A WINTER WEATHER CLIMATOLOGY FOR NORTHERN AND CENTRAL INDIANA

Brian F. O'Hara
National Weather Service
Reno, Nevada

Julie L. Adolphson
National Weather Service
Pleasant Hill/Kansas City, Missouri

Sally Pavlow
National Weather Service
Indianapolis, Indiana

Table of Contents

1. Introduction.

Cool season meteorological phenomena have been recorded over northern and central Indiana for many decades. These events have had significant impact on the population of this area. This paper is an examination of significant winter events in northern and central Indiana from 1950 to 2006. Synoptic-scale, as well as mesoscale, precipitation events are statistically analyzed to help meteorologists and their customers better understand and forecast such events.

The next section discusses the methodology including datasets and techniques used to complete this work. In general, datasets were analyzed using local computer resources and national datasets provided by the National Weather Service (NWS) Central Region. These included datasets maintained by the National Climatic Data Center (NCDC) and the National Center for Atmospheric Research (NCAR).

Section three discusses synoptic-scale snow events. Specific criteria for inclusion in the study are given as well as source regions and other pertinent information regarding 100 synoptic-scale systems. The greatest synoptic-scale systems are ranked, and measured parameters listed as a comparison to other large-scale snow events. Source regions are given in order to statistically determine the highest rate of occurrence from a given geographical region. Also listed for each of the 100 events is information regarding the surface and upper-level features.

In section four, the mesoscale phenomenon known as "lake-effect snow" is discussed. For South Bend, Indiana and the rest of the northwest portion the state, lake-effect snow is a major contributor to the yearly snowfall total. This section includes an examination of 77 lake-effect snow events, and the meteorological conditions surrounding these events. A comparison between lake and land surface temperatures for the period of October through April is given.

The next section (five) presents results of an analysis of 35 ice storm events which affected northern and central Indiana over the last fifty years. Statistics and microphysics are discussed in hopes to help forecasters identify conditions and more accurately predict ice storm occurrences.

Section six is a compilation of frost and freeze data to assist forecasters in determining appropriate dates for products related to these phenomena.

Finally, section seven is a discussion of extreme cold episodes, with an emphasis on the number of cases of below normal temperatures for various thresholds.

2. Methodology.

Data were collected from several sources, such as the National Climatic Data Center, and the University of Washington. Monthly *Local Climatological Data* (LCDs) summaries were examined to determine times and locations of winter events. Gridded re-analysis data

(Univ. of Washington and NCAR 1996) were analyzed using N-AWIPS software (National Centers for Environmental Prediction 1996) to render surface and upper-air data (St. Jean 1998). Tracks of significant surface lows were done by hand. Anomalies of atmospheric parameters were determined through a comparison of climatology with given storm events (Grumm 2000).

For the icing events, *Storm Data* (1959-2006) was used to determine significant icing events. The upper-air data for the cases were then extracted from "Radiosonde Data of North America" (FSL and NCDC 1996) and analyzed for specific parameters (e.g., maximum temperature of the warm layer, depth of cold air, etc.).

Frost/Freeze data were gathered from the U.S. Department of Commerce's *Climatography of the U.S., No. 20, Supplement No. 1: Freeze/Frost Data* (1988). Maps were then derived from these data and included in this paper.

3. Snow (synoptic systems).

a. Introduction.

Central and northern Indiana can experience snowfall during most years from November through March, especially in the lake-effect "snowbelt" in the northwestern part of the state. Snow has occurred as early as September and as late as May, although these events are rare. Visher (1944) stated that the first measurable snowfall of the season usually occurred by November 1st in northern Indiana and by mid-November in southern Indiana. He further stated that appreciable snowfall can occur sometimes even in April. A study of LCDs for stations in central and northern Indiana from the 1920s to the present confirms this. Figure 1 shows the seasonal snowfall totals from 1949-50 through 2005-06 for South Bend, Fort Wayne, and Indianapolis.

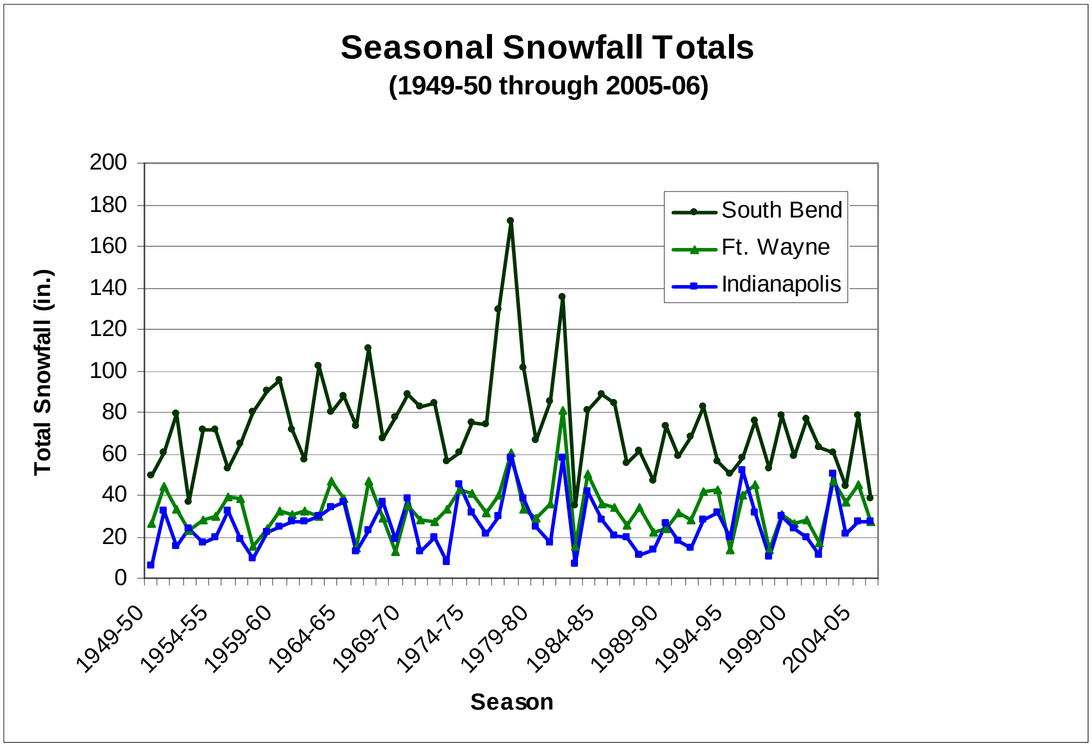

Fig. 1. Seasonal snowfall totals for South Bend, Fort Wayne, and Indianapolis, Indiana (1949-50 through 2005-06).

South Bend averages 76.5 inches of snowfall per winter (1971-2000 normals). Fort Wayne and Indianapolis receive less than half of South Bend's yearly total. The substantially greater total at South Bend is due mainly to lake-effect snow which occurs during most winters across northwestern Indiana. Fort Wayne averages 35.1 inches of snowfall each winter while Indianapolis averages 27.0 inches. Figures 2 through 4 show the snowiest winters recorded at South Bend, Fort Wayne, and Indianapolis, respectively, during the last half of the twentieth century and early twenty-first.

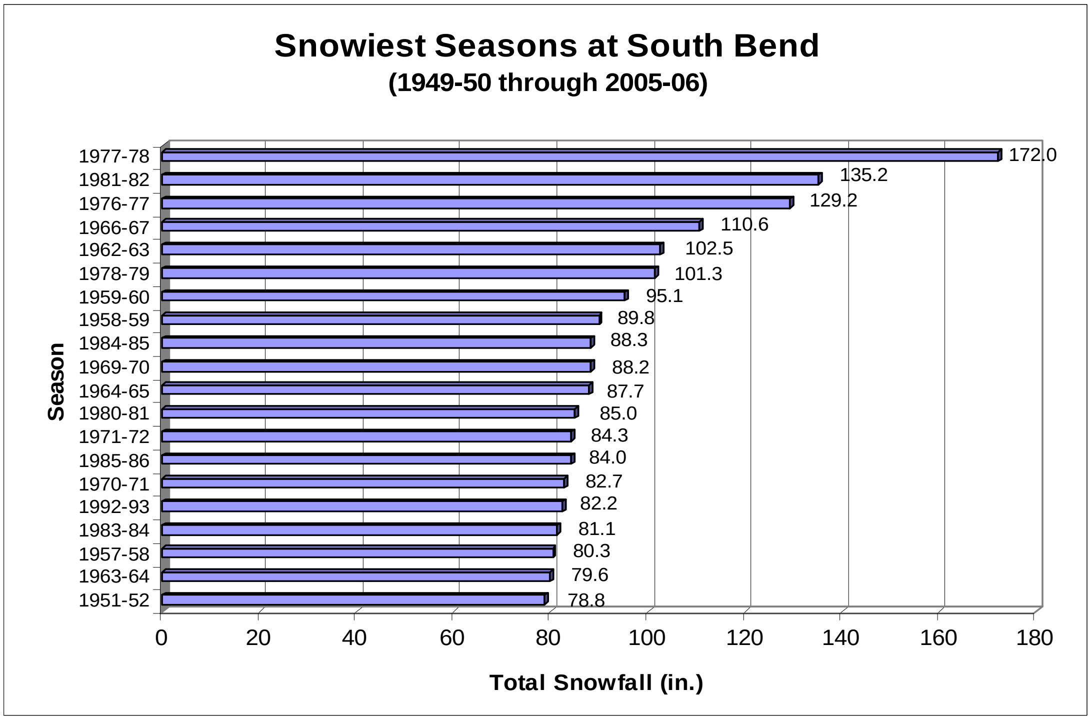

Figure 2. Snowiest seasons in South Bend, IN from 1949-50 through 2005-06.

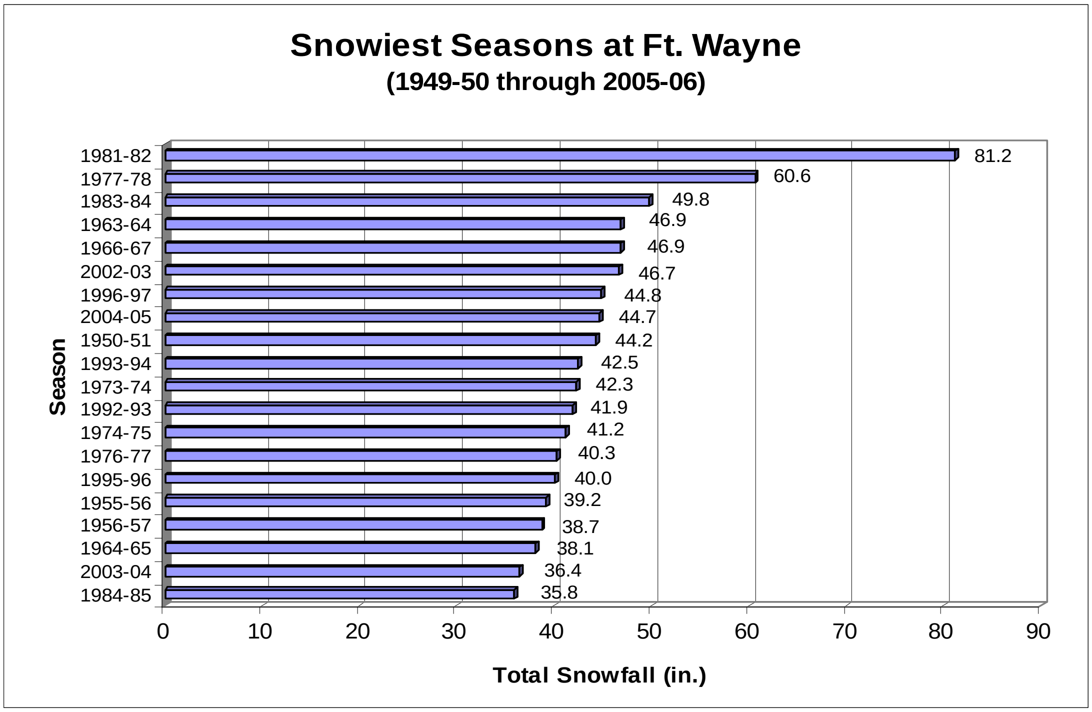

Figure 3. Snowiest seasons in Fort Wayne, IN from 1949-50 through 2005-06.

