A Statistical Analysis of Wisconsin Tornado Climatology

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1. Introduction

Tornado climatology in Wisconsin - an interesting topic. It is interesting because tornadoes have played their way into the Wisconsin history books, with such major events as Barnaveld in 1984, Oakfield in 1996, Siren in 2001, and now Ladysmith in 2002. In some years, Wisconsin has dozens of tornadoes across the state, including as many as 44 in 1980 and 37 in 1993. Certainly, Wisconsin has had both major and widespread tornado events, and this violent weather feature is an important part of Wisconsin weather history.

Wisconsinites must be prepared to deal with tornadoes each year. The threat of tornadoes on human life have been demonstrated time and again. Understanding the level of threat in any one location is a part of the knowledge base each individual requires to make appropriate decisions regarding personal, family and employee safety.

With these thoughts in mind, this paper had a number of objectives. All are designed to provide greater insight into the tornado climatology around the state of Wisconsin. First, the paper will review where Wisconsin fits into the national tornado statistics. It will then break down 158 years of statewide tornado reports to determine which areas appear to be most favorable for tornado occurrence. Finally, some possible rationale for the climatological data will be presented.

2. Tornado Climatology

Tornado climatology is not a straightforward subject. As with any climatological analysis, the presence of any biases in the data set are of major concern, as they are not only passed along throughout the analysis, but may eventually cause inaccurate conclusions. One of the most significant problems with the tornado data set is that each occurrence required someone to report it. Therefore, over the years, tornado reports may have been most numerous in areas with 1) greater population density (including both cities and the effect of major highways and freeways; see Galway, 1977; Kelly *et al*, 1978; and Doswell, 1980), 2) improvements in spotting and reporting networks, including the proliferation of tornado chasers, and 3) increased public tornado awareness efforts (Burley and Waite, 1965).

Educational activities over the past few decades, including the National Weather Service storm spotter training efforts and television documentaries, improvements in the radar detection network, and the proliferation of tornado chase teams with video recorders, has very likely decreased the chance of a tornado going unnoticed in many areas of the country. The fact that the number of observed tornadoes across the nation has seen a dramatic rise over the past few decades certainly *implies* that we're documenting a greater percentage of tornado occurrences these days.

The temporal and spatial variability in the national tornado data set may include inherent biases which can cause difficulties when analyzing the long term tornado climatology. Nevertheless, an analysis of the data can be instructive.

3. A National Scope of Tornado Frequency

Since the 1800s, numerous studies (e.g., Loomis, 1842) have analyzed and depicted geographical tornado distributions across the United States. Two fairly comprehensive studies (Pautz, 1969; Kelly, *et al*, 1978) have provided a more detailed statistical insight into national tornado frequencies. These studies covered periods of 13 and 27 years, respectively.

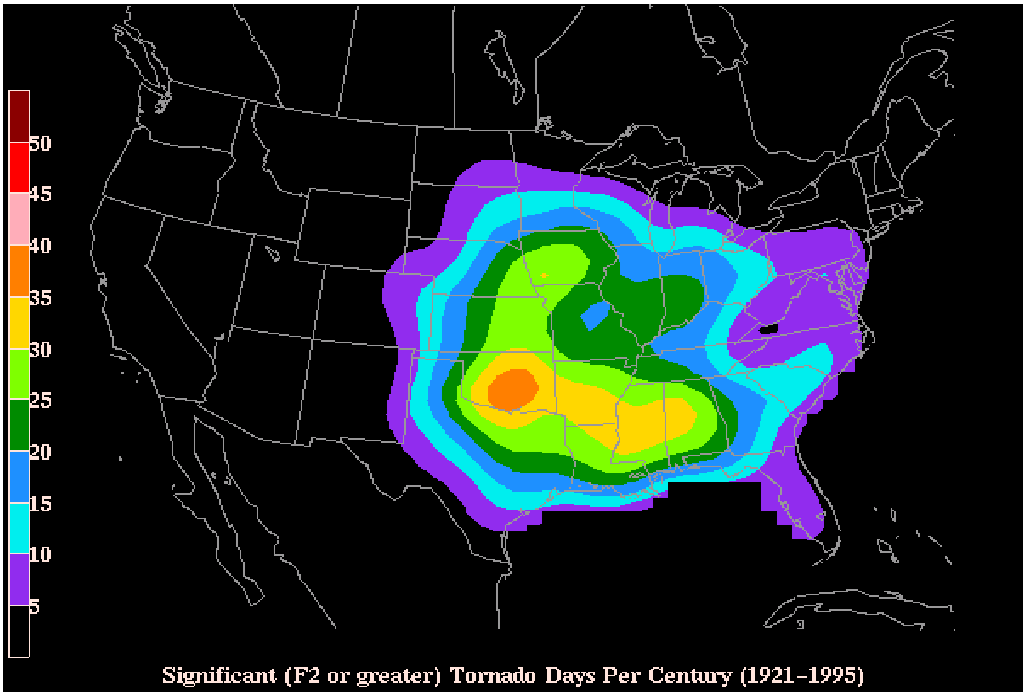

Figure 1. Mean number of days per century with at least an F2 or greater tornado touching down in 80km x 80km grid box. Based on data from 1921-1995. Contour interval 5 days with lowest contour 5.

Perhaps the most comprehensive recent work associated with tornado climatology can be found on the NSSL web site (NSSL, 2003). In this work, NSSL has broken down the data into 80 km grids, identifying the number of events in that grid per time period. Among other information, their analysis includes significant (F2 or greater) tornadoes per grid per century and total tornadoes per year in each grid box. Figure 1 shows their analysis of significant tornadoes, and demonstrates the well-known tornado alley which extends primarily through Oklahoma, eastern Kansas and into a good part of Iowa. It also identifies a higher risk region extending through the Gulf Coast states. Figure 2 shows the analysis of all tornadoes. This analysis shows that tornado occurrence not only is prevalent in tornado alley and along the Gulf Coast states, but also in central Florida and in an east-west band from northeast Colorado through Iowa and into northern Illinois. Both of these figures indicate a considerable dropoff in tornado activity as one moves northward through Wisconsin, such that the northern portion of the state appears to have only 25-30% as many tornadoes per square kilometer as the far southwestern counties.

