmer lakes of Michigan and Huron. Currently, Lake Superior is home to 49 established invasive species (USGS Non-indigenous Aquatic Species, 2008) whereas Lake Michigan and Lake Huron are home to 67 and 54 established invasive species, respectively.

Lake warming will negatively impact the fishing industry not only through introduction of invasive species, but through the aforementioned diminished ice cover and lower lake levels. The multi-million dollar charter/sport fishing industry currently accounts for large revenues for Michigan, Wisconsin, and Minnesota (Michigan Sea Grant, 2002); Minnesota alone collects $12.67 million to $17.54 million in revenues (including dining, entertainment, lodging, gas, etc). This does not include commercial fishing, which has decreased on the Great Lakes due to the poor quality of lake waters (specifically the southern lakes, Erie, Ontario, southern Huron, and most of Michigan) and the requirement of fishing nets. Lake Superior is the only Great Lake which yields a quality fish crop, amounting to ~$13 billion per year (Michigan Sea Grant, 2007). The rainbow smelt, lake whitefish, yellow perch, walleye, chubs, white bass, carp, lake trout and lake herring are the base crop for fishing. The largest threat with lake warming is on the whitefish and a specific species of lake trout, both of which thrive in the cold, deep waters of the lake and unlike the other Great Lakes, the trout population is not sustained by restocking programs. It is the only lake in

which lake trout can be fished successfully without anticipated depletion (Moy, 2001), whereas whitefish are sustained by the Department of Natural Resources (DNR) of the three border states (Michigan DNR, 2008). Lake warming would therefore endanger the habitat for this industry. It is viewed as a chain effect: the lake could warm slightly and still sustain the crop, but migrating species of plants, algae, fishes, and invertebrates (indigenous and non-indigenous) would additionally threaten their populations.

In addition to fisheries, Michigan has a sustainable wildlife program at Isle Royal National Park, situated on the island of Isle Royal in Lake Superior's northwest corner approximately 50 miles from the Keweenaw Peninsula of Michigan, 20 miles from the U.S./Canada border (at Minnesota) and 22 miles from Thunder Bay, Ontario. The park is known for its natural habitat for hikers and campers as well as an ongoing study site for predator and prey dynamics specific to the moose and wolf populations (hereby referred to as the *populations*). Wolves are vital to maintaining a sustainable and healthy moose population; the old, sick, and injured moose are prime prey for the wolves (Uhler, 2002). The current trend of decreasing numbers in the wolf population is attributed to inbreeding as there has been a high pup mortality rate. The study, which publishes findings yearly, recognizes the impact of decreasing ice cover on the populations' migratory patterns. In the winter of 2006-07, an ice bridge was present between Isle Royal and the mainland of Ontario for two weeks in early February (Vucetich and Peterson, 2007), the first occurrence since the late 1970s, attributed to colder than average regional air temperatures (Vucetich and Peterson, 2004) Researchers fear that the lack of a recurring ice bridge will further diminish

the stability of the wolf population, and therefore, the moose population (Figure 5) (Vucetich and Peterson, 2004; Uhler, 2002).

Tourism is a recognized industry along the south shore of Lake Superior, not only in the summer months, but also in the fall and winter months as well. The summer generates business for the wilderness traveller: those that hike, fish, camp, and seek natural wonders such as waterfalls, national parks (Pictures Rocks National Lakeshore, Isle Royal), and unabated solitude. The warming air and lake temperatures could benefit this sector, bringing an earlier start to the summer tourism season and therefore generating revenues earlier (and possibly later) than twenty years before. If lake warming continues at the current rate, summer water temperatures would become more tolerable, permitting an influx of water sports and water based recreation. This could negatively impact the lake, as there would be greater emissions in the lake from motorized watercraft, and possible litter from increased lake usage.

Fall and winter tourism are affected by the lake temperatures as they relate to air temperatures. The past few years have seen warmer than average temperatures, accounting for the increased melting of snow cover (reference Figure 2a; Federal Reserve Board, Ninth District, 2007; Jambekar and Brokaw, 2000). This will negatively affect the snowmobiling and skiing industries (including downhill and cross-country). Snowmobiling and skiing account for jobs and tax revenue, the latter not only from locals but tourists traveling from Illinois, Minnesota, downstate Michigan, and Wisconsin (Jambekar and Brokaw, 2000). The effects of decreased snow pack are obvious: if there is a deficiency, there will be no tourists.

The lake warming process could have serious ecological and economic ramifications for the south shore. The EL-Nino winter of 1997-98 caused a shift of the majority of the snowmobiling industry to the Keweenaw Peninsula. A result of extreme snow fall deficiencies across northern Minnesota, Wisconsin, and Michigan, the Keweenaw was not affected by this phenomenon. This resulted in congestion along the trails, exerting unprecedented amounts of snowmobile emissions to the area, in addition to mild destruction to the forest areas and the ground along the trails (Jembekar and Brokaw, 2000). The ski hills will have lesser economic impacts as they have the capacity to fabricate snow, whereas the economic effects for snowmobiling and cross-country skiing are evident: the winter tourism industry relies on the natural snow cover. A majority of the hotels and restaurants rely on this business, as the winter months are usually the "slow season" for tourism.

The Lake Superior warming trend is viewed by many governmental and non-profit educational agencies as a phenomenon that warrants concern. Researchers predict that at the current rate, the Lake could warm up to a yearly average of ~49ºF (~9°C) by 2050, ~58°F (~14°C) by 2100. Whether this warming trend is due to anthropogenic behavior or natural earth processes is disputable, but no matter what the cause, there are numerous issues that need to be addressed. It is predicted that Lake Superior will be ice-free in approximately 30 years (Austin and Coleman, 2007), and as discussed, this can have moderate to extreme effects on the ecology and industries the region relies upon. The pivotal factors are currently being studied, but there is a need for additional research on the chain effects that this warming trend could have.

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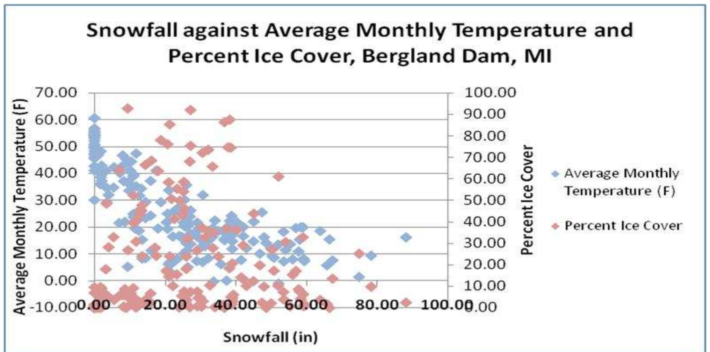
Appendix 1