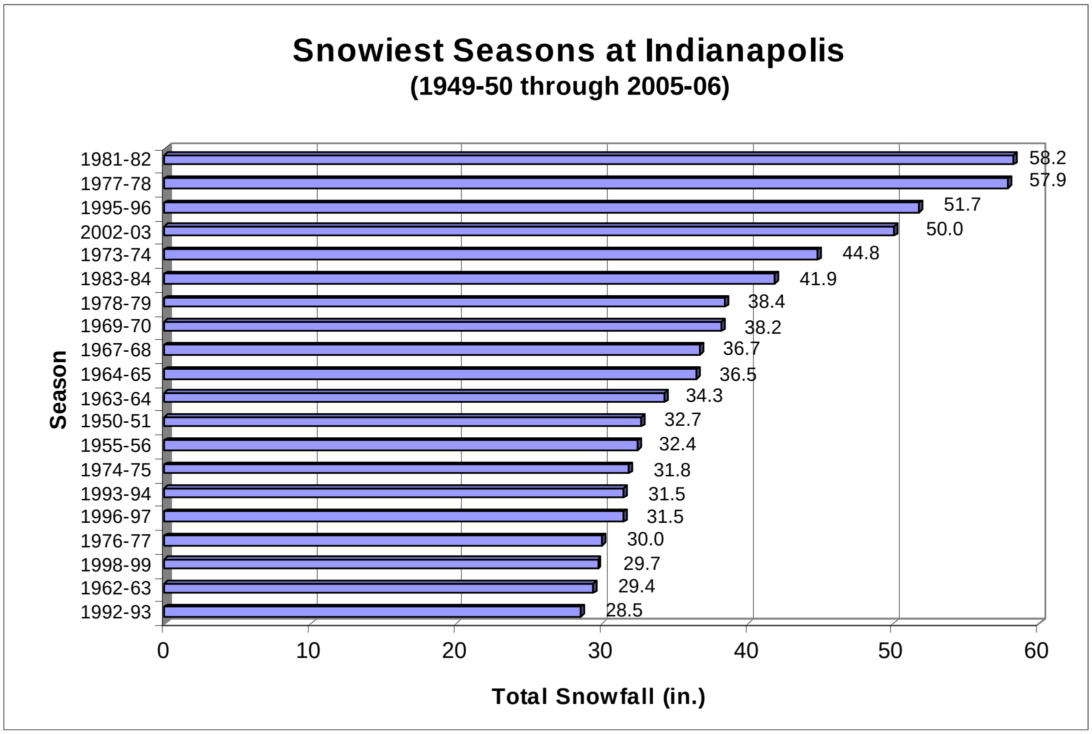

Figure 4. Snowiest seasons in Indianapolis, IN from 1949-50 through 2005-06.

As can be seen in Figures 1 through 4, the winters of 1977-78 and 1981-82 were the snowiest at each of the three locations in this study. Four significant synoptic systems affected northern and central Indiana during the winter of 1977-78. The snowstorm on 25-26 January 1978 was of historic proportions with 10 inches to over 20 inches of snowfall occurring across the region. The two largest lake-effect snow events in the last 50 years at South Bend also occurred during the winter of 1977-78. One event, in late November 1977, deposited over 24 inches of snow at South Bend. A second lake-effect snow event in early January 1978 generated over 23 inches of snowfall. These two events helped to make 1977-78 the snowiest winter of the last 50 years at South Bend.

Six significant synoptic systems affected northern and central Indiana during the 1981-82 snowfall season, resulting in the snowiest winter at both Fort Wayne and Indianapolis, and the second snowiest at South Bend. Four significant lake-effect snow events also occurred during this winter which contributed to the snowfall total at South Bend. Other winters which recorded high snowfall totals over much of the region were 1950-51, 1964-65, 1966-67, 1969-70, 1976-77, 1978-79, 1983-84, and 1995-96.

Even though snowfall can occur throughout the late-autumn to early-spring months, it is typically heavy snow that causes the most problems for residents of central and northern Indiana. The National Weather Service defines “heavy snow” as snowfall which accumulates to depths of 4 inches or more in 12 hours, or 6 inches or more in 24 hours (U.S. Dept. of Commerce 2008). In the lake-effect snow belts these definitions are adjusted upward to 6 inches or more in 12 hours and 8 inches or more in 24 hours.

Heavy snow causes many problems for the public. Snowfall rates can exceed an inch per hour. In addition to significant snowfall amounts, as synoptic systems intensify, wind speeds can approach hurricane force (74 mph). The blowing and drifting snow that results can paralyze a region. Automobiles are stranded on highways and peoples' lives are at risk in the absence of adequate shelter. With roads impassable, travel may be restricted for significant periods.

To further compound risks, cold air advecting south behind the retreating low pressure area can cause temperatures to plummet. As the arctic high pressure area behind the low builds into the region temperatures can fall to 20 to 30°F below normal. A cold air mass can stay over the region for up to a week. These conditions can strain utility systems that are already working at peak output.

The weight of the snow itself can also be a problem, especially if the snow has high water content. Tremendous weight of snow from significant storms can cause structures to collapse. Tree branches, especially on fully-leaved trees can easily break under the weight of heavy snow. For example, if a snow cover of 12 inches has a water equivalent of 1.0 inch of water it would weigh 5.2 pounds per square foot (Doesken and Judson 1996). Additional snowfall would continue to increase this weight and structures could eventually become stressed. Flat roofs are especially susceptible to this problem but sloping roofs, especially if the structural components are weak, can also be damaged.

For this study, daily snowfall totals recorded in the LCDs for Indianapolis (IND), Fort Wayne (FWA), and South Bend (SBN) were used. Strong systems were defined as systems which either (a) deposited total snow amounts of 4 inches or more in at least two of these locations or (b) deposited 6 inches or more storm totals at least one location. The first criterion reflects a system that would have a widespread areal effect on central and/or northern Indiana. The second criterion reflects a snowstorm that deposits a significant amount of snow that could inconvenience the public (even if it does not cover a large area). One hundred events satisfied these criteria during the 57 years of this study from 1949-50 through 2005-06.

As a caveat, more than 6 inches of snow can fall at South Bend during a lake effect event while Fort Wayne and Indianapolis receive almost no snowfall. For purposes of this study, a synoptic event was required to satisfy an additional criterion: The surface low would have to pass close enough to Indiana (typically within a couple hundred miles of the state) and deposit snowfall totals meeting the above criteria in at least one of the locations for the storm to be considered a synoptic event.

During some events, a surface low passed through the northern part of Indiana resulting in 5 to 10 inches of snow at South Bend while Fort Wayne and Indianapolis received little or no snow (much of their precipitation might have fallen as rain to the right of the surface low track). This would be considered a synoptic event. However, after the low moved out of the region, and northwesterly winds in the wake of the low moved across Lake Michigan, the snow accumulation at South Bend from this would then be considered lake effect. Three of the significant synoptic events in this study (17-18 Dec. 1954, 3-4 Mar. 1960, and 14 Feb. 1991) also saw significant lake effect snow affect northwestern Indiana the following day as the low moved away from the region.

South Bend occasionally received significant snowfall even if a low did not travel close to Indiana. To be considered a significant lake effect event (and be included in this study) South Bend had to receive 6 or more inches of snow while the other two sites received approximately an order of magnitude less (e.g., an inch or less). When this occurred, synoptic analysis typically indicated that a surface low had passed southeast of the region or that a surface high was located to the southwest. Under this scenario, surface winds would be from a northwesterly to a northerly direction (over Lake Michigan), which results in snow at South Bend but not farther inland at Fort Wayne or Indianapolis. Each of the events in this study that satisfied the snowfall criteria for strong systems was analyzed as either a synoptic system event or a lake effect event. The significant lake effect events are discussed in the lake effect section below.

b. Significant systems.

Table 1 describes each of the 100 major synoptic events that occurred during the period of this study (1949-50 through 2005-06). Total daily measurable synoptic snowfall recorded during the event is listed for South Bend, Fort Wayne, and Indianapolis. Also listed is the lowest 1200 UTC mean sea level pressure (MSLP) reported during each event, along with the pressure anomaly (departure from normal) this surface pressure reading represented. The source region of each system is listed. Finally, whether the 500-hPa contours showed a positive or a negative tilt, the type of 500-hPa wave (either remaining an open wave or becoming a closed circulation), and the lowest closed 500-hPa contour are also listed for each event.

Table 1.

Significant Synoptic Snowfall Events Across Northern and Central Indiana (1949-50 through 2005-06)

Event	Total Snowfall for Event			Lowest Sfc Press (hPa)	Surface Pressure Anomaly	Source Region	500-hPa Tilt	Type of 500-hPa Wave	Lowest Closed Contour (m)
	SBN	FWA	IND						
11-13 Mar. 1950	2.2	7.6	0.0	1005	-1	Central Rockies	Pos	Open	
25-26 Nov. 1950	8.3	8.0	3.3	988	-3	Atlantic Coast	Neg	Closed	5220
25-26 Dec. 1950	7.1	4.1	0.8	992	-2	Central Rockies	Neut	Closed	5040
6-7 Nov. 1951	13.6	3.1	3.4	1003	-2	Central Rockies	Neut	Closed	5460
14-15 Dec. 1951	8.3	4.5	2.2	991	-2	Southern Rockies	Pos	Open	
6 Feb. 1952	1.0	7.7	0.0	1016	0	Central Rockies	Pos	Open	
26-27 Nov. 1953	6.2	2.9	2.8	1004	-1	Central Rockies	Neut	Open	
14-16 Dec. 1953	10.4	5.1	3.4	984	-3	Alberta	Neut	Closed	5280
17-18 Dec. 1954	8.4	0.7	0.7	992	-2	Panhandle	Pos	Open	
29-30 Jan. 1956	7.7	3.7	4.8	1008	-1	Southern Rockies	Neut	Open	
9-10 Jan. 1957	6.7	3.6	0.4	1001	-1	Alberta	Pos	Open	
22-23 Jan. 1957	8.3	3.6	0.4	1012	0	Pacific	Neut	Open	
7-8 Apr. 1957	5.9	6.6	2.7	997	-2	Central Rockies	Pos	Open	
31 Dec. 1957- 1 Jan. 1958	6.6	0.8	0.4	1000	-1	Southern Rockies	Neut	Open	
25 Feb. 1960	5.2	7.0	4.6	998	-2	Gulf	Neg	Closed	5280
3-4 Mar. 1960	11.0	2.6	1.2	984	-2	Southern Rockies	Neg	Closed	5160
16-17 Mar. 1960	6.5	1.5	1.2	1000	-1	Southern Rockies	Pos	Closed	5340
20-21 Dec. 1960	10.1	6.5	2.2	1002	-2	Pacific	Pos	Open	
16-17 Apr. 1961	9.9	4.9	2.4	986	-3	Alberta	Neg	Closed	5280
23-24 Feb. 1962	5.8	5.8	5.8	999	-2	Southern Rockies	Neut	Open	
12-13 Jan. 1964	1.3	7.1	8.5	1000	-2	Gulf	Pos	Closed	5220
10-11 Mar. 1964	5.1	14.3	4.9	992	-3	Southern Rockies	Neg	Closed	5400
2 Dec. 1964	5.4	5.7	0.0	997	-2	Central Rockies	Pos	Open	
15-16 Jan. 1965	3.2	3.5	11.3	1004	-1	Alberta	Pos	Closed	5340
24-25 Feb. 1965	11.5	7.5	12.5	980	-4	Pacific	Neg	Closed	5160
2-3 Nov. 1966	5.8	6.6	8.3	989	-3	Gulf	Neg	Closed	5280
26-27 Jan. 1967	17.9	2.1	0.7	992	-3	Pacific	Neg	Closed	5340
5 Feb. 1967	5.8	5.0	1.2	999	-2	Alberta	Pos	Open	
13-14 Jan. 1968	6.1	5.2	11.1	1008	-1	Central Rockies	Neut	Closed	5280
6-7 Jan. 1969	10.8	3.2	9.2	994	-2	Pacific	Neg	Open	
23 Dec. 1969	5.4	3.3	5.1	998	-2	Pacific	Neut	Open	
16-17 Mar. 1973	4.7	12.5	2.0	980	-4	Southern Rockies	Neg	Closed	5220
19-20 Dec. 1973	12.5	14.0	12.6	1008	-1	Central Rockies	Neut	Open	
13-14 Nov. 1974	5.3	5.2	0.0	1004	-2	Central Rockies	Pos	Closed	5220
20-21 Dec. 1974	6.1	3.7	0.0	1012	-1	Panhandle	Neut	Open	
26-27 Nov. 1975	6.6	4.4	3.1	1012	-1	Central Rockies	Neg	Open	
9-10 Jan. 1977	11.9	3.2	6.7	988	-3	Southern Rockies	Neg	Closed	5100
21-22 Mar. 1977	5.7	5.2	1.2	997	-2	Panhandle	Neg	Open	
5-6 Dec. 1977	11.2	6.2	9.6	990	-4	Central Rockies	Neg	Closed	5160
8-9 Dec. 1977	5.6	6.2	3.8	997	-1	Pacific	Neut	Open	
1-2 Jan. 1978	11.2	2.9	1.1	1012	-1	Central Rockies	Neg	Open	
25-26 Jan. 1978	21.2	10.1	15.2	962	-5	Southern Rockies	Neg	Closed	5040
13 Jan. 1979	13.5	0.1	0.0	988	-2	Pacific	Neut	Open	
24 Jan. 1979	6.7	5.4	5.0	991	-3	Central Rockies	Neg	Closed	5280
11-12 Feb. 1979	8.1	5.5	0.8	1020	0	Southern Rockies	Pos	Open	
25 Feb. 1979	0.0	2.4	7.1	1000	-2	Southern Rockies	Neut	Closed	5460