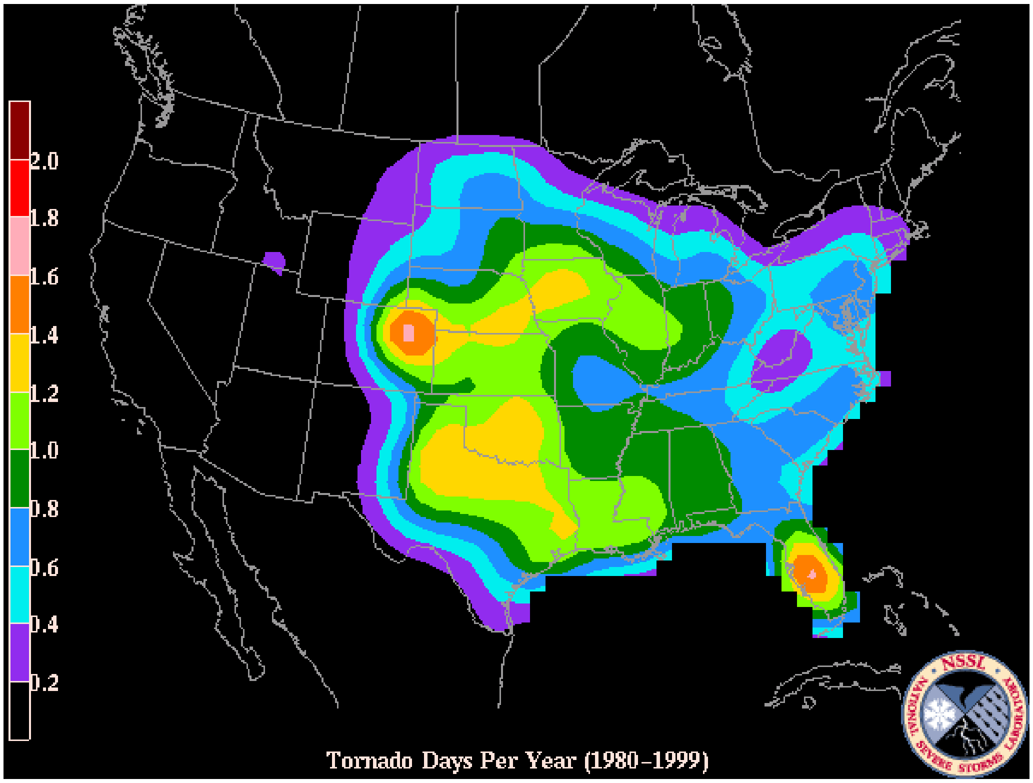

Figure 2. Mean number of days per year with at least one tornado touching down in 80km x 80km grid box. Based on data from 1980-1999. Contour interval 0.2 with lowest contour 0.2.

While Wisconsin isn't in the heart of tornado alley, its proximity is close. In fact, portions of southwest Wisconsin and adjacent areas of Minnesota and Iowa recorded as many tornado reports per square kilometer as many areas in the heart of "tornado alley". These statistics corroborate that tornadoes are an important climatological feature of Wisconsin. Nationally, Wisconsin is ranked 17th among the 50 states in number of tornadoes reported each year, based on events from 1950 through 1994 (SPC, 2002).

4. Data

In the early 1990s, the NWS Forecast Office in Milwaukee performed an extensive review of historical tornado records from around the state of Wisconsin. In the process, they identified all the tornado events they could that affected Wisconsin counties dating between 1844 and 1994. This tornado database has been updated annually through 2001. At the end of 2001, a total of 1188 tornadoes, affecting 1444 counties, had been catalogued across the state. This database represents the most complete historical set of tornado occurrence information in the state of Wisconsin through 2001.

Figure 3 shows a time series of the tornado reports in Wisconsin from 1844 through 2001. The actual numbers are provided in Table 1 (from Kapela, 2002). Assuming the occurrence of tornadoes didn't dramatically increase during the 1950s, it seems appropriate to surmise that most tornado

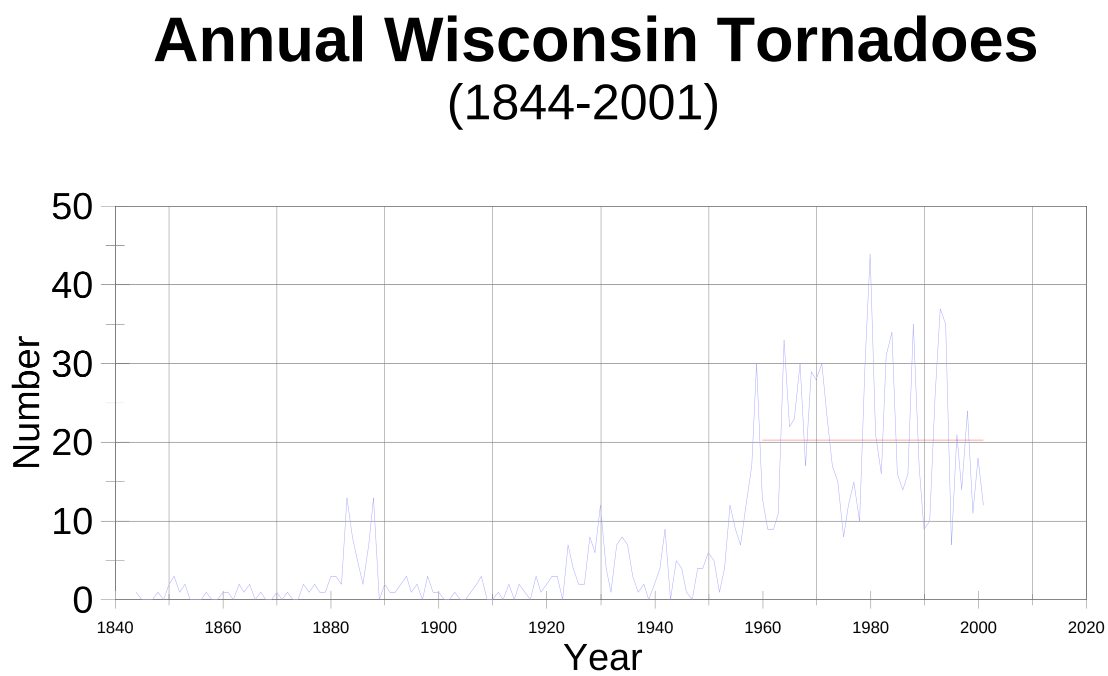

Figure 3. Annual tornadoes reported in Wisconsin, 1844-2001. The red line is the least squares fit for the period 1960-2001.

occurrences went unreported between 1844-1950. Even through much of the 1950s, it is possible that many events were not observed or reported. However, since 1960, the number of events has not shown an increasing trend and, in fact, has a nearly zero slope. In spite of the fact that the reports were very incomplete throughout the first 100 years (or more) of data, this is the most complete data set available and is deemed the most reliable we have for further analysis.