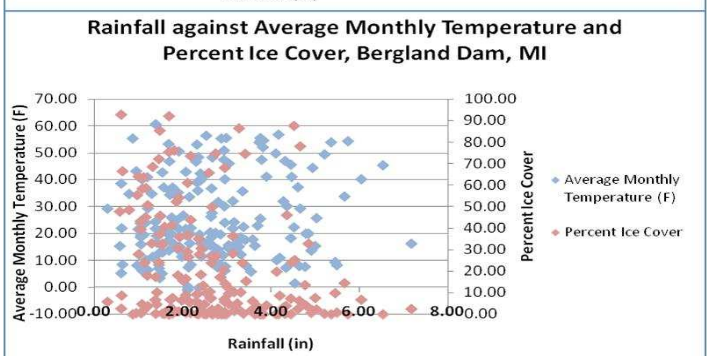
Detailed Station Information

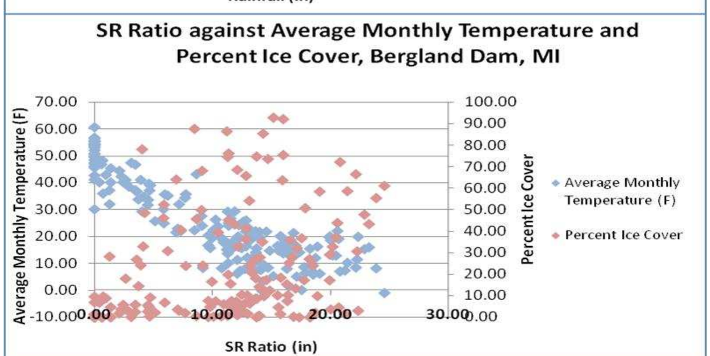
	Station	Name	NCDC Station ID	County	State	Lat (DD)	Long (DD)	Elevation	Period of Record
1	Bergland	Dam	200718	Ontonagon	MI	46.58	-89.54	1300.00 FEET	1888-11-01 => Present
2	Chatham	Exp	201484	Alger	MI	46.35	-86.93	880.00 FEET	1948-01-01 => 1988-07-01
2	Chatham	Exp Farm 2	201486	Alger	MI	46.34	-86.92	870.00 FEET	1987-07-09 => Present
3	Duluth	Int'l Airport	212248	Duluth	MN	46.83	-92.20	1428.00 FEET	1996-05-08 => Present
4	Houghton	County Airport	203908	Houghton	MI	47.16	-88.48	1074.00 FEET	1952-08-01 => Present
5	Ironwood		204104	Gogebic	MI	46.46	-90.18	1430.00 FEET	1901-07-01 => Present
6	Marquette		205178	Marquette	MI	46.54	-87.37	625.00 FEET	1891-12-01 => Present
6	Marquette	WSO AP	205184	Marquette	MI	46.53	-87.54	1415.00 FEET	1959-08-01 => Present
7	Mellen	4NE	475286	Ashland	WI	46.36	-90.64	1300.00 FEET	1926-09-01 => Present
8	Newberry	3S	205816	Luce	MI	46.31	-85.51	850.00 FEET	1896-09-01 => Present
9	Ontonagon	6 SE	206220	Ontonagon	MI	46.83	-89.20	790.00 FEET	1977-09-01 => Present
9	Ontonagon		206210	Ontonagon	MI	46.86	-89.31	702.00 FEET	1900-04-01 => 1977-09-17
10	Sault Ste. Marie	Sanderson Field	207366	Chippewa	MI	46.47	-84.35	722.00 FEET	1931-01-01 => Present
11	Whitefish Point		208920	Chippewa	MI	46.75	-84.97	605.00 FEET	1900-03-01 => Present