Table 1. (cont)

Significant Synoptic Snowfall Events Across Northern and Central Indiana (1949-50 through 2005-06)

Event	Total Snowfall for Event			Lowest Sfc Press (hPa)	Surface Pressure Anomaly	Source Region	500-hPa Tilt	Type of 500-hPa Wave	Lowest Closed Contour (m)
	SBN	FWA	IND						
15-16 Feb. 1980	6.9	4.1	2.1	997	-2	Southern Rockies	Pos	Open	
27-28 Nov. 1980	7.1	4.6	1.0	1004	-1	Southern Rockies	Neut	Closed	5340
24-25 Dec. 1980	6.7	3.2	1.2	1012	-1	Central Rockies	Pos	Open	
10-11 Feb. 1981	8.9	6.9	6.1	993	-2	Alberta	Neg	Open	
21-22 Dec. 1981	7.1	5.3	0.0	988	-2	Panhandle	Pos	Open	
27-28 Dec. 1981	2.0	7.8	2.4	999	-1	Alberta	Neg	Open	
15-16 Jan. 1982	8.4	2.1	1.5	995	-1	Alberta	Pos	Open	
31 Jan. 1982	4.4	10.8	7.2	1001	-2	Central Rockies	Neut	Open	
3 Feb. 1982	1.3	6.7	6.5	1016	-1	Gulf	Pos	Open	
5-6 Apr. 1982	9.1	5.0	1.3	990	-2	Central Rockies	Neg	Closed	5220
20-21 Mar. 1983	9.6	6.2	0.6	989	-3	Central Rockies	Neg	Closed	5340
21 Dec. 1983	8.0	3.3	0.6	1005	0	Gulf	Neut	Closed	5100
30 Jan. 1984	5.8	6.0	1.8	1002	-2	Alberta	Neut	Open	
27-28 Feb. 1984	6.0	5.6	12.2	992	-3	Panhandle	Neut	Closed	5340
10-11 Feb. 1985	11.8	5.9	4.9	1012	-1	Pacific	Neg	Open	
6-7 Feb. 1986	3.4	6.2	1.2	1002	-2	Southern Rockies	Neg	Open	
9-10 Jan. 1987	7.8	6.7	5.7	1002	-1	Southern Rockies	Pos	Closed	5340
18-19 Jan. 1987	7.0	9.1	3.5	998	-2	Southern Rockies	Neut	Closed	5340
3-4 Feb. 1988	2.2	6.0	2.1	1004	-1	Alberta	Pos	Open	
11-12 Feb. 1988	8.2	7.8	2.0	1008	-1	Panhandle	Neg	Closed	5220
19-20 Oct. 1989	8.8	8.0	7.5	1008	-1	Atlantic Coast	Neg	Closed	5400
24-25 Feb. 1990	7.2	2.5	2.2	1000	-2	Alberta	Neut	Open	
3-4 Dec. 1990	6.1	1.2	0.9	1000	-1	Central Rockies	Pos	Closed	5280
22-23 Dec. 1990	6.5	7.1	3.7	1004	-1	Great Lakes	Pos	Open	
14 Feb. 1991	7.3	2.3	0.0	983	-3	Alberta	Neut	Closed	5100
14-15 Jan. 1992	6.2	6.8	4.9	976	-4	Panhandle	Neg	Open	
9-10 Dec. 1992	6.7	6.3	3.2	1002	-1	Alberta	Neg	Open	
9-10 Jan. 1993	3.2	7.3	2.4	1016	-1	Southern Rockies	Neut	Open	
16-17 Feb. 1993	6.7	6.1	3.7	995	-1	Southern Rockies	Neg	Open	
10-11 Mar. 1993	6.1	2.0	0.1	1008	-1	Alberta	Neut	Open	
24-25 Feb. 1994	10.0	4.4	1.4	996	-2	Southern Rockies	Neut	Open	
6 Apr. 1994	0.4	6.0	0.8	1008	-1	Central Rockies	Pos	Open	
21-22 Jan. 1995	9.8	3.4	3.2	991	-3	Southern Rockies	Neg	Closed	5280
19 Dec. 1995	0.0	6.4	8.0	980	-3	Southern Rockies	Neut	Open	
9-11 Nov. 1996	10.4	2.5	0.0	1008	-1	Alberta	Neg	Closed	5280
16-17 Dec. 1996	1.2	7.1	7.5	1003	-1	Alberta	Pos	Closed	5220
9-10 Jan. 1997	7.5	4.7	7.5	981	-3	Central Rockies	Neut	Open	
15-16 Jan. 1997	14.8	4.0	3.0	984	-3	Alberta	Neut	Closed	5040
9-10 Dec. 1997	6.0	2.0	0.5	999	-1	Central Rockies	Pos	Closed	5400
2-3 Jan. 1999	16.0	8.4	8.7	994	-2	Panhandle	Neg	Closed	5220
5-6 Mar. 1999	8.1	1.3	0.0	1009	-1	Central Rockies	Neut	Open	
8-9 Mar. 1999	5.9	7.1	5.2	998	-2	Central Rockies	Neg	Open	
18-19 Jan. 2000	4.0	4.0	4.2	1000	-2	Pacific	Neg	Open	
11 Mar 2000	0.0	8.8	8.1	1003	-1	Central Rockies	Neut	Closed	5380
13-14 Dec. 2000	4.2	4.5	5.7	1015	0	Central Rockies	Pos	Open	
25-26 Feb. 2002	11.5	5.6	3.6	1001	-1	Alberta	Neut	Closed	5160
25-26 Mar 2002	5.0	6.2	0.5	1003	-1	Central Rockies	Pos	Open	
24-25 Dec. 2002	7.4	8.2	7.8	998	-2	Panhandle	Neg	Closed	5320
10-11 Feb. 2003	5.7	2.4	5.8	1006	-1	Alberta	Neut	Open	
22 Feb. 2003	1.1	6.4	6.3	986	-3	Southern Rockies	Neg	Closed	5500
26-27 Jan. 2004	10.0	8.5	3.9	996	-2	Alberta	Neg	Closed	5270
22-23 Dec. 2004	4.1	8.3	10.1	988	-2	Alberta	Pos	Open	
21-22 Jan. 2005	8.6	5.5	1.1	990	-3	Central Rockies	Neut	Closed	5180
8 Dec. 2005	7.7	8.3	7.7	1014	0	Alberta	Neut	Closed	5330

c. Greatest synoptic snow events.

On average, central and northern Indiana experience significant synoptic snow events once or twice per winter. As mentioned above, 100 such events occurred from 1949-50 through 2005-06. However, the largest snowstorms are often the ones that cause the most damage and inconvenience to the public and tend to be the ones that are the most easily remembered. A few, in fact, may be remembered for a lifetime.

A review of the data indicates that nearly half of the largest snowstorms to affect the region originated in the central and southern Rockies. Of the 25 synoptic events that deposited the most snowfall at Indianapolis, Fort Wayne, and South Bend, six systems formed over the central Rockies and six originated over the southern Rockies. The trajectories of these snowstorms resulted in the advection of copious moisture from the Gulf of Mexico, leading to significant snowfall totals.

Table 2 lists the 25 greatest synoptic snowstorms that affected central and northern Indiana during the 55 snowfall seasons in this study. Information listed with each event is the same data that are listed for each event in Table 1 above.

Table 2.

Greatest Synoptic Snowstorms to Affect
Northern and Central Indiana
(1949-50 through 2005-06)

Event	Total Daily Snowfall for Event			Lowest Sfc Press (hPa)	Surface Pressure Anomaly	Source Region	500 hPa Tilt	Type of 500 hPa Wave	Lowest Closed Contour (m)
	SBN	FWA	IND						
1. 25-26 Jan. 1978	21.2	10.1	15.2	962	-5	Southern Rockies	Neg	Closed	5040
2. 19-20 Dec. 1973	12.5	14.0	12.6	1008	-1	Central Rockies	Neut	Open	
3. 2-3 Jan. 1999	16.0	8.4	8.7	994	-2	Panhandle	Neg	Closed	5220
4. 24-25 Feb. 1965	11.5	7.5	12.5	980	-4	Pacific	Neg	Closed	5160
5. 5-6 Dec. 1977	11.2	6.2	9.6	990	-4	Central Rockies	Neg	Closed	5160
6. 10-11 Mar. 1964	5.1	14.3	4.9	992	-3	Southern Rockies	Neg	Closed	5400
7. 19-20 Oct. 1989	8.8	8.0	7.5	1008	-1	Atlantic Coast	Neg	Closed	5400
8. 27-28 Feb. 1984	6.0	5.6	12.2	992	-3	Panhandle	Neut	Closed	5340
9. 8 Dec. 2005	7.7	8.3	7.7	1014	0	Alberta	Neut	Closed	5330
10. 24-25 Dec. 2002	7.4	8.2	7.8	998	-2	Panhandle	Neg	Closed	5320
11. 6-7 Jan. 1969	10.8	3.2	9.2	994	-2	Pacific	Neg	Open	
12. 10-11 Feb. 1985	11.8	5.9	4.9	1012	-1	Pacific	Neg	Open	
13. 22-23 Dec. 2004	4.1	8.3	10.1	988	-2	Alberta	Pos	Open	
14. 31 Jan. 1982	4.4	10.8	7.2	1001	-2	Central Rockies	Neut	Open	
15. 13-14 Jan. 1968	6.1	5.2	11.1	1008	-1	Central Rockies	Neut	Closed	5280
16. 26-27 Jan. 2004	10.0	8.5	3.9	996	-2	Alberta	Neg	Closed	5270
17. 10-11 Feb. 1981	8.9	6.9	6.1	993	-2	Alberta	Neg	Open	
18. 15-16 Jan. 1997	14.8	4.0	3.0	984	-3	Alberta	Neut	Closed	5040
19. 9-10 Jan. 1977	11.9	3.2	6.7	988	-3	Southern Rockies	Neg	Closed	5100
20. 2-3 Nov. 1966	5.8	6.6	8.3	989	-3	Gulf	Neg	Closed	5280
21. 26-27 Jan. 1967	17.9	2.1	0.7	992	-3	Pacific	Neg	Closed	5340
22. 25-26 Feb. 2002	11.5	5.6	3.6	1001	-1	Alberta	Neut	Closed	5160
23. 9-10 Jan. 1987	7.8	6.7	5.7	1002	-1	Southern Rockies	Pos	Closed	5340
24. 6-7 Nov. 1951	13.6	3.1	3.4	1003	-2	Central Rockies	Neut	Closed	5460
25. 9-10 Jan. 1997	7.5	4.7	7.5	981	-3	Central Rockies	Neut	Open	

The most memorable system to affect central and northern Indiana during the last fifty-five years was the incredible snowstorm of 25-26 January 1978. This system originated over the southern Rockies. It moved south to near Brownsville, Texas, then out over the Gulf, and north through the Tennessee valley. It then merged with another system from the northern Plains. This combined system then moved across Lake Erie, setting low pressure records as it moved north through the Ohio Valley into eastern Canada. Over 21 inches of snow fell at South Bend, over 10 inches at Fort Wayne, and over 15 inches at Indianapolis during this two-day period. This combination of events produced what could be considered a "once-in-a-lifetime" snowstorm.

Eight other southern or central Rockies systems produced storm total snowfall of at least 10 inches at one or more of the three locations in this study. A system during the third week of December 1973 originated over the central Rockies. This system deposited over a foot of snow across central and northern Indiana. An interesting feature of this system was the 500-hPa pattern never formed a closed circulation. Unlike many strong storms, it remained an open wave throughout its existence. Surface pressure also remained relatively high. However, enough moisture was advected into the system to result in the large snowfall amounts.

Five Pacific systems made the list of top twenty-five most powerful systems to affect the study area. One of these systems was ranked number four. This snowstorm was responsible for 11.5 inches of snow in South Bend and 12.5 inches of snow in Indianapolis on 24-25 February 1965. This system, however, took an interesting track. It moved across Idaho and Wyoming on the 22nd and into the southern Rockies on the 23rd. It then rounded the Big Bend region of Texas, moved out into the Gulf, and then northeast along the Appalachian Mountains to the eastern Great Lakes. This system could have been considered a Gulf or southern Rockies low except that its circulation originated in the Pacific. Perhaps this should be considered a type of hybrid system since it curved so far to the south and was thus able to entrain significant Gulf moisture.