Figure 4 shows the 158-year county by county history of tornado observations throughout Wisconsin. These numbers alone are striking. While three counties (Dane, Dodge and Grant) reported at least 50 tornadoes, five others (Florence, Menominee, Ozaukee, Forest and Iron) reported 5 or less.

While it is interesting to note these raw numbers, such information does not tell the whole story regarding the statewide tornado climatology. This paper will provide a more in-depth statistical analysis of the Wisconsin tornado data set as the basis for gaining a better understanding of the true tornado climatology across the state of Wisconsin.

5. Analysis

The record of tornado occurrences in each Wisconsin county represents a unique opportunity to statistically examine how strongly the frequency of tornadoes does indeed drop off in northern Wisconsin - if indeed it does - as suggested by the earlier studies. Is it possible that population alone would account for the greater number of tornado sightings across southern Wisconsin over the years? What about other impacts, such as the effect of Lake Michigan on tornado frequency in counties which border the lake?

a. Data Assumptions

To help answer these questions using this data available, we will assume that there are four primary influences on the total number of tornado reports in each county. These influences include:

1) County size. As with the other studies, where tornado occurrence was normalized according to area, this must be taken into account. County sizes were obtained from the Wisconsin Department of Natural Resources, based on 1993 data (DNR, 1994). Assumptions in this analysis are that county sizes have not changed enough during the period of record to detrimentally impact the results.
2) Population density. As noted by Doswell (1980), the impact of population centers and major thoroughfares on tornado sightings is quite significant. Population density is preferred to population, per se, since population by itself is a function of county size, which has already been identified as an influence (above). The assumption made in this analysis is that the population density breakdown based on the 1980 census is representative of the average population density breakdown throughout the period of record. While this is likely not true for suburban counties, it is likely accurate for the main cities as well as those areas which remain rural to this date.

3) Synoptic scale climatology. By this we mean the larger scale interaction of jet streaks, moisture intrusion, and the influence of non-terrain induced low level wind shear.

4) Local climatology. This includes the impact of terrain (if any), local moisture sources, local convergence zones and so on.

We recognize that public awareness has likely not been equal in all counties during the period of record, nor has it been constant. However, for the purposes of this analysis, we assume changes in awareness do not significantly affect the results.

b. Regression Analysis Format and Results

The goal of this analysis is to determine the synoptic scale tornado climatology over Wisconsin. To achieve this, we will use statistical methods to obtain an approximation of the *total* climatological influence, including both synoptic scale and local climatology. Through 3-dimensional linear regression (Panofsky and Brier, 1958; Spiegel, 1975), which utilizes population density, area and number of tornadoes reported for each county, we can calculate the expected number of observed tornadoes for each county. This equation would be of the form:

$$T = Ax + By + C \quad (1)$$

where T is the number of tornadoes expected, x is the population density (population per square mile), y is the county area (in square miles) and A, B and C are the linear regression coefficients.

Year	Tors	Year	Tors	Year	Tors	Year	Tors	Year	Tors	Year	Tors
1844	1	1870	1	1896	2	1922	3	1948	4	1974	15
1845	0	1871	0	1897	0	1923	0	1949	4	1975	8
1846	0	1872	1	1898	3	1924	7	1950	6	1976	12
1847	0	1873	0	1899	1	1925	4	1951	5	1977	15
1848	1	1874	0	1900	1	1926	2	1952	1	1978	10
1849	0	1875	2	1901	0	1927	2	1953	4	1979	30
1850	2	1876	1	1902	0	1928	8	1954	12	1980	44
1851	3	1877	2	1903	1	1929	6	1955	9	1981	21
1852	1	1878	1	1904	0	1930	12	1956	7	1982	16
1853	2	1879	1	1905	0	1931	4	1957	12	1983	31
1854	0	1880	3	1906	1	1932	1	1958	17	1984	34
1855	0	1881	3	1907	2	1933	7	1959	30	1985	16
1856	0	1882	2	1908	3	1934	8	1960	13	1986	14
1857	1	1883	13	1909	0	1935	7	1961	9	1987	16
1858	0	1884	8	1910	0	1936	3	1962	9	1988	35
1859	0	1885	5	1911	1	1937	1	1963	11	1989	17
1860	1	1886	2	1912	0	1938	2	1964	33	1990	9
1861	1	1887	7	1913	2	1939	0	1965	22	1991	10
1862	0	1888	13	1914	0	1940	2	1966	23	1992	26
1863	2	1889	0	1915	2	1941	4	1967	30	1993	37
1864	1	1890	2	1916	1	1942	9	1968	17	1994	35
1865	2	1891	1	1917	0	1943	0	1969	29	1995	7
1866	0	1892	1	1918	3	1944	5	1970	28	1996	21
1867	1	1893	2	1919	1	1945	4	1971	30	1997	14
1868	0	1894	3	1920	2	1946	1	1972	23	1998	24
1869	0	1895	1	1921	3	1947	0	1973	17	1999	11
										2000	18
										2001	12

Table 1. Annual reported tornadoes in Wisconsin (Kapela, 2002).