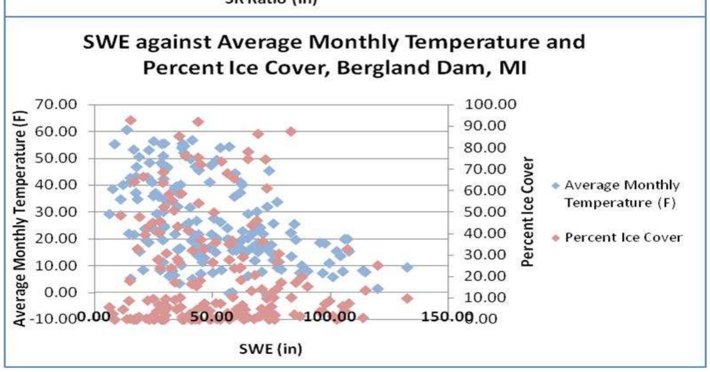
Appendix 2

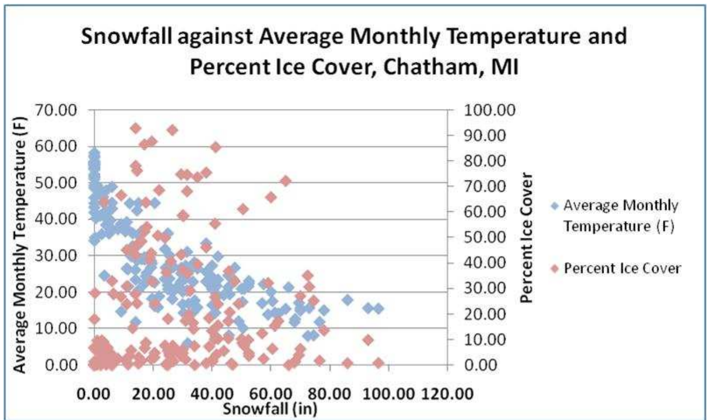
Graphs

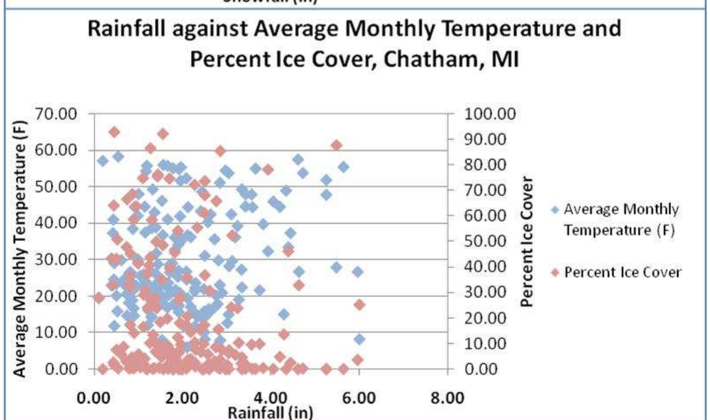


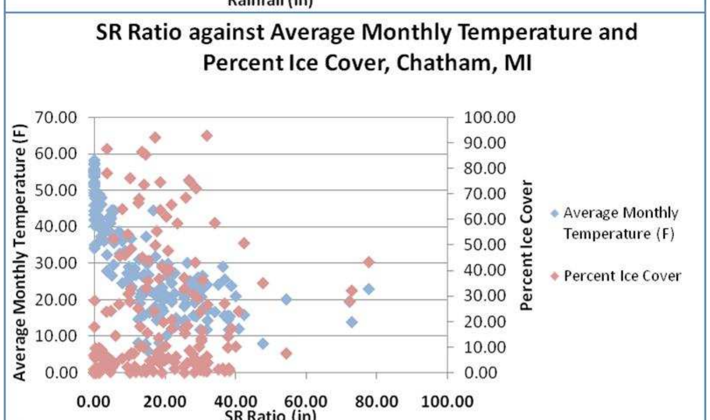


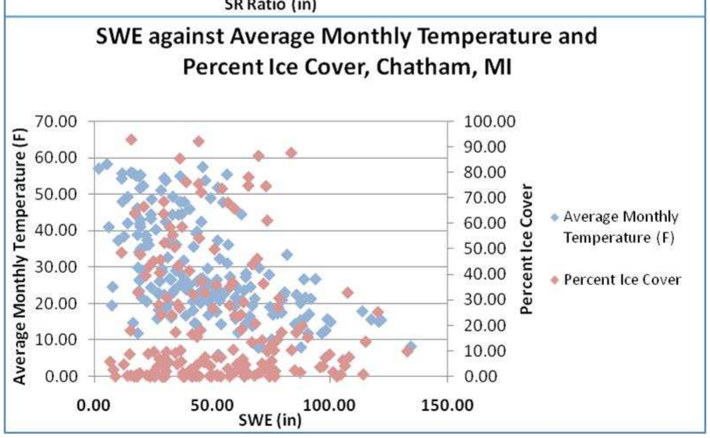


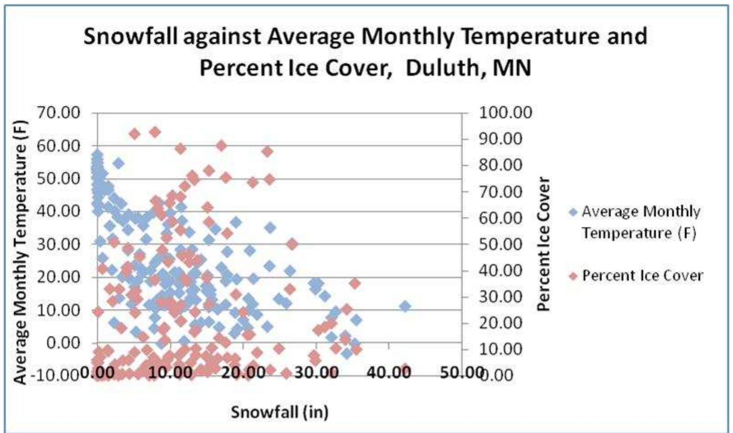


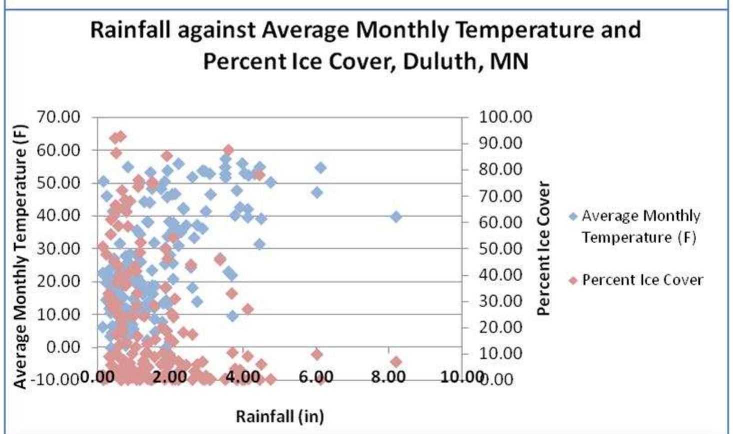

Snowfall against Average Monthly Temperature and Percent Ice Cover, Chatham, MI
Average Monthly Temperature (F)
Percent Ice Cover
Snowfall (in)
Average Monthly Temperature (F)
Percent Ice Cover
0.00 20.00 40.00 60.00 80.00 100.00 120.00
0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00
0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00 80.00 90.00 100.00

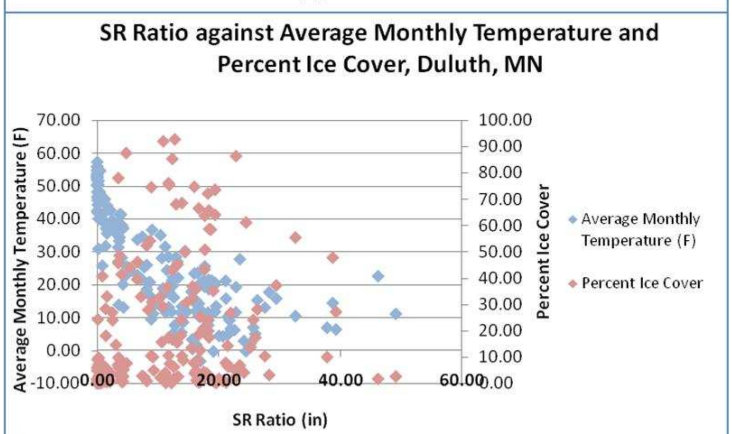

Rainfall against Average Monthly Temperature and Percent Ice Cover, Chatham, MI
Average Monthly Temperature (F)
Percent Ice Cover
Rainfall (in)
Average Monthly Temperature (F)
Percent Ice Cover
0.00 2.00 4.00 6.00 8.00
0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00
0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00 80.00 90.00 100.00

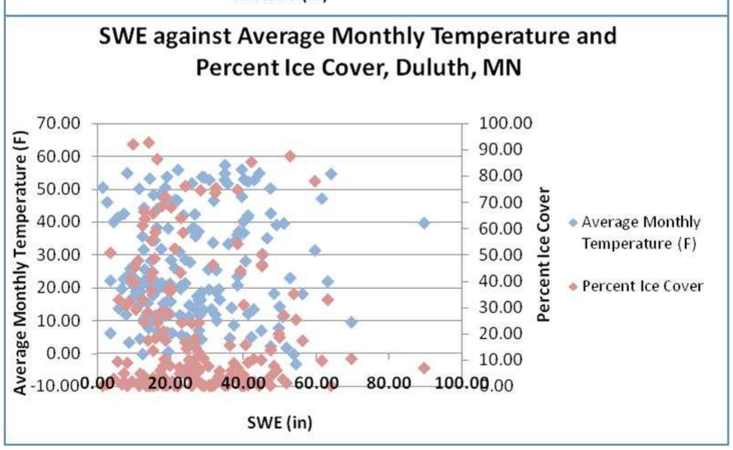

SR Ratio against Average Monthly Temperature and Percent Ice Cover, Chatham, MI
Average Monthly Temperature (F)
Percent Ice Cover
SR Ratio (in)
Average Monthly Temperature (F)
Percent Ice Cover
0.00 20.00 40.00 60.00 80.00 100.00
0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00
0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00 80.00 90.00 100.00

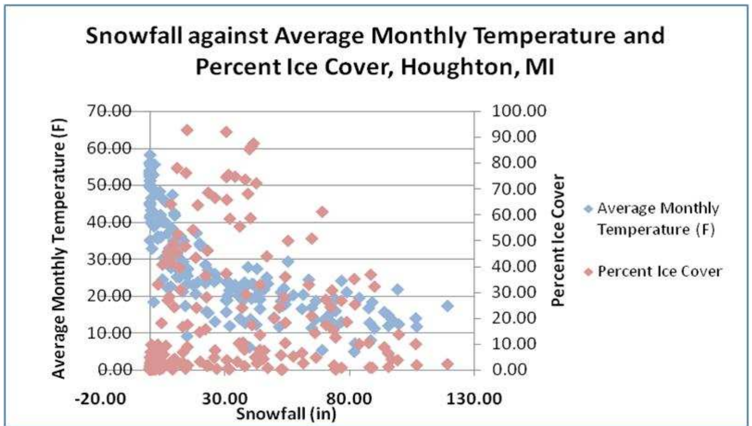

SWE against Average Monthly Temperature and Percent Ice Cover, Chatham, MI
Average Monthly Temperature (F)
Percent Ice Cover
SWE (in)
Average Monthly Temperature (F)
Percent Ice Cover
0.00 50.00 100.00 150.00
0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00
0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00 80.00 90.00 100.00

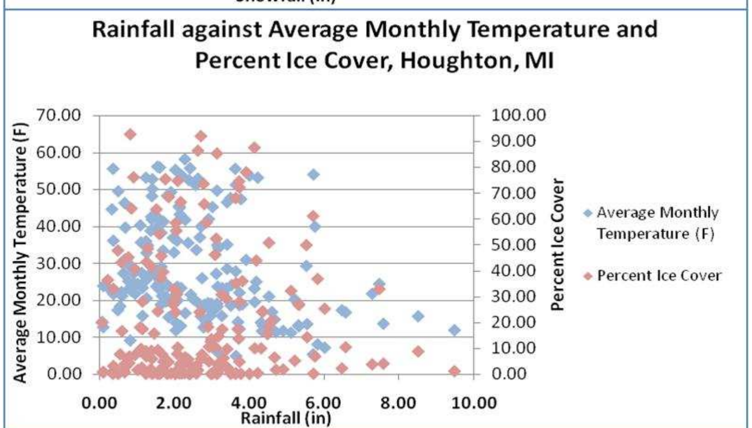

Snowfall against Average Monthly Temperature and Percent Ice Cover, Duluth, MN
Average Monthly Temperature (F)
Percent Ice Cover
Snowfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

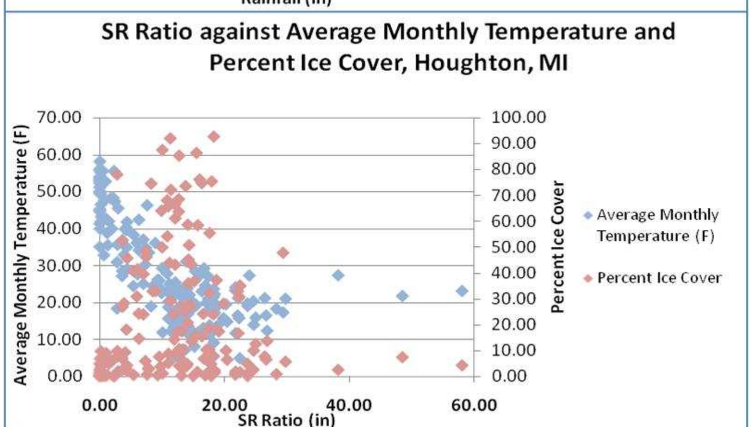

Rainfall against Average Monthly Temperature and Percent Ice Cover, Duluth, MN
Average Monthly Temperature (F)
Percent Ice Cover
Rainfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