The MSLP in this system fell to 980 hPa on the 25th (only five of the 100 systems studied recorded pressures this low or lower). The strong dynamics increased upward vertical velocities and low-level wind speeds, and advected Gulf moisture into the system. The residence time over the Gulf of Mexico allows a Pacific low to generate heavy snowfall over central and northern Indiana. Only two other Pacific lows (13-14 Jan. 1979 and 10-11 Feb. 1985) tracked this far south, but both spent relatively little time over the Gulf. The January 1979 system turned more northerly, and moved into the southern Great Lakes; only South Bend received significant snowfall. The February 1985 system moved up the Appalachians so central and northern Indiana received six inches to a foot of snow. The other eight Pacific systems all followed a more northerly track across the Plains and produced lesser amounts of snow over Indiana.

The only panhandle lows in the top twenty-five were ranked third and eighth. These systems deposited five or more inches of snowfall at each of the three locations. The system that moved through the region on 2-3 January 1999 resulted in over eight inches of snow at both Fort Wayne and Indianapolis and 16 inches at South Bend. Another panhandle low moved up the Appalachians in late February 1984. It dropped over 12 inches of snow on Indianapolis but half that amount at Fort Wayne and South Bend.

It is interesting to note that, of the 25 strongest systems, 14 of them exhibited a negative tilt of the trough axis at 500 hPa (in fact, 8 of the top 10 did). This is similar to what Kocin and Uccellini (1990) found in their study of major snowstorms that affected the U.S. east coast. Of the twenty systems they examined, nineteen showed a negative tilt at 500 hPa. Of the 100 systems that affected central and northern Indiana during the 55 years of this study 36 had a negative tilt at 500 hPa. Another 35 went from a positive to a neutral tilt. Since systems that developed a negative tilt are clustered among the top 25, this may imply that if a strong system develops a negative tilt at 500 hPa, there is a higher probability that it may produce relatively higher amounts of snow as it moves through a region. This may be a valuable predictand for forecasting snowfall amounts.

d. Strength of surface lows.

Meteorologists are well aware that the strength of a surface low pressure area can have a great effect on the resulting weather conditions. As a system intensifies, winds around the surface low strengthen and precipitation rates can increase. To determine storm intensity as related to a larger climatological database, Richard Grumm, Science and Operations Officer at the National Weather Service Forecast Office in State College, Pennsylvania, used an algorithm to quantify anomalies of specific synoptic-scale parameters. (Grumm 2000).

The algorithm used the difference between the observed parameter and the daily average value of the parameter for that location. This difference was then divided by the daily average variability (standard deviation) for that parameter at that location. The resulting integer represents the number of standard deviations from normal. A positive number indicates that a parameter is a certain number of standard deviations above normal. Conversely, a negative number shows that the parameter is below normal.

The standard deviation measures the degree of variability or “dispersion” of a variate (Panofsky and Brier 1958). The variability of many meteorological parameters can be seen as a normal distribution. In this distribution the average value of a parameter is at the center of the distribution. The parameter usually varies very little (such as the normal high temperature for a date, normal precipitation for a certain month, etc.). Any variance is usually close to the average. Larger variances are increasingly rare.

For example, if the average high temperature on July 15th for a location is 83 ^{O}F, it is not considered unusual if, during various years, the high temperature readings for July 15th range from the upper 70s to the upper 80s. It is not as common for the high temperature to be in the lower 70s or in the middle 90s. It is even rarer if the high temperature on this date is in the upper 60s or in the lower 100s. This distribution is displayed as a normal bell curve with the most common values clustered near the center of the graph.

By definition, in a normal distribution 68 percent of the values are located within one standard deviation of the mean (i.e., plus or minus one standard deviation). Ninety-five percent of the values are within two standard deviations of the mean. Only five percent of occurrences are further from the average than two standard deviations. Thus, the standard deviation of a parameter is a measure of the likelihood of an event occurring.

The surface pressure anomalies (or departure from average) for the events in this study were generally negative. This meant that the surface pressures of these strong systems were less than normal. This would seem reasonable since the study included strong synoptic systems, and larger snowfall totals are usually associated with more intense low pressure systems. Many of the anomalies were impressive. The greatest winter storm during the period of this study (the incredible 25-26 January 1978 blizzard) had a surface pressure that, when at its most intense, was five standard deviations below normal! This was truly a rare event. Only four events out of the 100 studied had surface pressures that were average (zero standard deviation). None of the events had a positive anomaly.

e. Source regions of synoptic systems.

Since synoptic systems may have a significant effect on the residents of the southern Great Lakes region, a study of the source regions of these systems would be of benefit to forecasters. Early diagnosis and prediction can increase lead time which in turn may minimize effects on the public.

The authors found that the strong low pressure systems affecting central and northern Indiana could be described as coming from eight source regions. These regions, in order of their importance, are (a) the central Rocky Mountains, (b) the southern Rocky Mountains, (c) Alberta, (d) the Pacific Ocean, (e) the Texas/Oklahoma panhandle, (f) the Gulf of Mexico, (g) the Atlantic Coast, and (h) the Great Lakes.

Other researchers found similar results when looking at source regions of lows that affect the Great Lakes. Eichenlaub (1979) described eight paths that correlated closely with the tracks found in this study. Eichenlaub’s tracks were referred to as Alberta, north Pacific, north Rocky Mountain, Colorado, Panhandle, south Pacific, Texas, and east Gulf. In his cyclone climatology, Angel (1996) analyzed cyclone tracks affecting the Great Lakes throughout the year. In investigating the frequency of strong winter cyclones, he found two preferred tracks. The northern track ran east out of Alberta and the southern track was out of the southwestern U.S. In this climatology Angel also described a study conducted by Lewis. Lewis studied 92 Great Lakes cyclones over a nearly 30-year period and found eight source regions: Alberta, Colorado, Texas, Gulf of Mexico, Cape Hatteras, Great Lakes, Northwest, and Pacific. Eighty-three percent of these cyclones occurred between November and March.

Black (1971) made a study of blizzards which affected the north-central U.S. during the ten-year period from 1957-58 through 1966-67. He found two main source regions for systems which affected the northern Great Plains and upper Mississippi valley. Of the 53 blizzards he studied, 25 systems originated as Colorado lows and 20 were Alberta lows. He found that most Alberta lows formed during December, January, and February. He stated that this temporal pattern may be because the Canadian storm track is farthest south during these months.

This is similar to the results of this study of systems affecting central and northern Indiana. Fourteen of the 17 Alberta lows formed during December, January, and February. All nine of the Pacific lows formed during these three months. In addition, 77 percent of the southern Rockies lows and 88 percent of the panhandle lows occurred during these three months.

Black also found that in November and March there were more blizzards from Colorado lows than from Alberta lows. This is also reflected in the results of this study for Indiana. Even though blizzards were not looked at specifically, seventy percent of the one hundred strong systems that affected this area of the southern Great Lakes during October and November, and again in March and April, originated in the southern and central Rockies. This may also be related to the fact that these two source regions provided most of the systems throughout the winter seasons studied.

Table 3 gives the total number of systems originating in each source region and indicates the months during which these systems affected central and northern Indiana during the period of this study. (The 31 December 1957 - 1 January 1958 event was listed in the December totals since the low formed during that month.)

Table 3.

Temporal Distribution of Systems from
Various Source Regions

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Central Rockies		4	8	6	1	6	3	28
Southern Rockies		1	3	7	8	4		23
Alberta		1	6	6	7	1	1	22
Pacific			3	5	2			10
Panhandle			4	2	2	1		9
Gulf		1	1	1	2			5
Atlantic Coast	1	1						2
Great Lakes			1					1
Total	1	8	26	27	22	12	4	100

1) Central Rockies lows.

The largest number of low pressure systems (28) that affected central and northern Indiana during the fifty years of this study was lows that originated in the central Rocky Mountains. For this study the central Rockies is defined as the area from northern Idaho and Montana south to southern Nevada, Utah, and Colorado. These lows tend to move southeast into the central and southern Plains before curving and moving through the Ohio valley and into the northeastern U.S. Figure 5 shows the tracks of central Rockies lows from the 1950s through the 1970s. Figure 6 shows the tracks from the 1980s through 2005.

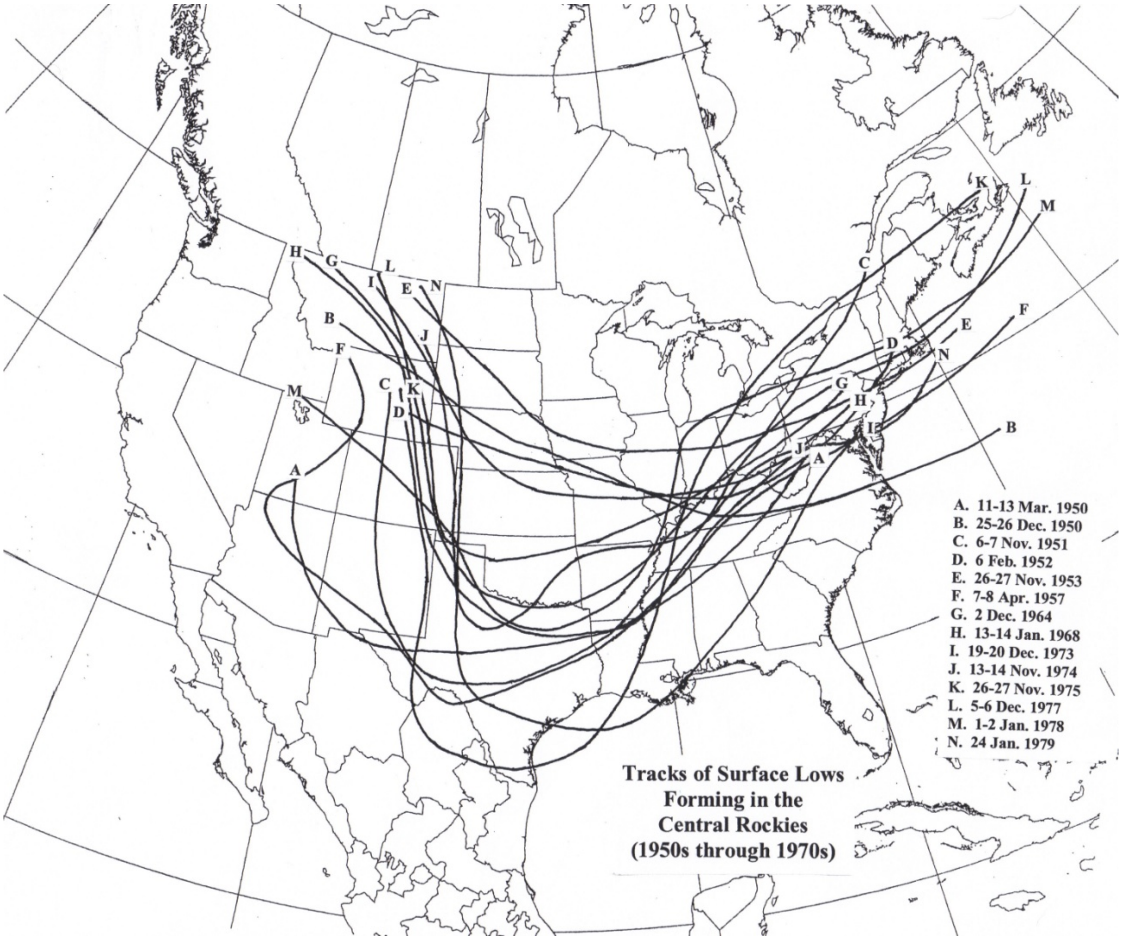

Figure 5. Tracks of surface lows forming in Central Rockies from 1950s through 1970s.