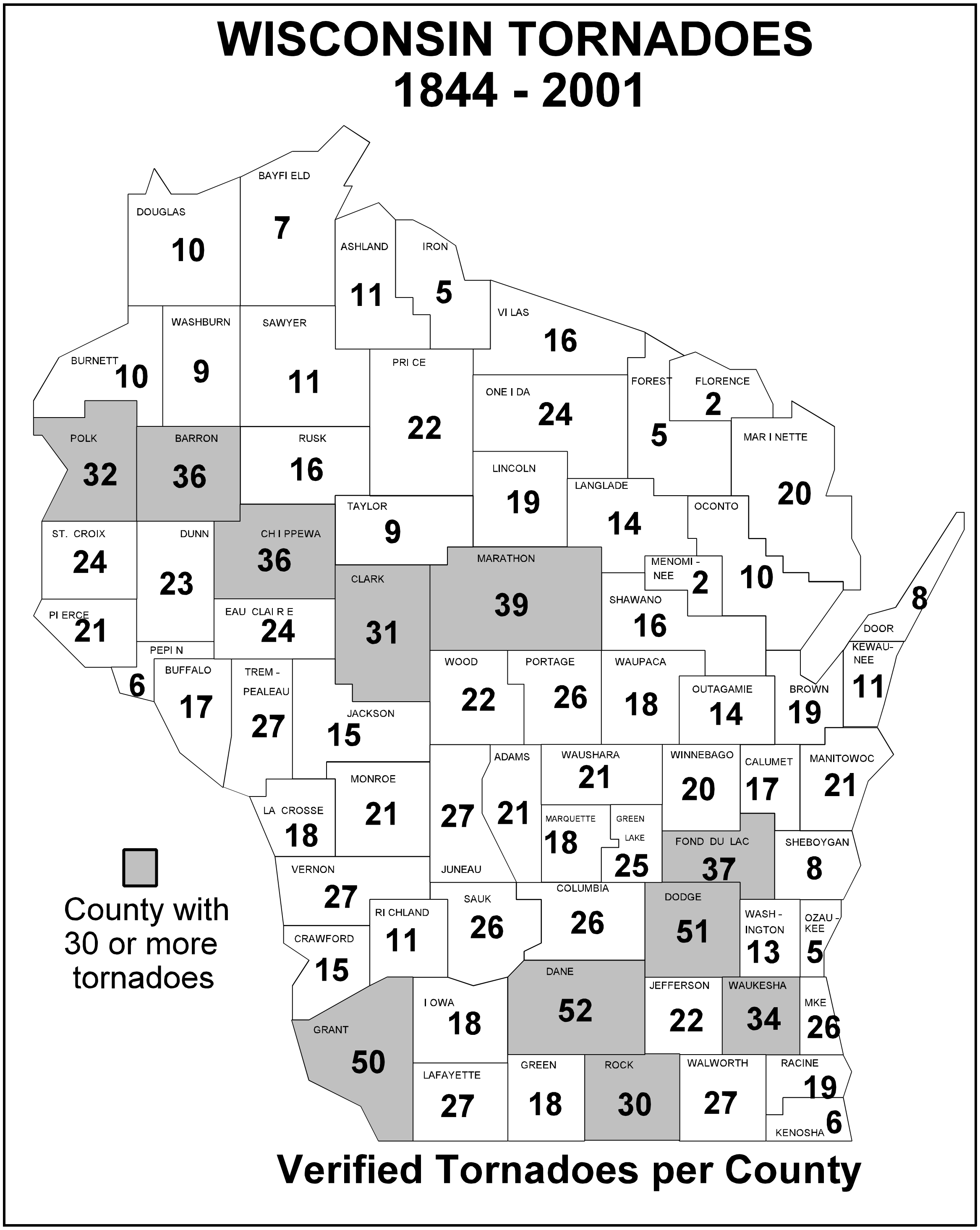

Figure 4. Total number of tornadoes for each Wisconsin county (1844-2001).

In employing this regression methodology, the 72 Wisconsin counties were arranged according to population density. Two test multiple regression analyses were run: one on the 20 counties with the lowest density and the other on the 20 counties with the highest population density. The resultant equations were:

$$T = 1.099x + 0.007y - 10.39 \quad \text{(lowest 20 counties), and} \qquad (2)$$

$$T = 0.0052x + 0.0420y - 4.03 \quad \text{(highest 20 counties).} \qquad (3)$$

From these two tests, it became clear that the regression equations were markedly different for the various types of counties. This was considered important in light of the fact that the percentage of total variance(R^2) explained by the equations was 66% and 69%, respectively. Clearly, there was significant variation in how strongly the population density and square mileage were weighted in the two test equations.

Equally as clear, a regression including all statewide counties would be highly biased toward the effect of the highly populated areas. This would yield a very low value of explained variance (R^2), rendering the resultant equation meaningless for most locations. Such a regression test was performed, utilizing all 72 counties. The resultant equation, in fact, explained only 8.6% of the variance.

Since the goal of this analysis is to identify a *statewide* perspective of tornado climatology, numerous regression analyses incorporating a variety of spatial representations would be required to minimize the effect of such a marked difference in regression equations between the highly populated and lesser populated areas. The results of the various regression analyses performed are shown in Table 2.

It is interesting to note that when the regression tests are run on a smaller number of counties representing (generally) similar locations in the state, along with similar population characteristics, the percent variance explained by the resultant equation is quite high. While the variance explained by these equations is high, their application to the statewide climatology is limited, since the areas represented by each equation are limited.

The regression equations which represent a broader spectrum of the state have lower values of explained variance. A portion of the reduction is likely due to the fact that there is a much greater disparity between the population densities around the state (from 8 to over 4000) than there is among the area covered by each county (from 242 to 1619). However, some of this reduction may also be due to the climatological differences which exist around the state.

In an effort to reduce the impact of non-climatological influences on this analysis, nine different regression equations were selected which had reasonably high explained variance while representing a fairly broad segment of the state. Those regression tests are shaded in Table 2. Spatial distribution of counties associated with each test is shown in Table 3. See Section 5 for more information on the use of this breakdown in the analysis.

Estimates for tornado occurrences, based on the regression equations highlighted in Table 1, were made for each county included in each of the equations. All estimates for each county were then averaged to determine the mean expected number of tornadoes in each county, based solely on the pertinent regression equations. These values are all shown in Table 4.

Regression Test Number	Counties in Regression Sample[#]	Regression Coefficients			
		A	B	C	R^2 (%)
1	1-20	1.0990	.0070	-10.39	66.4
2	1-30	.6285	.0097	-5.87	43.3
3	1-40	.6415	.0084	-5.70	51.6
4	1-50	.3781	.0114	-2.77	42.2
5	11-40	.5706	.0078	-2.88	31.4
6	11-50	.2565	.0129	1.1529	28.8
7	11-60	.0903	.0144	6.04	21.8
8	22-51	.1870	.0132	0.88	27.3
9	23-60	.0747	.0173	5.31	25.4
10	23-67	.0262	.0218	4.12	31.6
11	23-71	.0167	.0226	4.20	32.4
12	23-72	.0040	.0208	6.92	30.9
13	26-46	.4800	.0174	-10.82	29.8
14	26-71	.0167	.0257	2.45	36.4
15	26-72	.0042	.0239	5.16	34.9
16	28-71	.0155	.0253	3.00	35.7
17	28-72	.0041	.0236	5.59	34.6
18	33-72	.0044	.0313	1.69	55.0
19	35-72	.0044	.0324	1.26	59.0
20	38-72	.0044	.0331	1.10	61.1
21	51-72	.0053	.0457	-5.71	68.2
22	53-72	.0052	.0420	-4.03	68.8
23	55-72	.0056	.0471	-6.97	74.8
24	59-72	.0059	.0453	-7.29	78.1
25	63-72	.0055	.0462	-6.24	84.6
26	66-72	.0049	.0474	-4.43	90.9
27	69-72	.0056	.0833	-16.50	93.6
28	1-72	.0038	.0098	12.04	8.6

County number 1 has the lowest population density. County number 72 has the highest population density.

Table 2. Results of the various multiple linear regression equations, where the coefficient values are listed in accordance with equation (1). Highlighted regression tests are those included in the analysis as noted in the text.