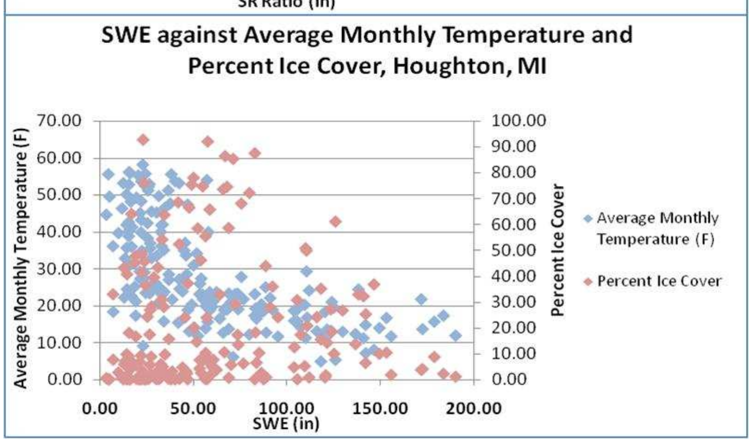

SR Ratio against Average Monthly Temperature and Percent Ice Cover, Duluth, MN
Average Monthly Temperature (F)
Percent Ice Cover
SR Ratio (in)
Average Monthly Temperature (F)
Percent Ice Cover

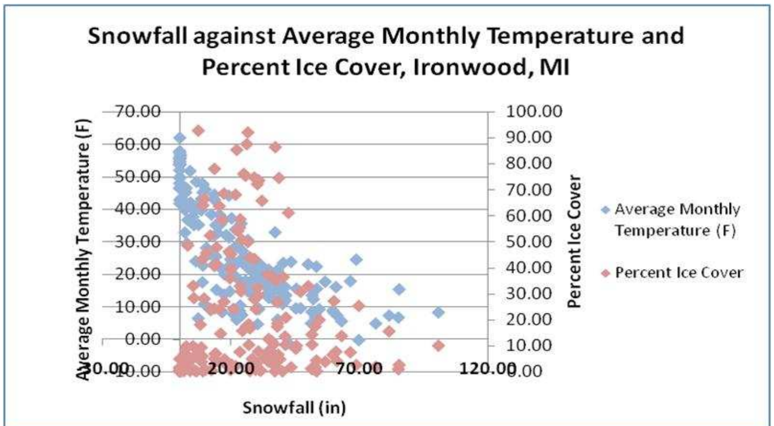

SWE against Average Monthly Temperature and Percent Ice Cover, Duluth, MN
Average Monthly Temperature (F)
Percent Ice Cover
SWE (in)
Average Monthly Temperature (F)
Percent Ice Cover

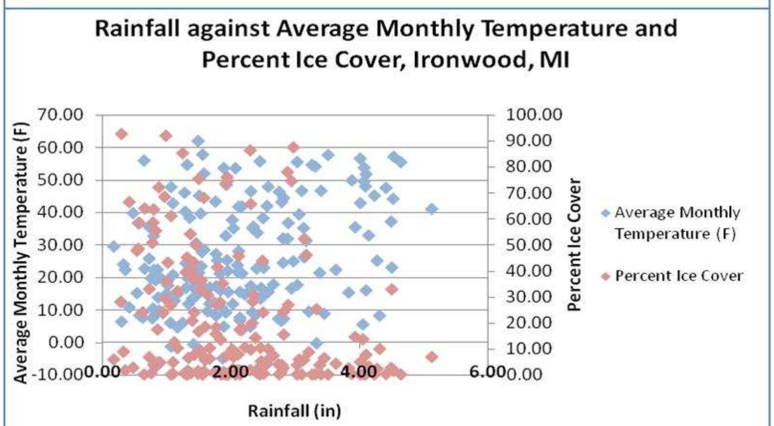

Snowfall against Average Monthly Temperature and Percent Ice Cover, Houghton, MI
Average Monthly Temperature (F)
Percent Ice Cover
Snowfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

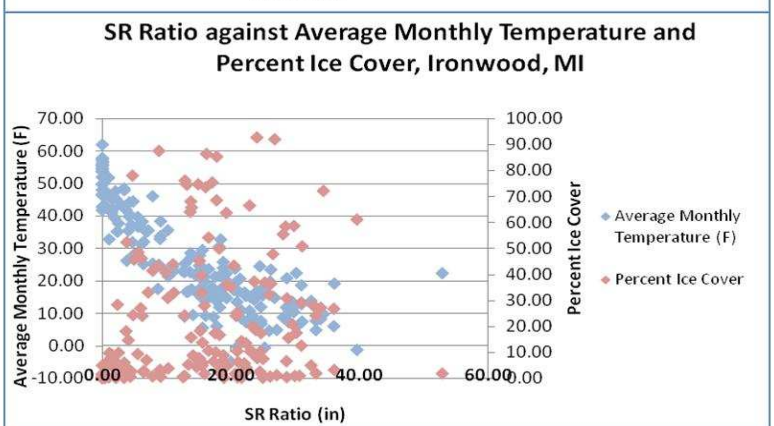

Rainfall against Average Monthly Temperature and Percent Ice Cover, Houghton, MI
Average Monthly Temperature (F)
Percent Ice Cover
Rainfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

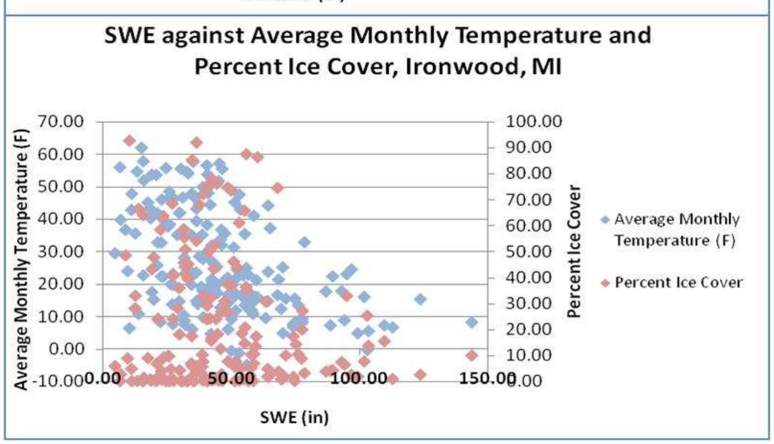

SR Ratio against Average Monthly Temperature and Percent Ice Cover, Houghton, MI
Average Monthly Temperature (F)
Percent Ice Cover
SR Ratio (in)
Average Monthly Temperature (F)
Percent Ice Cover

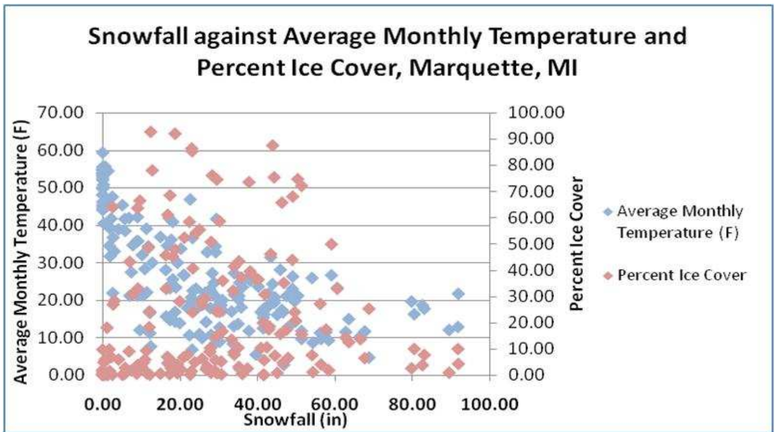

SWE against Average Monthly Temperature and Percent Ice Cover, Houghton, MI
Average Monthly Temperature (F)
Percent Ice Cover
SWE (in)
Average Monthly Temperature (F)
Percent Ice Cover