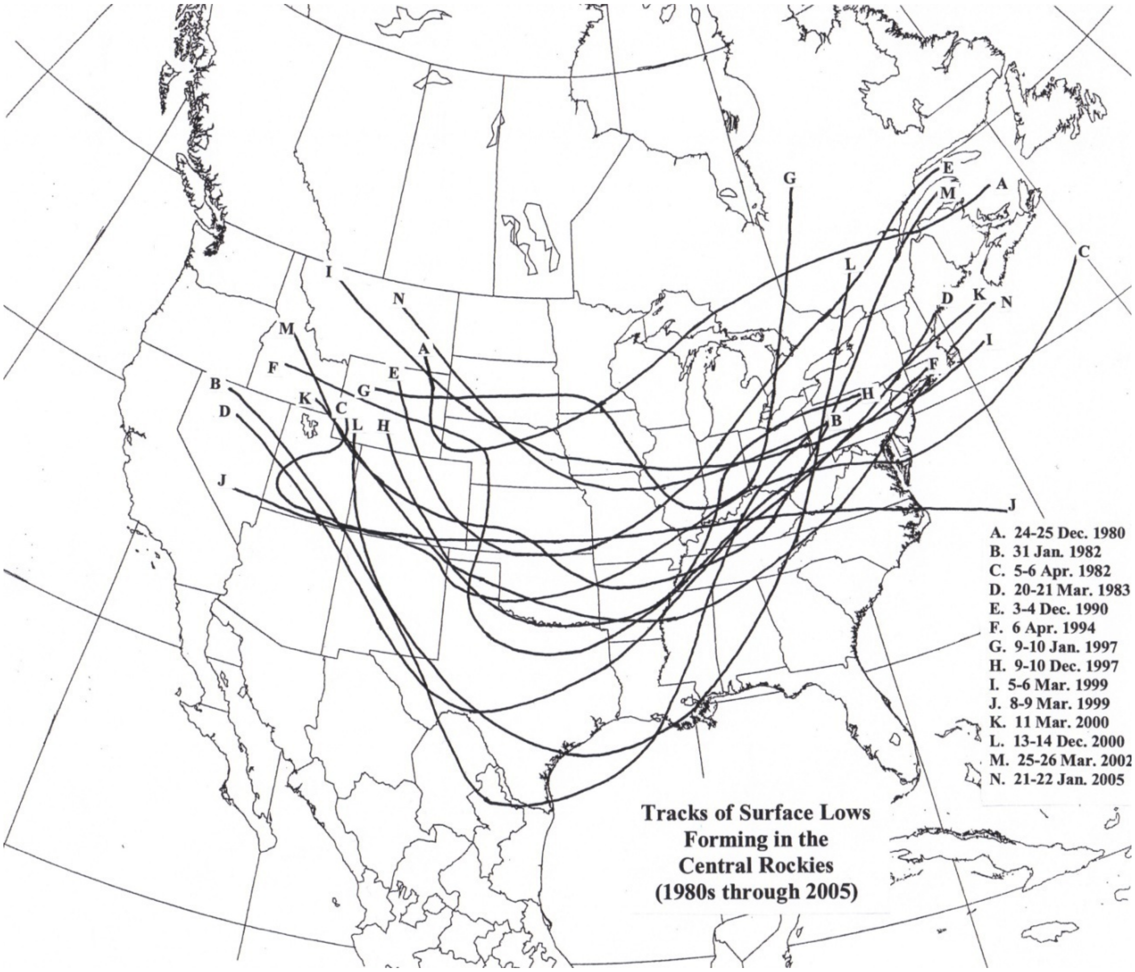

Figure 6. Tracks of surface lows forming in Central Rockies from 1980s through 2005.

2) Southern Rockies lows.

In this study the southern Rockies is defined as the area from northern Arizona and New Mexico south into northern Mexico. Twenty-three lows originated in this region. These systems typically followed a curved trajectory through southern Texas into the lower Mississippi valley, and then along the western edge of the Appalachian Mountains into the northeastern U.S. Like central Rockies lows, these systems can deposit large snowfall amounts over the Great Lakes as they entrain Gulf moisture on their trek into the northeastern U.S. These strong systems occur approximately once every two years.

The tracks of these systems are almost identical to those of central Rockies lows. One difference is that the source region of central Rockies lows is farther north. Another difference is that, in this study of strong systems, central Rockies lows tended to occur earlier in the season (from November through January). As the synoptic-storm tracks migrated farther south during the winter, lows tended to form over the southern Rockies later in the season (from January through March). Over half of the 100 synoptic systems in this study originated in either the central or southern Rockies. Figure 7 shows the tracks of these systems from the 1950s through the 1970s. Figure 8 shows the tracks for systems from the 1980s through 2005.

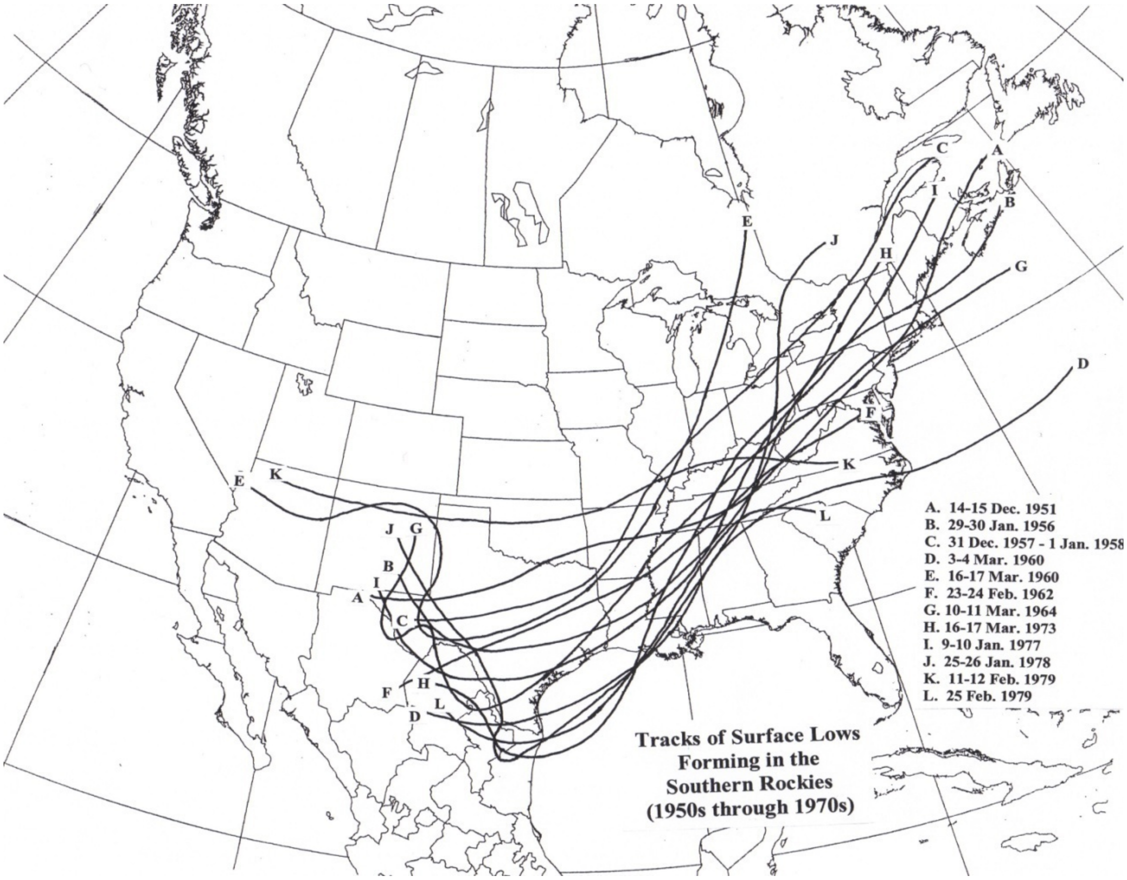

Figure 7. Tracks of surface lows forming in Southern Rockies from 1950s through 1970s.

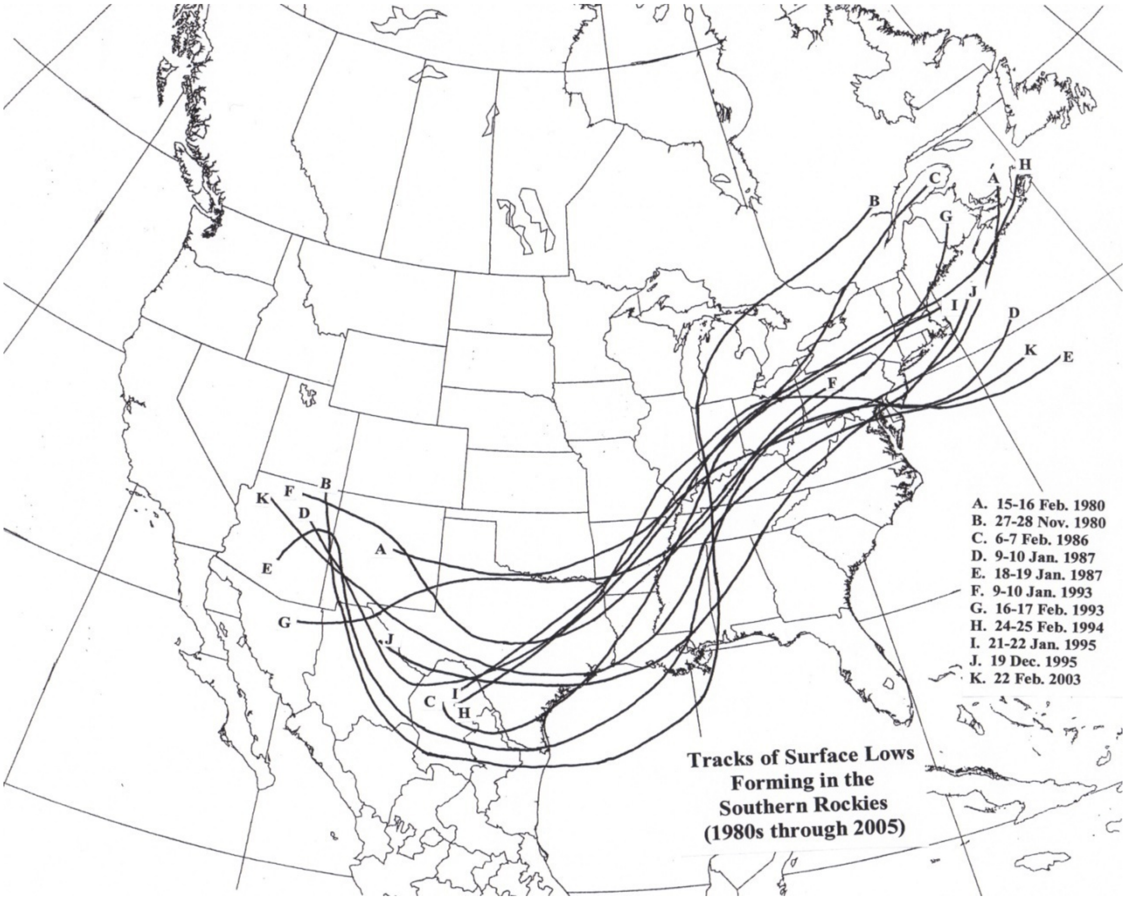

Figure 8. Tracks of surface lows forming in Southern Rockies from 1980s through 2005.

3) Alberta lows.

Alberta lows ("Alberta Clippers") affect the Great Lakes region fairly often each winter. These systems originate in the Canadian Rockies in or near the province of Alberta (hence their name) and, often aided by a strong polar jet stream, quickly move across the northern Great Plains. Moisture is often already in place over the Great Lakes region before these systems arrive. Strong upper-level dynamics and cold air aloft help to make these systems quite potent as they move out of the Plains. During the 57 years this study reviewed, 22 systems were classified as Alberta lows. Figure 9 shows the tracks of Alberta lows from the 1950s through 2005.

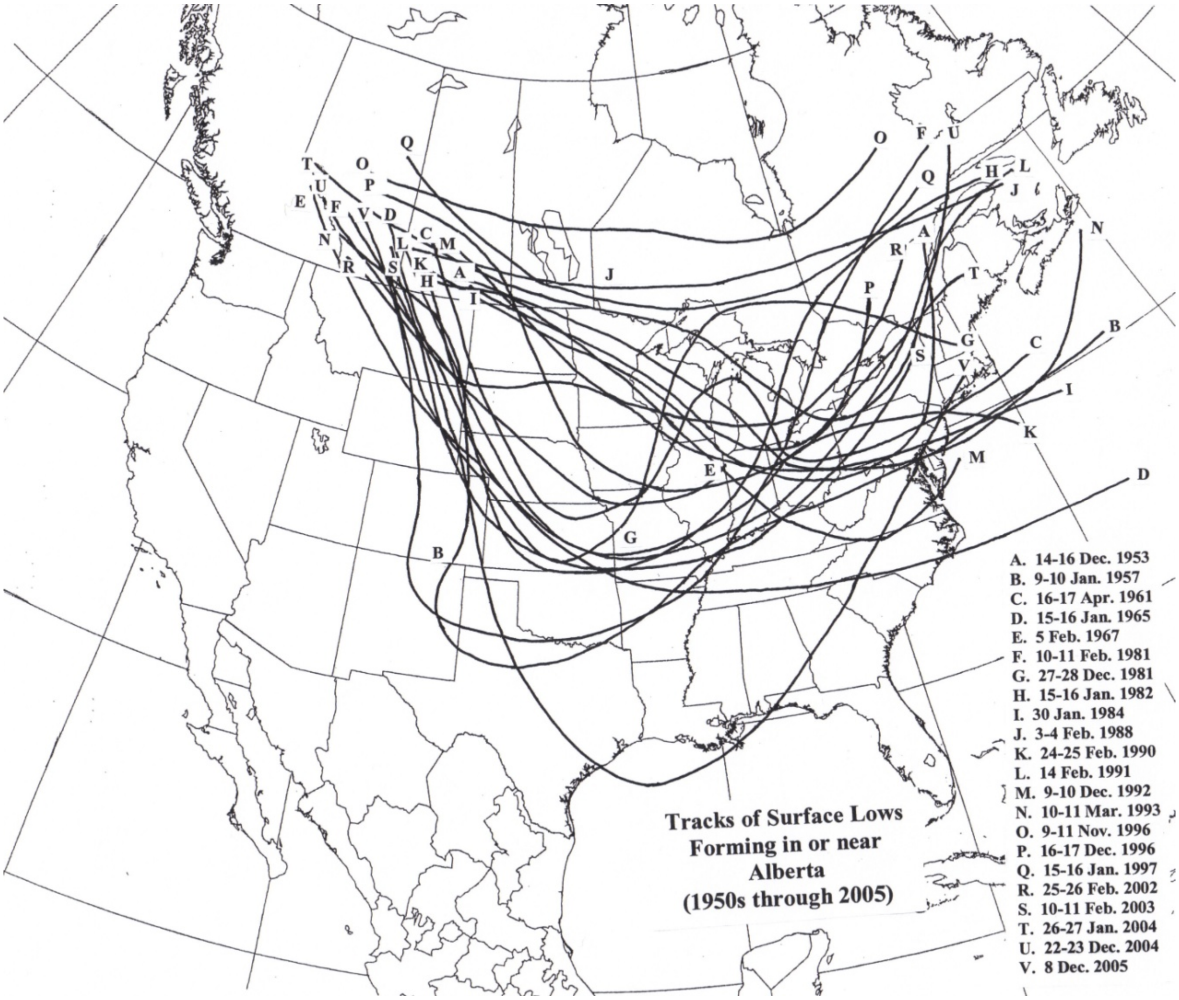

Figure 9. Tracks of surface lows forming in or near Alberta, Canada, from 1950s through 2005.