Regression Test Number	Counties in Sample	R^2 (%)	Statewide representation of counties in sample (see Figure 5 for breakdown)		
2	1-30	43.3	NW 4/5	NC 7/7	NE 6/7
			WC 4/12	C 5/10	EC 0/9
			SW 4/9	SC 0/7	SE 0/6
3	1-40	51.6	NW 5/5	NC 7/7	NE 7/7
			WC 8/12	C 6/10	EC 0/9
			SW 7/9	SC 0/7	SE 0/6
4	1-50	42.2	NW 5/5	NC 7/7	NE 7/7
			WC 11/12	C 8/10	EC 2/9
			SW 8/9	SC 2/7	SE 0/6
5	11-40	31.4	NW 1/5	NC 4/7	NE 4/7
			WC 8/12	C 6/10	EC 0/9
			SW 7/9	SC 0/7	SE 0/6
8	22-51	32.5	NW 1/5	NC 2/7	NE 3/7
			WC 8/12	C 6/10	EC 2/9
			SW 6/9	SC 2/7	SE 0/6
11	23-71	32.4	NW 1/5	NC 0/7	NE 3/7
			WC 9/12	C 7/10	EC 9/9
			SW 7/9	SC 7/7	SE 5/6
14	26-71	36.4	NW 1/5	NC 0/7	NE 2/7
			WC 9/12	C 6/10	EC 9/9
			SW 6/9	SC 7/7	SE 5/6
19	35-72	59.0	NW 0/5	NC 0/7	NE 0/7
			WC 7/12	C 5/10	EC 9/9
			SW 4/9	SC 7/7	SE 6/6
21	51-72	68.2	NW 0/5	NC 0/7	NE 0/7
			WC 1/12	C 2/10	EC 7/9
			SW 1/9	SC 5/7	SE 6/6

Table 3. Regression equations which explain the greatest variance while covering the broadest area of the state.

County	A	B	C	1-30	1-40	1-50	11-40	22-51	23-71	26-71	35-72	51-72	Average	Diff.	County	Rgn
Florence	8	502	2	3.72	3.65	5.98							4.45	-2.45	Florence	NE
Menominee	9	365	2	3.10	3.14	4.79							3.68	-1.68	Menominee	NE
Iron	9	788	5	6.95	6.69	9.62							7.75	-2.75	Iron	NC
Forest	9	1042	5	9.26	8.83	12.51							10.20	-5.20	Forest	NE
Sawyer	9	1350	11	12.06	11.41	16.02							13.16	-2.16	Sawyer	NW
Bayfield	9	1502	7	13.44	12.69	17.76							14.63	-7.63	Bayfield	NW
Price	12	1288	22	13.38	12.82	16.45							14.22	7.78	Price	NC
Burnett	14	895	10	11.06	10.80	12.73							11.53	-1.53	Burnett	NW
Washburn	15	858	9	11.36	11.13	12.68							11.72	-2.72	Washburn	NW
Vilas	16	1019	16	13.45	13.12	14.90							13.82	2.18	Vilas	NC
Ashland	16	1038	11	13.62	13.28	15.11	14.35						14.09	-3.09	Ashland	NC
Rusk	17	913	16	13.11	12.87	14.07	13.94						13.50	2.50	Rusk	WC
Jackson	17	991	15	13.82	13.53	14.96	14.55						14.21	0.79	Jackson	WC
Taylor	19	982	9	15.00	14.74	15.61	15.62						15.24	-6.24	Taylor	NC
Adams	20	659	21	12.69	12.67	12.30	13.67						12.83	8.17	Adams	C
Buffalo	20	725	17	13.29	13.22	13.06	14.19						13.44	3.56	Buffalo	WC
Langlade	23	870	14	16.49	16.36	15.84	17.03						16.43	-2.43	Langlade	NE
Lafayette	24	645	27	15.08	15.11	13.66	15.85						14.92	12.08	Lafayette	SW
Marquette	25	465	18	14.07	14.24	11.98	15.01						13.83	4.17	Marquette	C
Juneau	25	830	27	17.39	17.31	16.14	17.86						17.17	9.83	Juneau	C
Iowa	26	772	18	17.49	17.46	15.86	17.98						17.20	0.80	Iowa	SW
Oneida	26	1218	24	21.54	21.21	20.95	21.46	24.63					21.96	2.04	Oneida	NC
Clark	27	1222	31	22.21	21.89	21.37	22.06	24.93	32.27				24.12	6.88	Clark	C
Crawford	28	598	15	17.16	17.29	14.63	17.76	15.24	18.18				16.71	-1.71	Crawford	SW
Marinette	28	1406	20	24.51	24.07	23.85	24.06	28.09	36.44				26.84	-6.84	Marinette	NE
Richland	29	592	11	17.74	17.88	14.94	18.29	15.38	18.06	18.15			17.20	-6.20	Richland	SW
Waushara	29	634	21	18.12	18.23	15.42	18.61	16.05	19.01	19.23			17.81	3.19	Waushara	C
Lincoln	29	907	19	20.60	20.52	18.53	20.74	20.39	25.18	26.24			21.74	-2.74	Lincoln	NC
Oconto	29	1009	10	21.53	21.38	19.70	21.54	22.01	27.49	28.87			23.22	-13.22	Oconto	NE
Pepin	31	242	6	15.81	16.22	11.71	16.70	10.29	10.19	9.19			12.87	-6.87	Pepin	WC
Vernon	32	807	27		21.61	18.53	21.67	19.51	22.97	23.72			21.34	5.66	Vernon	SW
Douglas	33	1344	10		26.76	25.03	26.43	28.28	35.13	37.54			29.86	-19.86	Douglas	NW
Trempealeau	36	742	27		23.63	19.30	23.45	19.42	21.57	22.12			21.58	5.42	Trempealeau	WC
Shawano	39	926	16		27.10	22.53	26.60	23.06	25.78	26.90			25.33	-9.33	Shawano	NE
Polk	40	814	32		26.80	21.63	26.29	21.51	23.26	24.04	27.81		24.48	7.52	Polk	WC
Dunn	40	863	23		27.21	22.19	26.68	22.29	24.37	25.30	29.40		25.35	-2.35	Dunn	WC
Monroe	41	862	21		27.84	22.56	27.24	22.51	24.37	25.29	29.37		25.60	-4.60	Monroe	SW
Barron	43	903	36		29.47	23.78	28.70	23.64	25.33	26.38	30.71		26.86	9.14	Barron	WC
Grant	43	1183	50		31.82	26.97	30.88	28.09	31.65	33.57	39.78		31.82	18.18	Grant	SW
Green Lake	48	383	25		28.31	19.75	27.50	16.55	13.66	13.09	13.88		18.96	6.04	Green Lake	C
Door	49	518	8			21.66		18.93	16.73	16.58	18.26		18.43	-10.43	Door	EC
Chippewa	49	1043	36			27.65		27.28	28.59	30.07	35.27		29.77	6.23	Chippewa	WC
Green	51	586	18			23.19		20.49	18.30	18.36	20.47		20.16	-2.16	Green	SC
Sauk	51	858	26			26.29		24.81	24.44	25.35	29.28		26.04	-0.04	Sauk	SW
Pierce	52	588	21			23.59		20.76	18.36	18.43	20.54		20.34	0.66	Pierce	WC
Columbia	55	798	26			27.12		24.81	23.15	23.88	27.36		25.26	0.74	Columbia	SC
Waupaca	56	764	18			27.11		24.50	22.40	23.02	26.26		24.66	-6.66	Waupaca	C
St.Croix	58	748	24			27.69		24.72	22.07	22.64	25.75		24.57	-0.57	St.Croix	WC
Kewaunee	59	332	11			23.32		18.34	12.69	11.97	12.28		15.72	-4.72	Kewaunee	EC
Marathon	69	1619	39			41.78		41.17	41.94	45.21	54.02		44.82	-5.82	Marathon	C
Portage	71	816	26					28.88	23.83	24.61	28.01	31.96	27.46	-1.46	Portage	C
Dodge	81	904	51						25.98	27.04	30.91	36.03	29.99	21.01	Dodge	SC
Wood	89	812	22						24.04	24.80	27.96	31.87	27.17	-5.17	Wood	C
Calumet	99	316	17						12.99	12.22	11.93	9.26	11.60	5.40	Calumet	EC
Jefferson	112	589	22						19.38	19.46	20.84	21.80	20.37	1.63	Jefferson	SC
Eau Claire	122	655	24						21.04	21.32	23.02	24.87	22.56	1.44	Eau Claire	WC
Fon du Lac	124	727	37						22.70	23.20	25.36	28.17	24.86	12.14	Fon du Lac	SC
Walworth	125	578	27						19.35	19.39	20.54	21.37	20.16	6.84	Walworth	SE
Manitowoc	141	593	21						19.96	20.04	21.09	22.14	20.81	0.19	Manitowoc	EC
Winnebago	185	706	20						23.25	23.68	24.95	27.53	24.85	-4.85	Winnebago	EC
La Crosse	190	472	18						18.04	17.75	17.39	16.87	17.51	0.49	La Crosse	SW
Sheboygan	191	530	8						19.37	19.26	19.27	19.52	19.36	-11.36	Sheboygan	EC
Rock	191	727	30						23.82	24.32	25.66	28.53	25.58	4.42	Rock	SC
Washington	198	434	13						17.32	16.91	16.19	15.17	16.40	-3.40	Washington	SE
Outagamie	202	638	14						21.99	22.22	22.82	24.52	22.89	-8.89	Outagamie	EC
Dane	264	1234	52						36.50	38.57	42.40	52.08	42.39	9.61	Dane	SC
Ozaukee	283	236	5						14.26	13.24	10.15	6.58	11.06	-6.06	Ozaukee	SE
Brown	336	528	19						21.74	21.63	19.85	20.20	20.86	-1.86	Brown	EC
Kenosha	440	278	6						17.83	16.94	12.20	9.33	14.08	-8.08	Kenosha	SE
Waukesha	472	585	34						25.30	25.37	22.29	23.53	24.12	9.88	Waukesha	SE
Racine	509	343	19						20.45	19.77	14.61	12.66	16.87	2.13	Racine	SE
Milwaukee	4021	239	26								26.70	26.52	26.61	-0.61	Milwaukee	SE