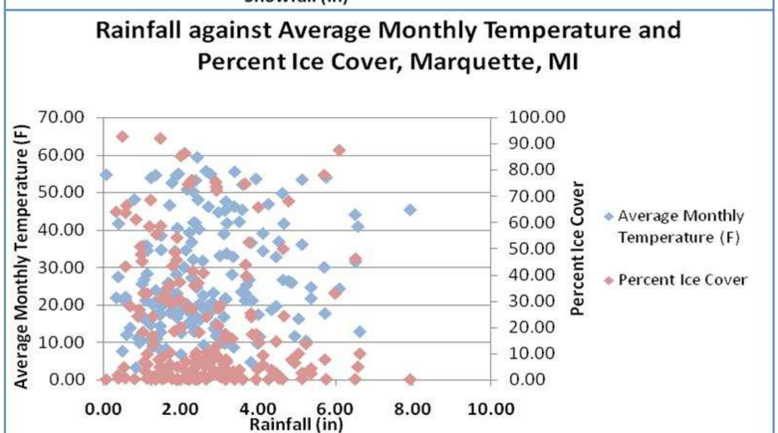

Snowfall against Average Monthly Temperature and Percent Ice Cover, Ironwood, MI
Average Monthly Temperature (F)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-30.00
20.00
70.00
120.00
Snowfall (in)
Percent Ice Cover
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Average Monthly Temperature (F)
Percent Ice Cover

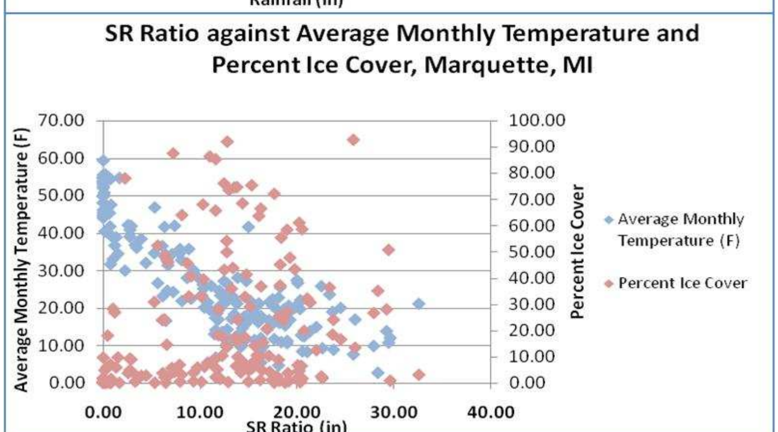

Rainfall against Average Monthly Temperature and Percent Ice Cover, Ironwood, MI
Average Monthly Temperature (F)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
0.00
2.00
4.00
6.00
Rainfall (in)
Percent Ice Cover
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Average Monthly Temperature (F)
Percent Ice Cover

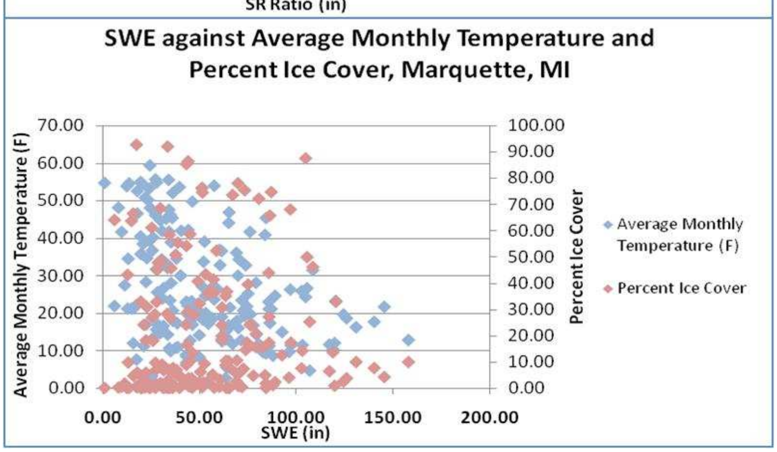

SR Ratio against Average Monthly Temperature and Percent Ice Cover, Ironwood, MI
Average Monthly Temperature (F)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
0.00
20.00
40.00
60.00
SR Ratio (in)
Percent Ice Cover
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Average Monthly Temperature (F)
Percent Ice Cover

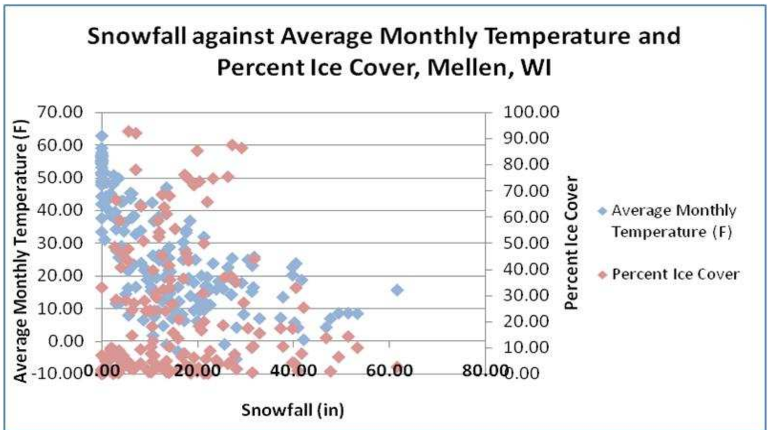

SWE against Average Monthly Temperature and Percent Ice Cover, Ironwood, MI
Average Monthly Temperature (F)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
0.00
50.00
100.00
150.00
SWE (in)
Percent Ice Cover
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Average Monthly Temperature (F)
Percent Ice Cover

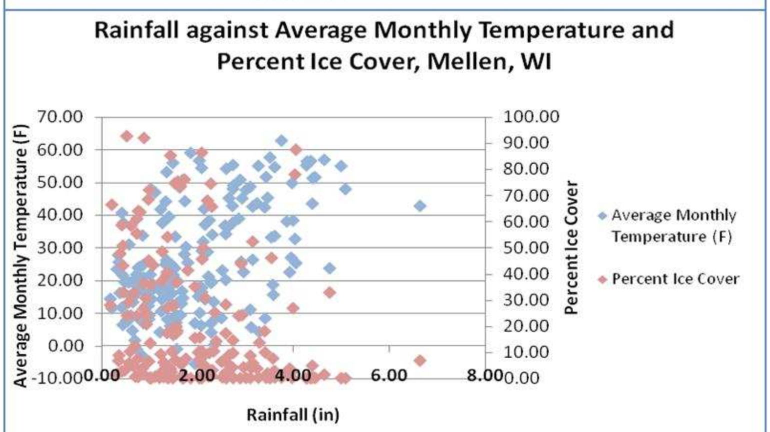

Snowfall against Average Monthly Temperature and Percent Ice Cover, Marquette, MI
Average Monthly Temperature (F)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Percent Ice Cover
0.00
20.00
40.00
60.00
80.00
100.00
Snowfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

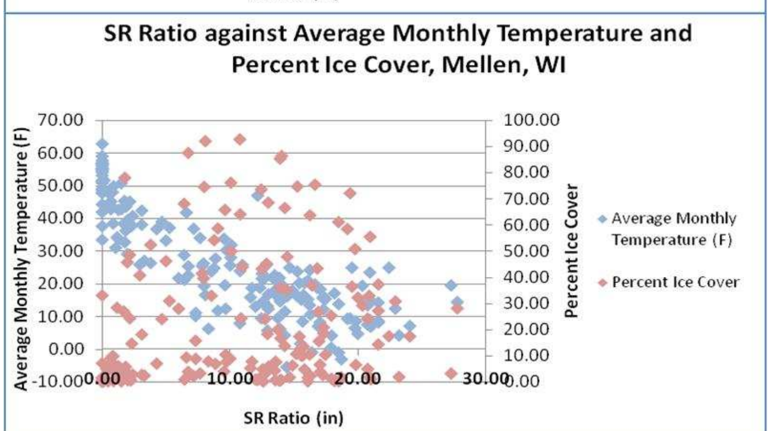

Rainfall against Average Monthly Temperature and Percent Ice Cover, Marquette, MI
Average Monthly Temperature (F)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Percent Ice Cover
0.00
2.00
4.00
6.00
8.00
10.00
Rainfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