4) Pacific lows.

Like Alberta lows, Pacific lows are not as common as the central and southern Rockies systems mentioned above. Of the 100 systems studied, ten originated over the northeastern Pacific off the Washington and Oregon coasts. Synoptic charts showed these systems with closed circulations off the Pacific northwest coast. These surface lows maintained their identities and could be followed across the continental divide into the central and southern Plains of the U.S. With this curved trajectory these lows advected Gulf moisture north into their circulations. This possibly replaced much of the moisture they lost while passing over the Rockies. The ten Pacific lows in this study occurred only during the depth of winter (from December through February).

Pacific lows deposited some of the largest snowfall totals in this study. A remarkable storm during the last week of February 1965 deposited 12.5 inches of snow at Indianapolis, 11.5 inches at South Bend, and 7.5 inches at Fort Wayne. A system in early January 1969 produced 10.8 inches of snow at South Bend and 9.2 inches at Indianapolis. Still another generous storm in February 1985 left 11.8 inches of snow at South Bend, 5.9 inches at Fort Wayne, and 4.9 at Indianapolis. Figure 10 shows the tracks of Pacific lows from the 1950s through 2005.

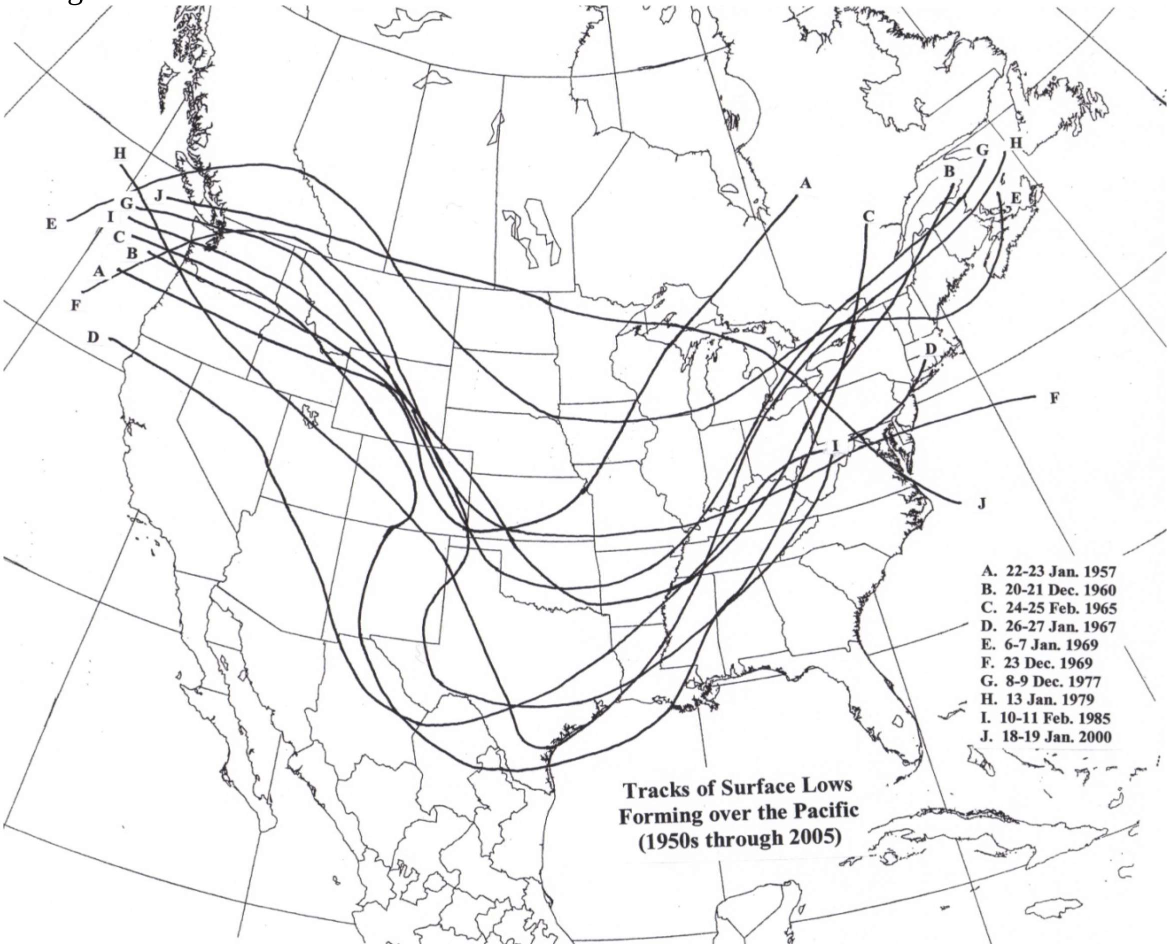

Figure 10. Tracks of surface lows forming over the Pacific Ocean from the 1950s through 2005.

5) Panhandle lows.

Nine synoptic events which produced significant amounts of snow over the study region can be defined as panhandle lows. These lows originate in the region of the Texas/Oklahoma panhandles and move to the northeast into the Great Lakes and northeastern U.S. Panhandle lows can produce high snowfall totals as they advect Gulf moisture into their circulations and move out of the Plains into the lower-Mississippi and Ohio valleys. One of the strongest snowstorms to hit the southern Great Lakes region during the last half of the twentieth century was a panhandle low. This powerful system on January 2-3, 1999 produced 16.0 inches of snow at South Bend, 8.7 inches at Indianapolis, and 8.4 inches at Fort Wayne. Another system, in late February 1984, left 12.2 inches of snow at Indianapolis and almost half that at both South Bend and Fort Wayne. Figure 11 shows the tracks of panhandle lows from the 1950s through 2005.

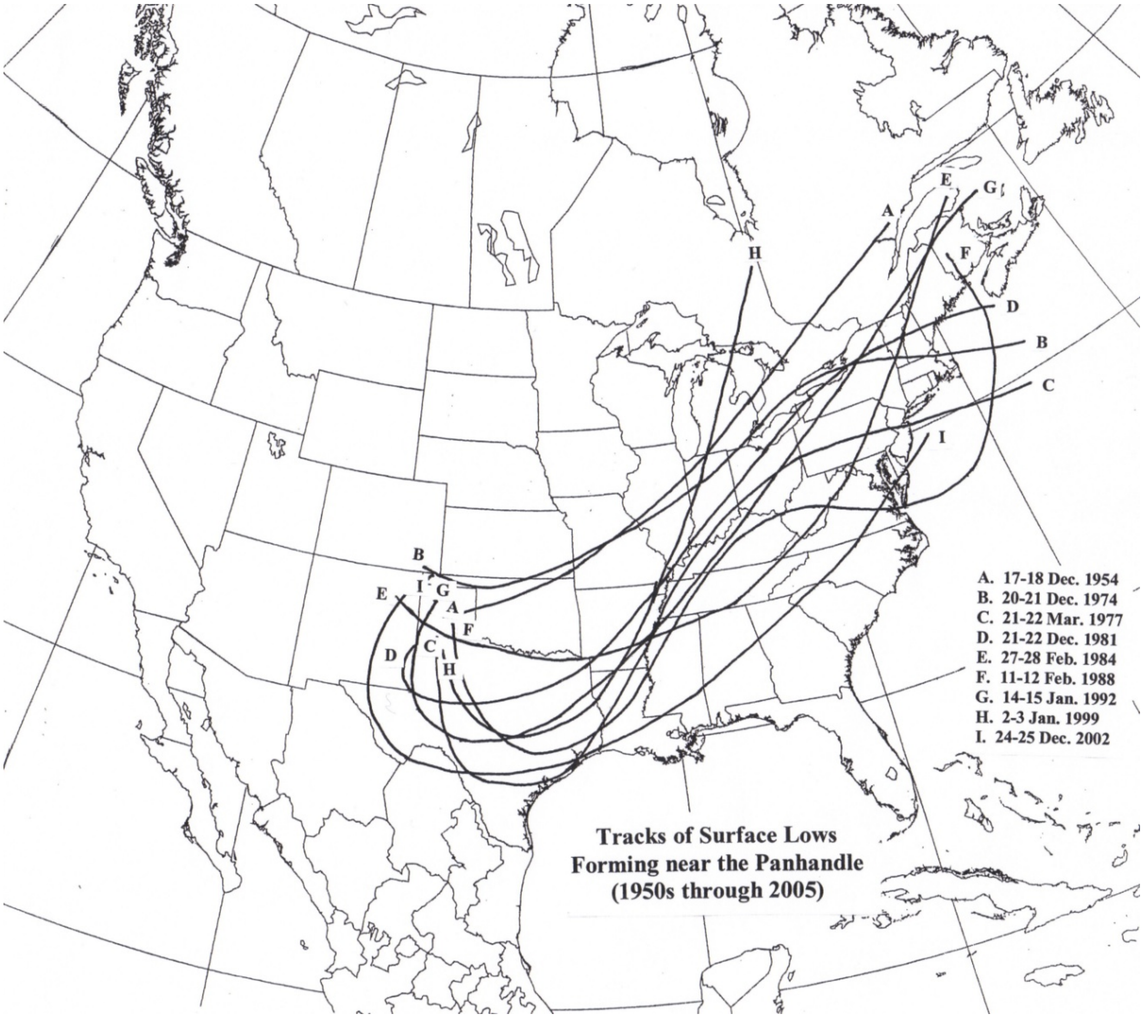

Figure 11. Tracks of surface lows forming near the Oklahoma/Texas “panhandles” from the 1950s through 2005.

6) Gulf lows.

Another low pressure system that infrequently affects Indiana during the winter is the Gulf low. These systems entrain copious amounts of moisture as they move into the Great Lakes and northeastern U.S. The upper level-trough that is often over eastern Canada and the U.S. during the winter provides these systems with a northeasterly track. These lows can bring large snowfall totals to the Great Lakes and the eastern seaboard.

Only five Gulf systems affected central and northern Indiana during the period of this study. November, December and January each recorded an event, and the remaining two were in February. This temporal clustering during late fall and winter may simply be due to the small number of systems that met the criteria of this study. Therefore, Gulf lows that produce smaller amounts of snowfall in the southern Great Lakes region (and thus not included in this study) may be more evenly distributed from late fall to early spring. Figure 12 shows the track of Gulf lows from the 1950s through 2005.