Table 4. County population density (A), area in square miles (B) and observed tornadoes (C). Middle columns represent the resultant estimates from the individual regression equations. Tornado anomalies (Diff.) are based on the difference between the observed tornadoes and the average from the regression equations (Average). Assignments of each county within the 9 statewide regions are shown on the far right (Rgn).

6. Discussion

The nature of the regression analysis shown here is to essentially filter out the effects of county size and population density on tornado observations. As a result, the averaged regression estimate values may be expected to provide a good statistical representation of how many tornadoes should have been observed in each county if there were no synoptic or local scale climatological influences. Therefore, comparing these estimates to the actual observations should provide some insight regarding the statewide climatology of tornadoes in Wisconsin. The far right numeric column of Table 4 shows the county by county difference between the regression estimates and the actual observations. (Hereafter, this difference is referred to as "tornado anomalies"). These county tornado anomalies are assumed to include both synoptic scale and local climatological information.

In an effort to filter out any local or mesoscale influences to obtain a more accurate indication of the synoptic scale climatology of Wisconsin tornadoes, the state was divided into 9 regions. The regional assignment of each county is shown on the far right column of Table 4, and graphically in Figure 5. All the tornado anomalies in each region were combined to obtain "regional tornado anomalies" within the state. An added byproduct of this step is to further filter out any statistical quirks from single counties in any location in the state.

The resultant values, assumed here to represent the synoptic scale climatology for Wisconsin tornadoes, are shown in Table 5 below.

	West	Central	East
North	-33.90	- 2.82	-41.15
Central	+27.47	+19.17	-36.52
South	+24.66	+47.39	+1.30

Table 5. Wisconsin regional tornado anomalies. Negative (positive) anomalies indicate fewer (more) tornadoes were observed than suggested by the regression analyses for the 158-year period.

These numbers indicate the regional tornado anomalies covering nearly 150 years beginning in 1844. For example, in the 7-county area comprising south-central Wisconsin, over 47 more tornadoes were reported than would have been expected based on the statewide tornado climatology, the regional population density and the size of the region.

Table 6 below shows the *percentage* difference between the actual tornadoes observed in each region to those expected through the regression analysis (mathematically, the tornado anomaly divided by the expected tornadoes times 100%).

	West	Central	East
North	-42%	-3%	-37%
Central	+11%	+8%	-24%
South	+13%	+25%	+1%

Table 6. The percentage difference between actual regional tornado distribution and that expected through the regression equations. Negative (positive) anomalies indicate fewer (more) tornadoes than suggested by the regression analyses for the 158-year period.