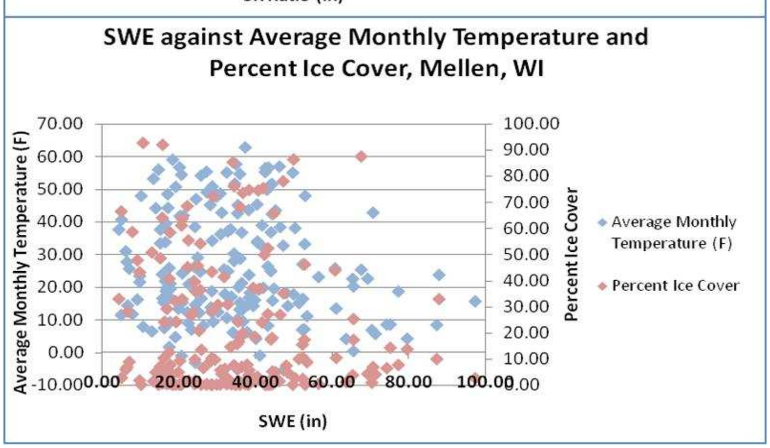

SR Ratio against Average Monthly Temperature and Percent Ice Cover, Marquette, MI
Average Monthly Temperature (F)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Percent Ice Cover
0.00
10.00
20.00
30.00
40.00
SR Ratio (in)
Average Monthly Temperature (F)
Percent Ice Cover

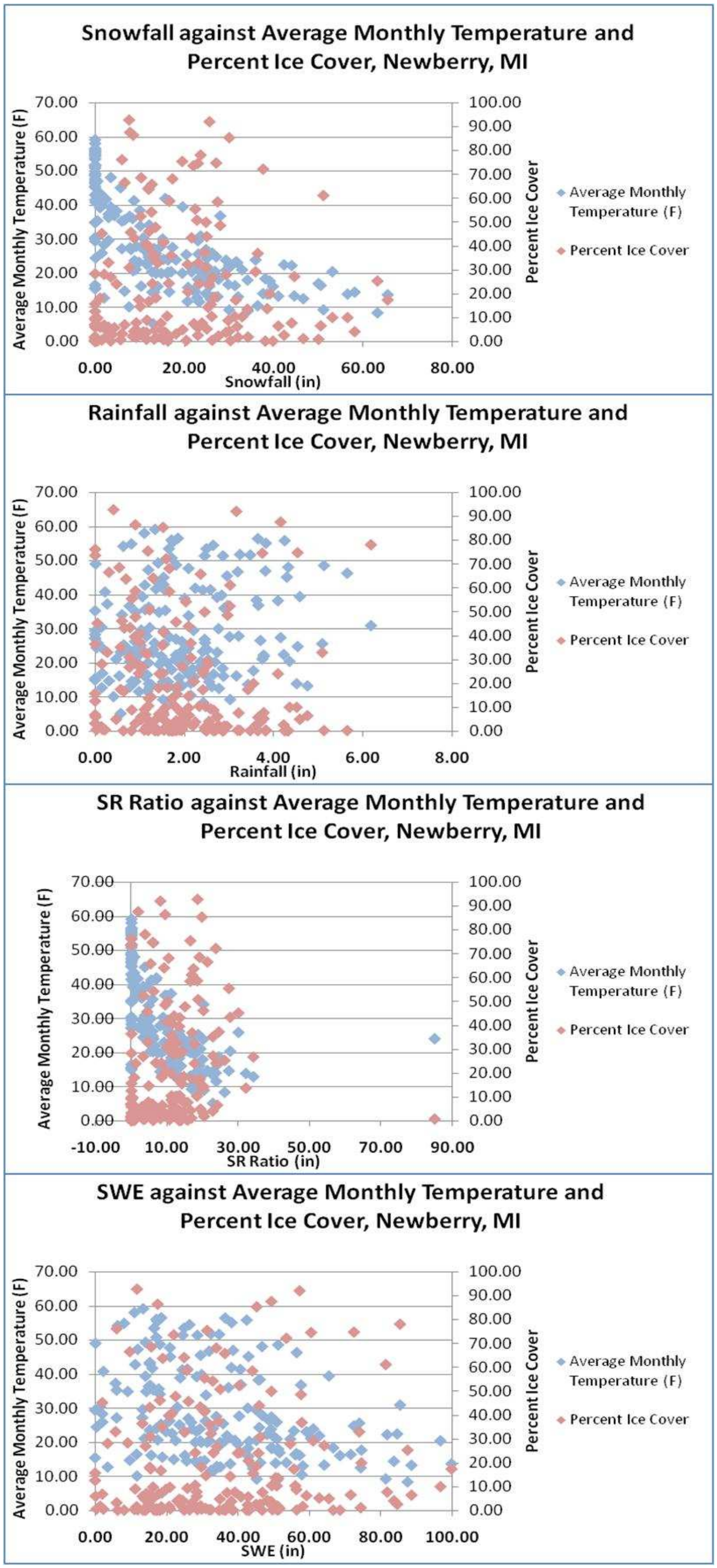

SWE against Average Monthly Temperature and Percent Ice Cover, Marquette, MI
Average Monthly Temperature (F)
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Percent Ice Cover
0.00
50.00
100.00
150.00
200.00
SWE (in)
Average Monthly Temperature (F)
Percent Ice Cover

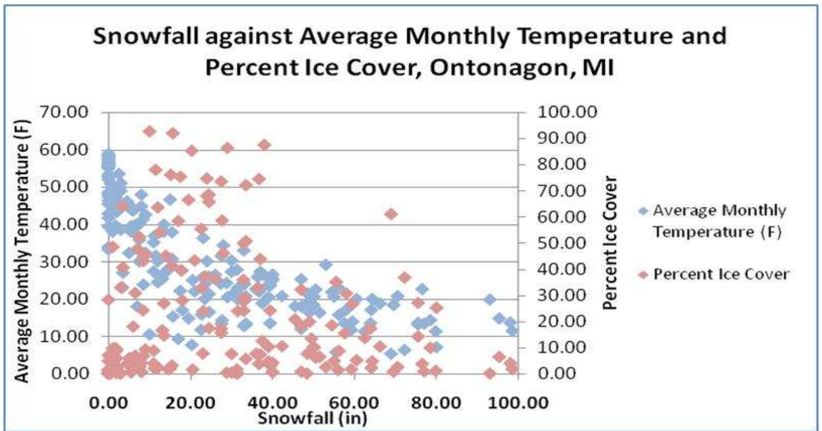

Snowfall against Average Monthly Temperature and Percent Ice Cover, Mellen, WI
Average Monthly Temperature (F)
Percent Ice Cover
Snowfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

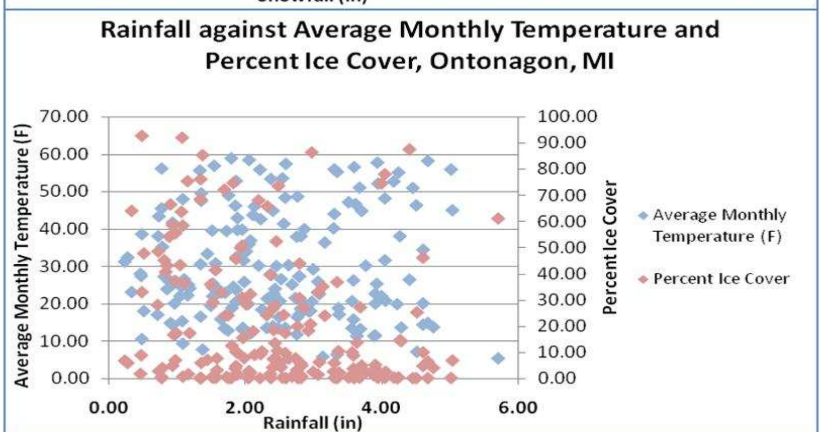

Rainfall against Average Monthly Temperature and Percent Ice Cover, Mellen, WI
Average Monthly Temperature (F)
Percent Ice Cover
Rainfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