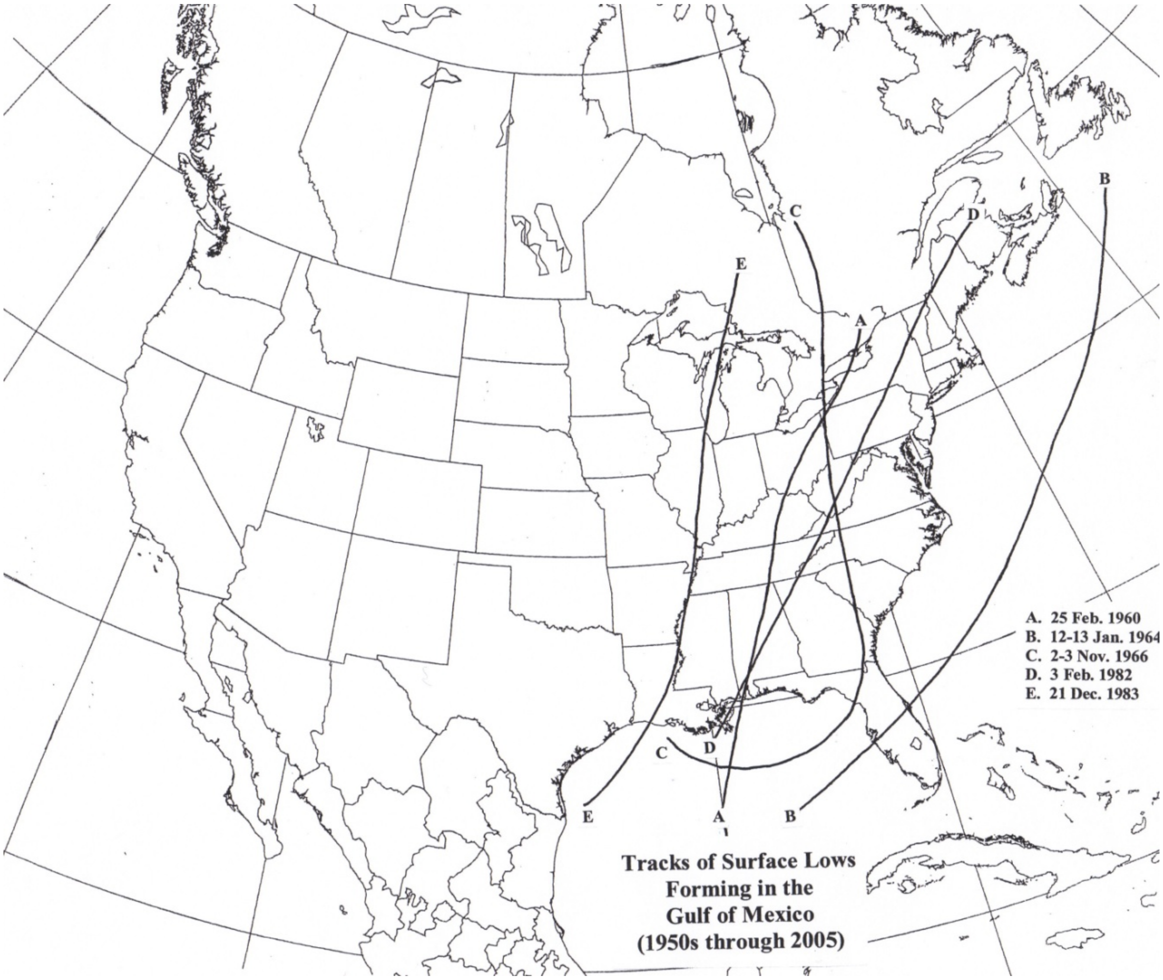

Figure 12. Tracks of surface lows forming in the Gulf of Mexico from the 1950s through 2005.

7) Atlantic Coast lows.

These are lows which form over the coast of the southeastern U.S. or just offshore. They travel in a northerly direction and can produce snow over a large portion of the eastern U.S. Due to their movement from the south, central Indiana can experience heavy snowfall from these systems. During the 57 years this study reviewed, only two systems were classified as Atlantic Coast lows, but both are among the 25 strongest systems to affect the region. The famous Thanksgiving blizzard of 1950 resulted from an Atlantic Coast low. The surface low associated with this event moved northwest from North Carolina on 25 November and stalled over western Lake Erie on the 26th. Almost 10 inches of snow fell across northern Indiana, paralyzing the region.

In mid-October 1989, a truly remarkable early-fall snowstorm produced over a half-foot of snow across the southern Great Lakes region. The low pressure system associated with this snowstorm formed over the North Carolina coast on 19 October and moved to the north-northwest. The system passed through the central Great Lakes on the 20th then curved to the northeast. On the 19th and 20th, 8.8 inches of snow fell at South Bend, 8.0 inches fell at Fort Wayne, and 7.5 inches were recorded at Indianapolis. Figure 13 shows the tracks of Atlantic Coast lows during the period of this study.

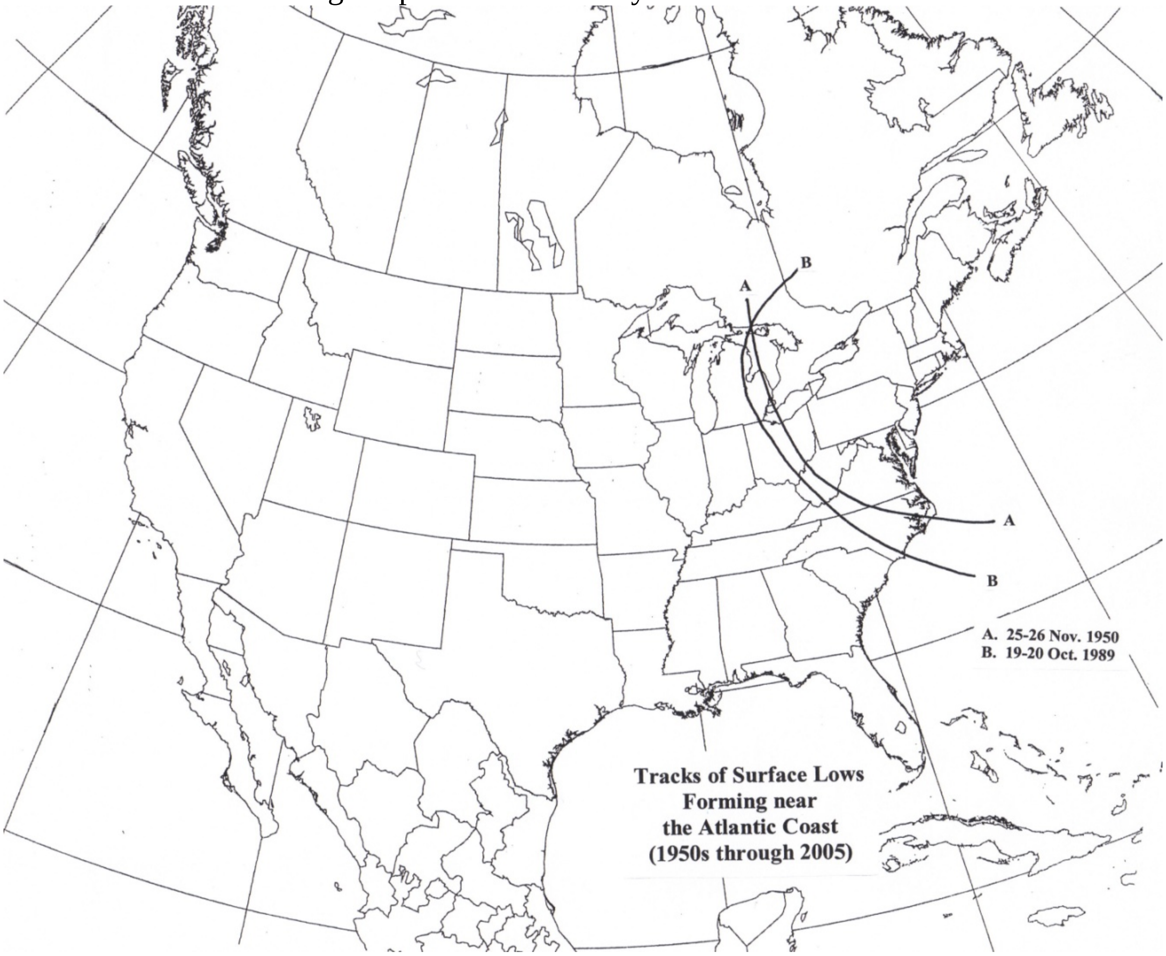

Figure 13. Tracks of surface lows forming near the Atlantic Coast from the 1950s through 2005.

8) Great Lakes lows.

Only one system of the 100 studied could be classified as a Great Lakes low. This system formed over northern Indiana on 21 December 1990 and slowly moved to near Sault Ste. Marie, Michigan by 1200 UTC on the 22nd. The low then moved to the east on the 23rd. At Fort Wayne 7.1 inches of snow fell on the 22nd and 23rd. At South Bend 6.5 inches of snow fell. November 1990 was one of the warmest on record across the southern Great Lakes (around 5 degrees Fahrenheit above normal) and December 1990 was approximately 3 degrees warmer than normal. The warmer lake surface temperatures and relative lack of ice on the Great Lakes may have contributed to the formation of this system. Figure 14 shows the track of the only significant Great Lakes system during the fifty-five years of this study.

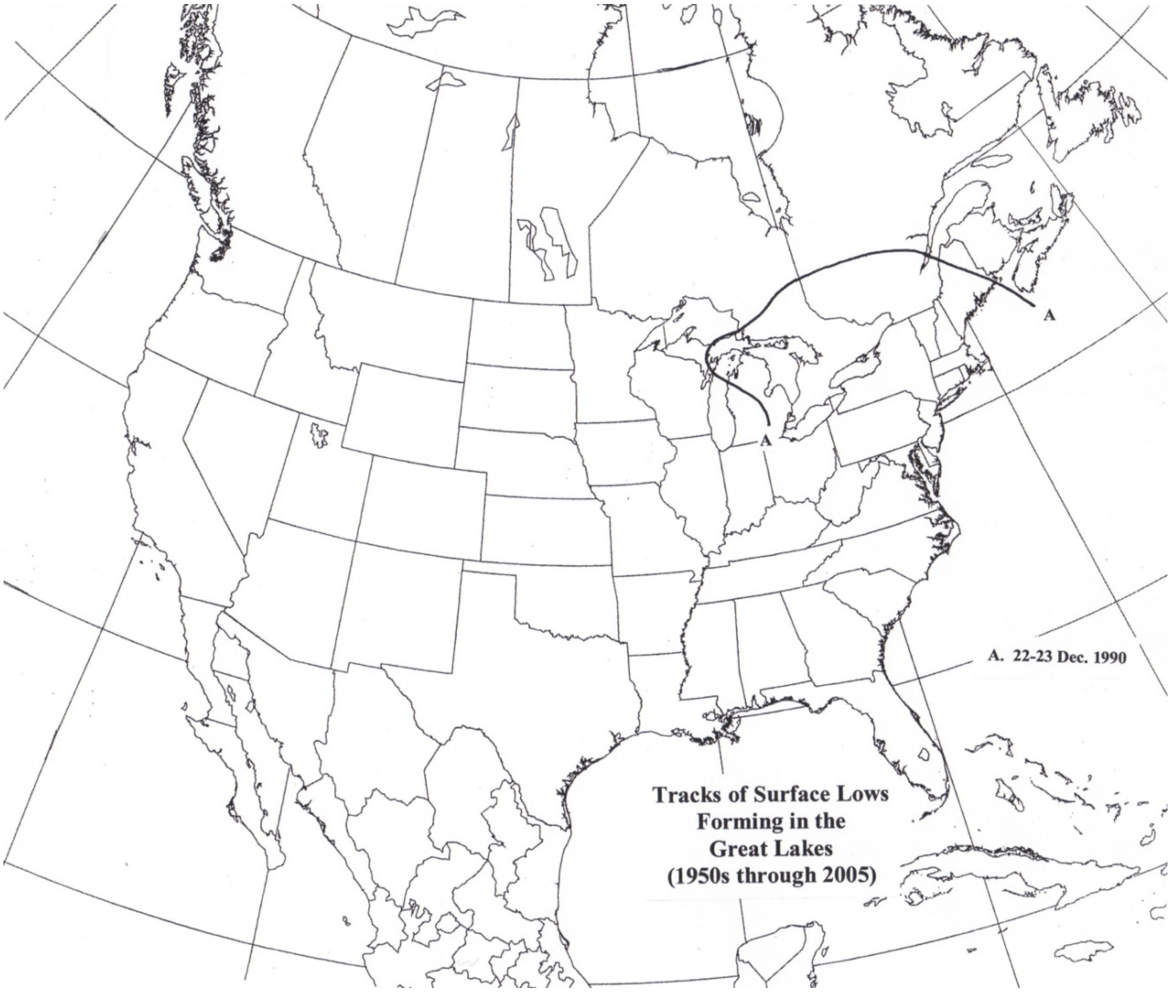

Figure 14. Track of the only significant surface low originating in the Great Lakes region for the period 1950 to 2005.