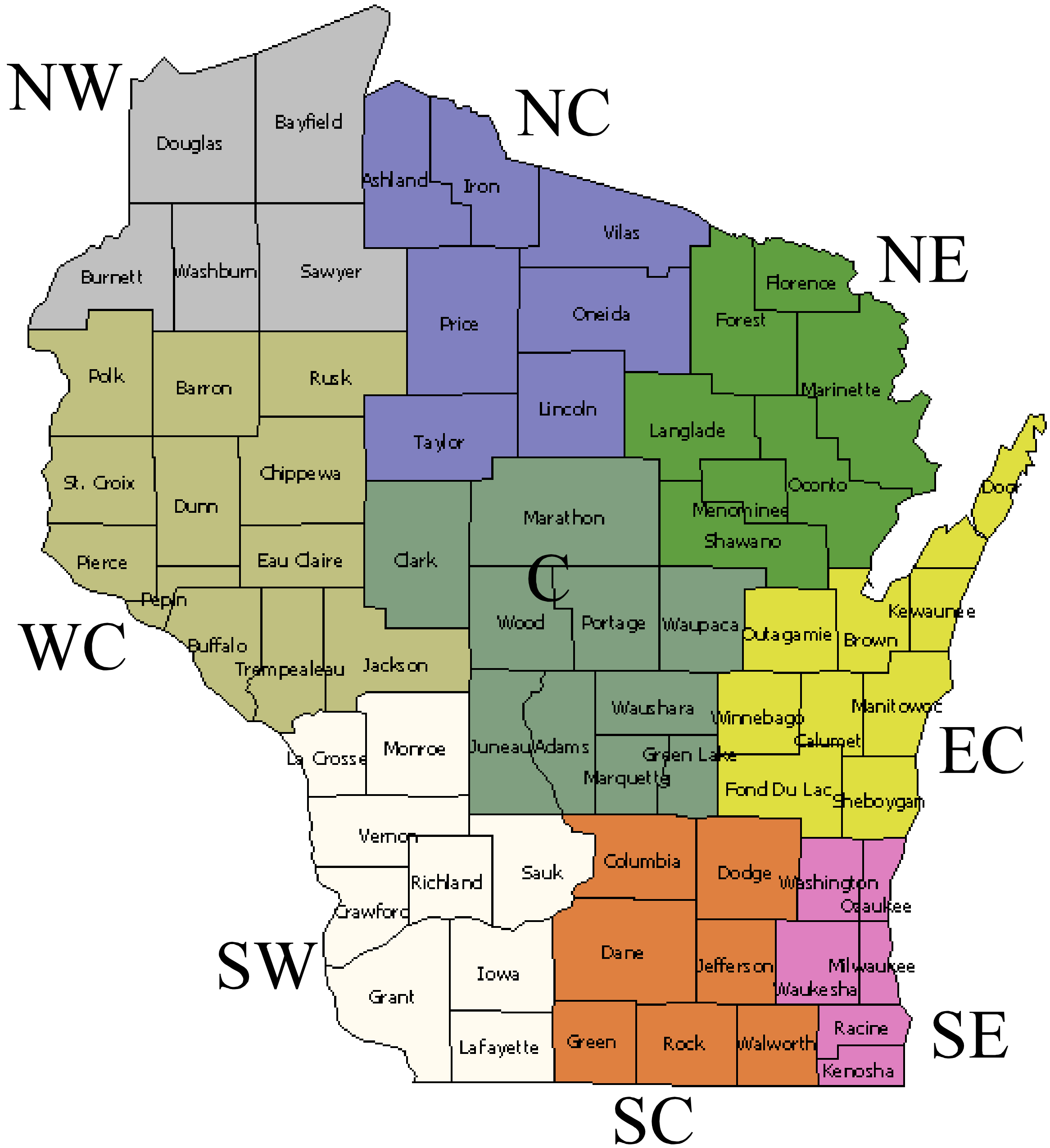

Figure 5. County Breakdowns for Wisconsin regions as noted in text.

Based on this analysis, which has accounted for all differences in population density and county size, the climatological influence on tornado occurrences across the state of Wisconsin can be estimated. Normalizing Table 6 to a base value (one), we obtain climatological comparisons between the statewide regions, as shown in Table 7 below.

	West	Central	East
North	0.58	0.97	0.63
Central	1.11	1.08	0.76
South	1.13	1.25	1.01

Table 7. Normalized regional tornado probabilities based on climatology alone.

This table shows the expected relative frequency of tornado occurrences across Wisconsin. For example, southcentral Wisconsin has around twice as great a chance of a tornado as does northeast Wisconsin (1.25/0.63). Similarly, southwest Wisconsin has twice the chance of a tornado than does northwest Wisconsin (1.13/0.58).

These tables provide results which are meteorologically rational, lending confidence to the methods employed. Earlier in the paper, we noted that NSSL (2003) showed a strong gradient of tornado frequency extending from SSW to NNE across the state. This gradient is represented by the positive anomalies across the southwestern 5 Wisconsin regions, while the northern and eastern regions all exhibited negative anomalies.

It is not the intent of this paper to identify specific causes of the anomalies shown here. However, it is worth noting a few meteorological reasons which support the statewide differences.

1) Latitudinally Based Climate Variation

Meteorologists recognize that the higher the surface temperature and dew point during the warm season, the greater the chance for explosive convective development, assuming the appropriate upper level conditions exist for any development at all. Historical temperature data across the state clearly indicate that the southwestern four Wisconsin regions have the highest maximum temperatures during the month of July (see Table 8). Maximum temperatures in these four regions in July average anywhere from 1.4 to 4.5 degrees warmer than the other Wisconsin regions.

	West	Central	East
North	82.2	80.2	82.2
Central	83.8	83.7	81.7
South	84.7	84.5	82.3

Table 8. Average July maximum temperatures as cooperative observing stations in each Wisconsin region (DOC, 1962).

A similar pattern emerges in minimum temperatures (Table 9), except that the influence of Lake Michigan is evident in the east central and southeast regions of the state. Clearly, there is a distinct gradation in minimum temperatures from south to north across western and central Wisconsin. Implied in this data as well is that dew point temperatures would have a similar gradient, with considerably more moisture (on average) in southwestern Wisconsin than northwestern Wisconsin. This moisture would, on average, increase the convective available potential energy (CAPE) available for strong updrafts across southern Wisconsin. Since the stronger updraft will enhance the thunderstorm's ability to develop pre-existing low level wind shear into a potential tornado (whether through supercellular development or localized rotation along a boundary), thunderstorms over southwestern Wisconsin should be climatologically favored to produce tornadoes relative to those over the northern portion of the state. (Note that this discussion does not account for any differences in upper level temperatures and their impact on stability. It is assumed that the lower level temperature differences across the state would impact stability more than climatological differences in upper level temperatures. For specific cases, this may not be a correct assumption).