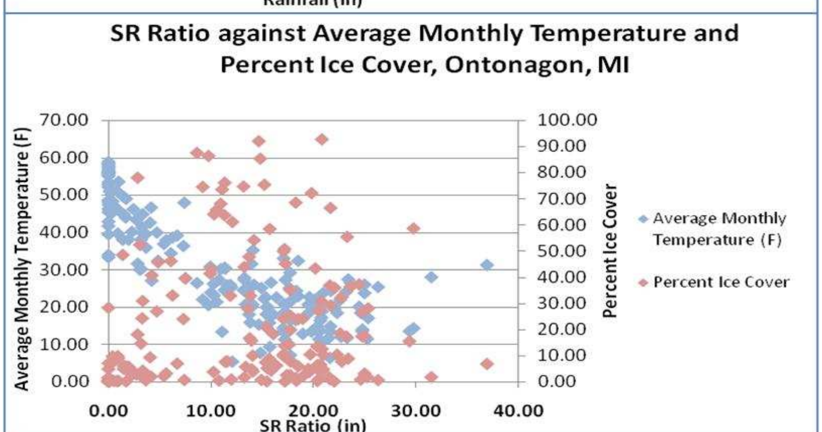

SR Ratio against Average Monthly Temperature and Percent Ice Cover, Mellen, WI
Average Monthly Temperature (F)
Percent Ice Cover
SR Ratio (in)
Average Monthly Temperature (F)
Percent Ice Cover

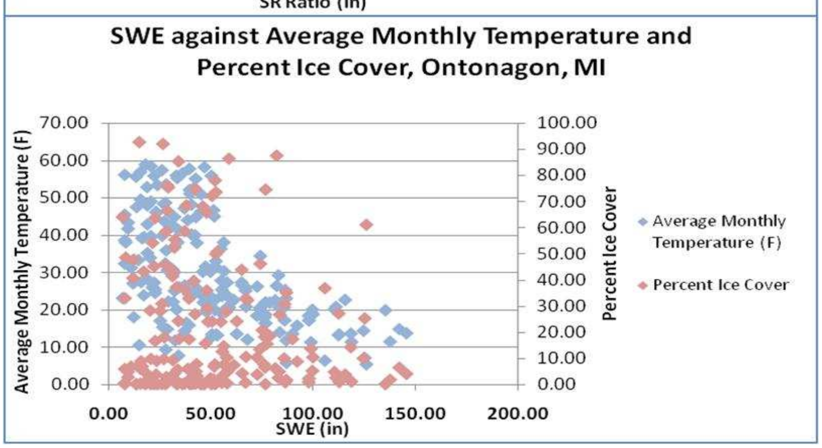

SWE against Average Monthly Temperature and Percent Ice Cover, Mellen, WI
Average Monthly Temperature (F)
Percent Ice Cover
SWE (in)
Average Monthly Temperature (F)
Percent Ice Cover

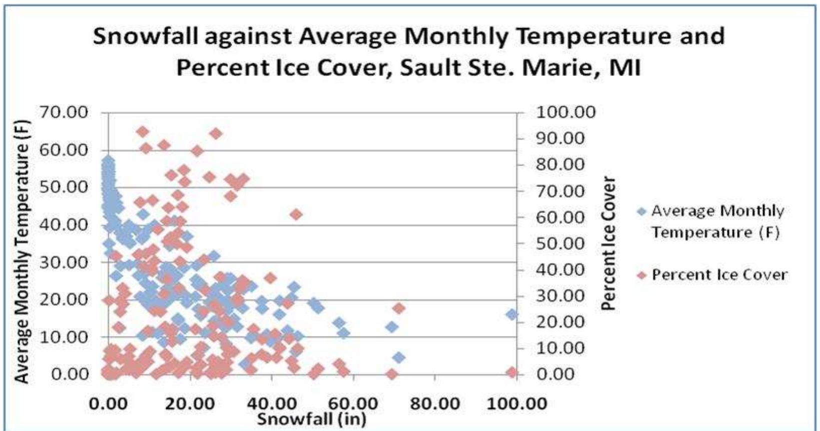

Snowfall against Average Monthly Temperature and Percent Ice Cover, Newberry, MI
Average Monthly Temperature (F)
Percent Ice Cover
Snowfall (in)
Average Monthly Temperature (F)
Percent Ice Cover
Rainfall against Average Monthly Temperature and Percent Ice Cover, Newberry, MI
Rainfall (in)
SR Ratio against Average Monthly Temperature and Percent Ice Cover, Newberry, MI
SR Ratio (in)
SWE against Average Monthly Temperature and Percent Ice Cover, Newberry, MI
SWE (in)

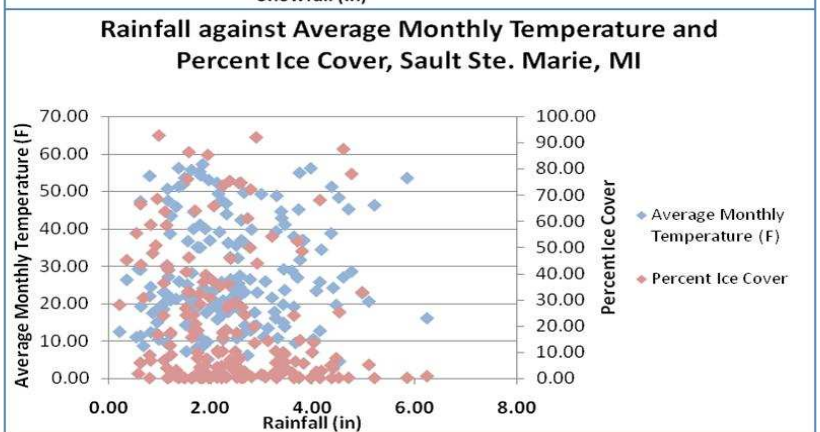

Snowfall against Average Monthly Temperature and Percent Ice Cover, Ontonagon, MI
Average Monthly Temperature (F)
Percent Ice Cover
Snowfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

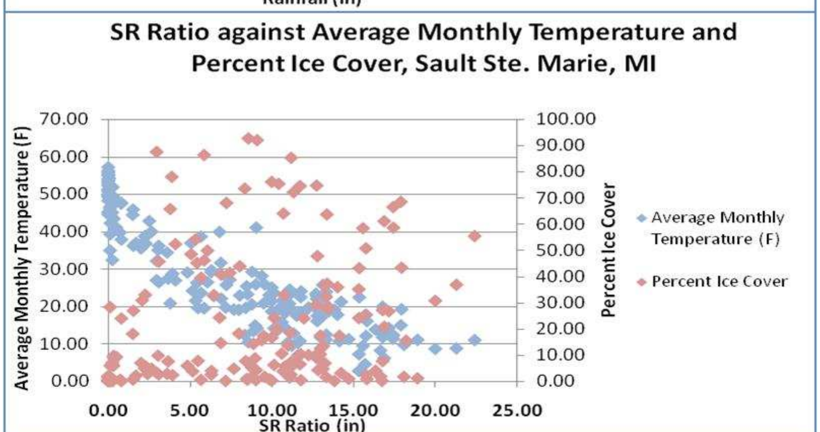

Rainfall against Average Monthly Temperature and Percent Ice Cover, Ontonagon, MI
Average Monthly Temperature (F)
Percent Ice Cover
Rainfall (in)
Average Monthly Temperature (F)
Percent Ice Cover

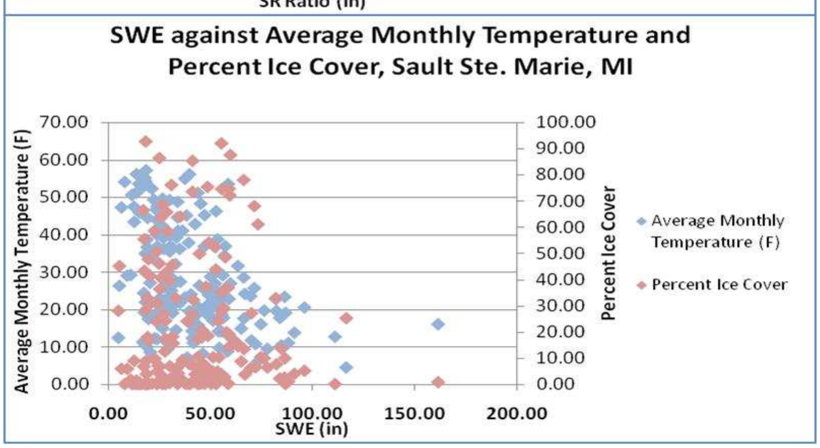

SR Ratio against Average Monthly Temperature and Percent Ice Cover, Ontonagon, MI
Average Monthly Temperature (F)
Percent Ice Cover
SR Ratio (in)
Average Monthly Temperature (F)
Percent Ice Cover

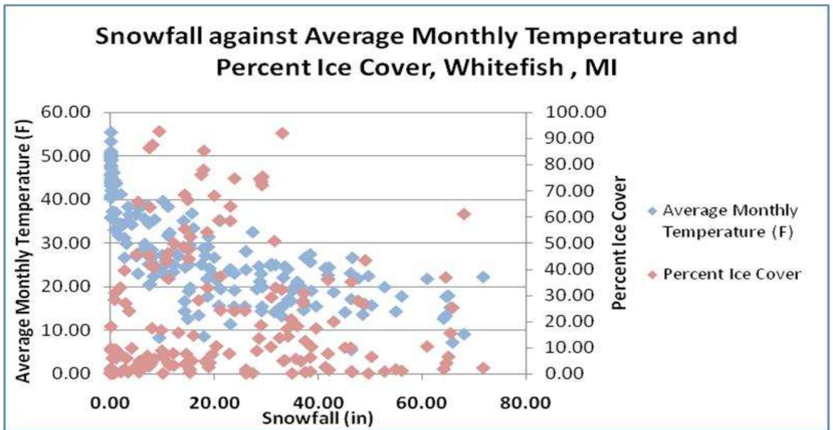

SWE against Average Monthly Temperature and Percent Ice Cover, Ontonagon, MI
Average Monthly Temperature (F)
Percent Ice Cover
SWE (in)
Average Monthly Temperature (F)
Percent Ice Cover

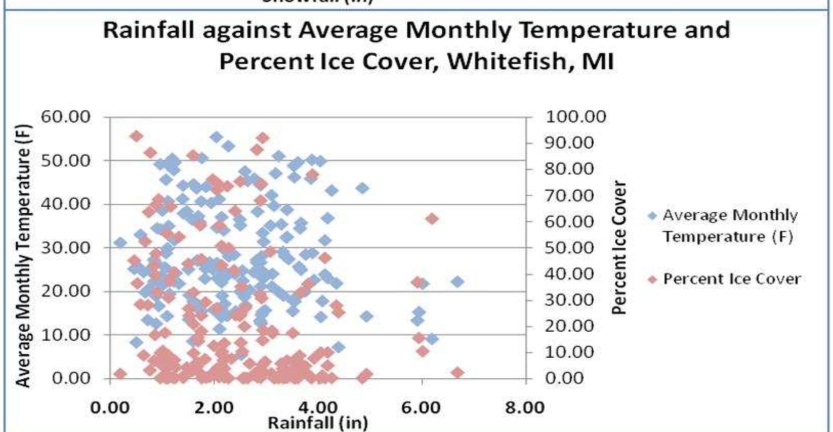

Snowfall against Average Monthly Temperature and Percent Ice Cover, Sault Ste. Marie, MI
Average Monthly Temperature (F)
Percent Ice Cover
Snowfall (in)
Average Monthly Temperature (F)
Percent Ice Cover
0.00
20.00
40.00
60.00
80.00
100.00

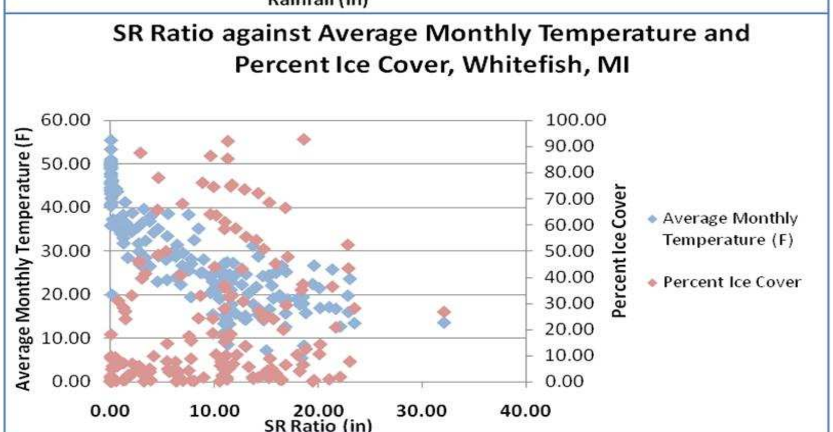

Rainfall against Average Monthly Temperature and Percent Ice Cover, Sault Ste. Marie, MI
Average Monthly Temperature (F)
Percent Ice Cover
Rainfall (in)
Average Monthly Temperature (F)
Percent Ice Cover
0.00
2.00
4.00
6.00
8.00

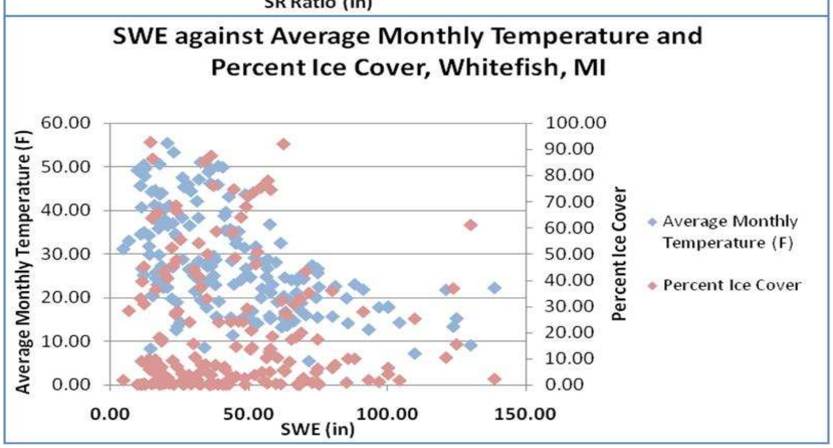

SR Ratio against Average Monthly Temperature and Percent Ice Cover, Sault Ste. Marie, MI
Average Monthly Temperature (F)
Percent Ice Cover
SR Ratio (in)
Average Monthly Temperature (F)
Percent Ice Cover
0.00
5.00
10.00
15.00
20.00
25.00


SWE against Average Monthly Temperature and Percent Ice Cover, Sault Ste. Marie, MI
Average Monthly Temperature (F)
Percent Ice Cover
SWE (in)
Average Monthly Temperature (F)
Percent Ice Cover
0.00
50.00
100.00
150.00
200.00


Snowfall against Average Monthly Temperature and Percent Ice Cover, Whitefish , MI
Average Monthly Temperature (F)
Percent Ice Cover
Snowfall (in)
Average Monthly Temperature (F)
Percent Ice Cover


Rainfall against Average Monthly Temperature and Percent Ice Cover, Whitefish, MI
Average Monthly Temperature (F)
Percent Ice Cover
Rainfall (in)
Average Monthly Temperature (F)
Percent Ice Cover


SR Ratio against Average Monthly Temperature and Percent Ice Cover, Whitefish, MI
Average Monthly Temperature (F)
Percent Ice Cover
SR Ratio (in)
Average Monthly Temperature (F)
Percent Ice Cover


SWE against Average Monthly Temperature and Percent Ice Cover, Whitefish, MI
Average Monthly Temperature (F)
Percent Ice Cover
SWE (in)
Average Monthly Temperature (F)
Percent Ice Cover

Vita

Angela (Pelkie) Maki was born and raised outside of Marquette, Michigan and has watched the winters vary from year to year. She received her B.A. in hospitality business from Michigan State University in 2004 and subsequently moved to New Orleans. She decided to pursue an M.A. in geography due to her interests in weather and climate studies.