	West	Central	East
North	55.1	55.1	56.3
Central	58.9	58.8	60.1
South	61.0	61.3	60.4

Table 9. Average July minimum temperatures at cooperative observing stations in each Wisconsin region (DOC, 1962).

The averages identified in Tables 8 and 9 are very similar to the mean temperatures published for the 1941-1970 time period (DOC, 1973). This suggests that Tables 8 and 9 provide an accurate comparison of climatic regions within the state of Wisconsin.

2) The Lake Effect

The effect of Lake Michigan on average high temperatures in east central and southeast Wisconsin is apparent in Table 8. Examining individual station records (not shown) indicates that average July maximum temperatures along or near the Lake Michigan shore are often 3 to 5 degrees cooler than locations at similar latitudes in central and western Wisconsin. The effect of the lake breeze is evident in these numbers.

The impact of the lake breeze is also apparent in the tornado statistics. This makes sense, assuming the areas impacted by the lake breeze experience a decrease in potential instability during those daylight hours due to a more stable boundary layer. Counties directly adjacent to the lake might therefore be expected to have negative tornado anomalies. By and large, this was the case. Only Racine County had a positive anomaly (+2.13), while a number of counties had anomalies at or near minus ten. In fact, six of the eight most negative anomalies were for counties which bordered either Lake Michigan or Lake Superior. These counties are:

Douglas	-19.86	(Superior)	Door	-10.43	(Michigan)
Oconto	-13.22	(Michigan)	Kenosha	- 8.08	(Michigan)
Sheyboygan	-11.36	(Michigan)	Bayfield	- 7.63	(Superior)

For the counties along Lake Superior, it is not clear whether the anomalies were due mainly to the synoptic scale climatology or if the lake played a role as well. Station temperature data suggests that the lake effect is stronger along Lake Michigan. Similarly, given that tornadic episodes will often be associated with southeasterly low level winds (which increase the low level helicity), the impact of Lake Michigan on the eastern Wisconsin counties will be much greater than that of Lake Superior on the northern counties.

Counties slightly inland from Lake Michigan exhibit considerable variability in their anomalies, ranging from strongly positive in Walworth, Waukesha, Dodge and Fond du Lac to solidly negative in Shawano, Outagamie, Winnebago and Washington. The natural convergence zone associated with the lake breeze may help enhance thunderstorm development in these counties. At the same time, the negative anomalies in Outagamie and Winnebago Counties (and possibly Shawano County) may be related to the lake effect associated with Lake Winnebago.

3) The Southwest Enigma

One of the very interesting results of this study is that the largest positive tornado anomaly is located in south central Wisconsin and not southwestern Wisconsin, which is more directly in line with the upstream "tornado alley". The NSSL analysis does not suggest that this, though their analysis contains "intentionally heavy" smoothing so as to leave only the strongest signals. In that process, they likely lost some of this detail across southern Wisconsin. It is also interesting to note that the positive tornado anomaly in west central Wisconsin is almost as great as that in southwest Wisconsin.

There are a number of factors which *may* play a role in these observations.

a) The strongly undulating terrain in southwestern Wisconsin

While tornadoes have been observed to traverse the Grand Tetons in Wyoming and the Appalachians in Pennsylvania, the disruptive influence of terrain on the near-surface inflow to mesocyclone updrafts and the organization of low level boundaries could play a role in preventing tornadic development in some cases. Southwest Wisconsin is characterized by significant undulation in the terrain, which may at times impact the ability of boundaries to organize well enough to focus rotation sufficiently to develop tornadoes. This may be one reason the positive tornado anomaly is lower in southwest Wisconsin than in the adjacent areas to the north and east.

b) The Mississippi River basin

Apart from the undulating nature of the terrain adjacent to the Mississippi River, there would appear to be no specific reason that the river would play a role in limiting tornadoes in southwestern Wisconsin. In fact, as a readily available moisture source, one may tend to argue the opposite.

The primary negative influence the Mississippi River basin may have on tornado development in southwestern Wisconsin may be that the average tornadic thunderstorm path is from southwest to northeast, or at least has a westerly component. Thunderstorms entering southwestern Wisconsin from the southwest experience lower terrain (a drop of approximately 600 feet) as they approach the river valley. Contrary to forced uplift, which would presumably enhance the updraft, forced descent might be expected to decrease the updraft intensity as the storms approach the river. Therefore, one might assume the thunderstorms enter southwestern Wisconsin in a slightly weaker state, and then increase in intensity again east of the river.

It's a theoretical possibility, but the county-by-county numbers don't consistently bear it out. Therefore, *if* the river and the river valley are a factor in some locations, they do not appear to be a factor everywhere.

c) The Lake Breeze

It is possible that enhanced convergence associated with the afternoon lake breeze (from Lake Michigan) extends far enough west at times into south central Wisconsin, especially with ambient southeasterly winds, to create more favorable conditions (including enhanced convergence and/or low level helicity) across the south central part of the state.

d) Urbanization

Studies from the early 1970s (METROMEX; Changnon, 1981) suggest that the impact of a large metropolitan area can be significant on the enhancement of rainfall, hail and lightning in areas downstream from the urban area. While the METROMEX study only extended out to about 40 miles from the city, the enhancement of these fields extended to the limits of their study, and may have remained positive even farther downstream. With this in mind, it is worth considering the potential impact of the large metropolitan area of Minneapolis-St. Paul on the development of storms over the urban area, and their impact as the storms progress east-northeastward (the prevailing direction) from the metro area. Indeed, the two most notable positive tornado anomalies in the west central area of Wisconsin are in Polk and Barron Counties (+7.52 and +9.14, respectively). *Perhaps* not coincidentally, those two counties are immediately downstream from the prevailing east-northeast direction from the metro area.

Regardless of the reason for the difference between the southwest and the adjacent areas, it is important to recognize that southwestern Wisconsin is still a relatively favored region in Wisconsin for tornadoes. Any rationale which suggests reasons why tornadoes may be hindered slightly in southwestern Wisconsin must also be tempered with the knowledge that the same area is a climatologically favored region in the state for tornadoes to occur.

7. Conclusions

This paper attempted to statistically show the statewide climatological breakdown of tornadoes in Wisconsin. The results of the statistical analyses indicated that the southwestern four regions of the state were most climatologically favored for tornado occurrence compared to the northern and eastern portions of the state. These results were very similar to other studies which used different data sets and covered shorter periods of time. The results also allow for the consideration of meteorologically plausible explanations for most of the statewide variances.

Knowledge of this information should be useful by meteorologists as a basis for climatological recognition and background. It may also serve as effective material for public education, especially for those who deal directly with public severe weather instruction.

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