In a study of the source regions of Great Lakes cyclones for the period 1899 - 1996 it was found that approximately 20 percent of the cyclones that crossed the Great Lakes originated in the region itself (Isard et al. 2000). That is a much higher proportion than that found in this study. This may be because only strong systems that produced relatively large snowfall totals over Indiana were considered in this study. Isard et al., however, looked at all cyclones that moved through the region. They found that cyclones form or are present over the Great Lakes mainly during the summer. This might be why so few Great Lakes cyclones were found in this study. Also, the systems that form over the Great Lakes during the winter tend to be weaker than systems that originate in other regions, particularly during the genesis period. Therefore, these systems will produce less snow over the Indiana than lows which develop elsewhere, and have sufficient time to entrain more moisture and evolve dynamically.

f. Synoptic snow forecasting (Review of literature).

Forecasting the location of the snowfall with a synoptic system can be difficult. The location and amount of snow depend largely on the track and intensity of the surface low and the associated upper-level dynamics. If the system moisture is limited, decreased snowfall totals can be expected. However, strong upper-level dynamics can contribute to larger amounts in a relatively dry air mass. The location of upper-level systems in relation to the surface low also has a significant effect on where the heaviest snow will accumulate. Finally, areas of elevated terrain, although not substantial in the Great Lakes region, can have an effect on accumulations.

Discussed below are brief summaries of some established methods for predicting snowfall patterns and totals. An excellent summary of winter weather forecast techniques was compiled by Gordon (1997). Periodic review of the original publications before the winter season begins can be very beneficial. It is hoped that these methods provide tools for the forecasters, albeit some (e.g., Cook method) may be considered empirical rules and are not based directly on atmospheric dynamics.

1) **Surface low tracks.**

Most systems researched for this study followed a track from the western U.S. eastward to the Great Lakes and northeastern U.S. Low pressure systems originating in the central and southern Rocky Mountains and in the Texas/Oklahoma panhandle generally traveled along cyclonically-curved tracks through the southern Plains and then into the northeastern U.S. Along these tracks, the systems were able to draw moisture from the Gulf of Mexico. Thus, the southerly flow ahead of the surface feature would often increase low-level moisture over the Ohio valley and Great Lakes regions prior to the arrival of the surface low.

Goree and Younkin (1966) determined the favored location for heavy snow in relation to surface and 500-hPa features. In their study heavy snow was defined as 4 inches or more in 12 hours. They found that the “favored location with respect to the surface low-pressure center is about 5 latitude degrees along and 2.5 latitude degrees to the left of its path.” A degree of latitude is approximately 60 nautical miles (nm) in the mid-latitudes, so the area of heaviest snow is typically 150 nm left of the track of the surface low.

2) **850-hPa low.**

Browne and Younkin (1970) studied 81 heavy snowfall events which occurred during two winters (1965-66 and 1966-67) over the central and eastern U.S. Although their results showed "warm advection to be a major contributor to the upward motion producing heavy snow, there is a net slight cooling during the 12-hr period in the region of heavy snowfall." (Browne and Younkin 1970). This net cooling is likely due to latent heat release, or to lift (often referred to as "dynamic cooling"). In almost all of their cases (94%) the 850-hPa low deepened during the 12-hour snowfall period.

It was found that the "highest probability of heavy snow lies approximately 90 nm to the left of the track of the 850-mb low center." (Browne and Younkin 1970). They also found that, on the average, "the initially observed -5^{O} C isotherm nearly bisects the observed subsequent 12- hr heavy snowfall area." However, the "initially observed 850-mb temperature over the surface low center is above 0^{O} C most of the time when heavy snow occurs during the subsequent 12 hours." (Browne and Younkin 1970).

3) **700-hPa level isentropic mixing ratio advection.**

Garcia (2000) developed a method of predicting snowfall amounts by investigating moisture advection along isentropic surfaces. This was an update to a technique he published in 1994. The isentropic surface used in this technique is the one that crosses the 700- to 750-hPa layer over the forecast area of interest. By studying the mixing ratio and wind fields on this surface, moisture advection over the next 12 hours can be predicted. In the study he published in 1994 Garcia found that "a 2 to 1 relationship exists between the maximum snowfall amount and the average mixing ratio." (Garcia 2000).

A number of heavy snowfall events since the publication of his original study led Garcia to update his forecast technique. He found that "the snow/water ratio, in a very cold and dry Arctic air mass, [was required] to adjust the snowfall forecast." (Garcia 2000). The influence of jet couplets and jet streaks led him to develop a convective snowfall scale. This new convective scale "establishes a 4 to 1 snowfall to mixing ratio relationship that is more suited to the tremendous lift and brief nature of these convective events." (Garcia 2000). The original 2 to 1 relationship would still work for the majority of winter snowstorms.

4) **Upper-level temperatures in warm conveyor belt.**

As a cold front moves through the Midwest, moisture is typically advected into the region ahead of the front mainly from the Gulf of Mexico (and to a lesser extent from the Atlantic Ocean). This moisture rises into higher levels of the atmosphere as it travels north (what Carlson (1980) called the "warm conveyor belt"). Auer (1987) said that this "is the primary delivery source of water vapor and resulting condensate into the wave system ascending through 700 mb, 600 mb (level of nondivergence) and 500 mb." Auer studied upper-air soundings from 213 heavy snowfall episodes and determined the most common temperatures found at 700, 600, and 500 hPa.

Auer defined heavy snowfall as snowfall of greater than 6 inches in 12 hours. He found that during 77% of these heavy snowfall episodes the 500-hPa temperatures in the warm conveyor belt were from -22^{O} C to -25^{O} C. Temperatures at 600 hPa were from -14^{O} C to -16^{O} C, and 700-hPa temperatures were from -5^{O} C to -8^{O} C. He also found that with 500-hPa temperatures colder than -25^{O} C, the probability of heavy snowfall decreased significantly.

According to Auer, the temperatures at 600 hPa of -14^{O} C to -16^{O} C were in the area of maximum vertical velocity associated with the level of nondivergence. These temperatures correlated well with the temperatures necessary for the highest rates of maximum dendritic crystal growth (-13^{O} C to -17^{O} C). It was also found that closed upper circulations, "more apt to be quasi-stationary, were found to be more likely to produce amounts in the 10-12 in range with the proper thermal fields." (Auer 1987). This result corroborates what was found in the current study of synoptic systems affecting northern and central Indiana: Events with the largest snowfall totals tended to have closed circulations at 500 hPa.

5) **500-hPa trough**.

Goree and Younkin (1966) found that the favored location of heavy snow was along the path of the 500-hPa low, and "slightly downstream from the point where contour curvature changes from cyclonic to anticyclonic." Before a system occludes, its 500-hPa low is generally located to the left of the path of the associated surface low. Surface winds are generally northerly 100 to 300 miles west of the surface low. The dynamics associated with the 500-hPa trough can help to produce some of the largest snowfall rates. This heavy snowfall can be expected to continue until the system occludes.

6) **500-hPa vorticity maxima**.

Goree and Younkin (1966) also found that the most favorable location for heavy snow was "6.5 to 7 latitude degrees downstream and 2.5 latitude degrees to the left of the track of the [vorticity] maximum during the following 12 hours." In studying the 500-hPa pattern for snowstorms that brought the heaviest snow, they found that "a strong vorticity maximum is a prime requisite for the occurrence of heavy snowfall of major proportions." In their study, strong vorticity maxima were typically on the order of 20.0 to 25.0×10^{-5} sec^{-1}.

7) **500-hPa height fall centers.**

Weber (1978) suggested that the identification of the main low pressure system and its subsequent track were two of the most challenging forecast problems with snowstorms moving east from the Rocky Mountains. He studied six years of Midwest snowstorms that produced at least 4 inches of snow in 24 hours and found a relationship between the 500-hPa height fall centers (HFCs), the location of the main low, and the location of the resulting heavy snow.

Weber found that HFCs at 500 hPa “usually have good continuity of movement and the associated 500-mb low will move parallel to, and on the cold air side, of these centers.” (Weber 1978). Cold air advection within the 500-hPa trough in association with the HFC were found to be good indicators of surface cyclogenesis.

Height fall centers tended to move quickly southeast to the base of the upper trough as a surface and upper-level low deepened. They then begin to move to the east, reach minimum surface pressure, then trek northeast, when the low has temporarily stopped intensifying. As the low and the associated HFCs move to the northeast, the system often re-intensifies.

In the study, Weber found that HFCs generally followed two main cyclonic tracks. Lows that reached their minimum 500-hPa height value in the southern Plains (southern Kansas to northern Texas) turned north-northeasterly and moved into the upper Mississippi Valley. Lows that reached their minimum 500-hPa height value over the central and southern Rockies (Utah and Arizona), however, followed a more northeasterly track into the Great Lakes. Thus, this second group, with its more easterly track, would pose a greater threat of significant snowfall over Indiana. Weber found that the heaviest snowfall generally occurred just to the left of the 500-hPa low/trough axis track.

8) **200-hPa warm advection.**

Cook (1980) developed a method of determining snowfall amounts that would accumulate over a 24-hour period. This method used temperature advection at the 200-hPa level with modifications from the 700-hPa level and surface charts. Cook noted that warm air “normally occurs in 200mb troughs and cold air in the ridges.” (Cook 1980). Strong 200-hPa troughs had temperatures in the -40^{O} C to -45^{O} C range. In strong ridges temperatures were -65^{O} C and colder. This “thermal pattern at 200mb reflects the strength of the system occurring at the lower levels.” (Cook 1980). Cook’s method is analogous to the current use of potential vorticity in forecasting.

Cook stated that the vertical motion field can be inferred from the 200-hPa temperature advection pattern. In examining 200-hPa charts, Cook found that the heaviest 24-hour snowfall totals occurred near the coldest 200-hPa air downstream from the warm pocket (provided the column below was cold enough for snow). Vorticity maxima at 500-hPa almost always coincided with the warm pocket at 200 hPa. And 500-hPa vorticity maxima tend to move toward 200-hPa cold pockets. A vorticity maximum would tend to induce the surface low to strengthen and thus intensify any snowfall occurring.

To use Cook’s Index, determine the amount of warm air advection (in degrees C) for the 24-hour period of interest. The average snowfall (in inches) for that 24-hour period will be approximately one-half of the warm advection along the 200-hPa contours. For this method to be successful, warm or neutral advection must be occurring lower in the atmosphere at 700 hPa. This is because warm advection infers upward motion.

If cold advection at 700 hPa is observed within 8 degrees latitude of the area of interest, divide the snowfall forecast in half. This results in snowfall amounts of one quarter of the 200-hPa warm advection. Cook stated that this forecast technique is to be used mainly from mid-October through mid-March.

4. Lake-effect snow.

a. Introduction.

Lake-effect snow (LES) is a fairly common occurrence downwind of the Great Lakes, and a substantial proportion of seasonal snowfall can result from lake-effect snow events. The impact of lake-effect snowfall can be seen when comparing the annual snowfall totals of South Bend and Fort Wayne. South Bend receives an average of 76.5 inches of snow (1971-2000 thirty-year normals) while Fort Wayne records an average of 35.1 inches. Since both locations are often affected by the same synoptic-scale systems that move through the region, this large difference in snowfall totals can be attributed mainly to lake-effect snow that falls on South Bend but does not reach Fort Wayne.

The authors studied LCDs for both South Bend and Fort Wayne for the winter seasons from 1949-50 through 2005-06 to determine the occurrence of significant lake-effect snow events over northern Indiana. These dates closely matched the dates contained on the NCEP reanalysis CD-ROM (1946-1994) which contained much of the data that were used in this study. To ascertain the surface synoptic features of possible lake-effect events this NCEP reanalysis data was studied. The NOAA publication *Daily Weather Maps* was used for dates after 1994.

For purposes of this study a significant lake-effect snow event was defined as one during which at least 6 inches of snow fell at South Bend while a substantially smaller amount of snow (often by an order of magnitude) fell at Fort Wayne and Indianapolis (farther inland). This snowfall total also correlates well with the National Weather Service definition of heavy snow (U.S. Dept. of Commerce 2008). It was also determined that a synoptic system was not near the region. If a low pressure system passed through Indiana and deposited significant snowfall to the left of the surface track at South Bend, with a lesser amount of snow (or liquid or freezing precipitation) at Fort Wayne and Indianapolis, it was defined as a synoptic system and included with the synoptic events discussed in the previous section.

A total of 77 events was determined to fit these criteria for significant lake-effect snow events. This is an average of just over one event per season. Examination of synoptic charts for the time of these events showed that a surface low had typically just passed through the southern Great Lakes region, or that high pressure was located to the southwest over the mid-Mississippi valley. Approximately 61 additional lake-effect snow events occurred during this study period but did not satisfy the criterion of at least 6 inches of snow at South Bend. Lake-effect snow events with two to three inches of snow at South Bend and none at Fort Wayne would not seem to be a significant threat to the public. These amounts are also below NWS lake-effect snow warning criteria.

Since Lake Michigan rarely freezes completely during the winter, lake-effect snow can occur throughout the winter season (Assel et al. 1979). However, over northern Indiana, lake-effect snow is most common from late autumn through mid-winter when the lake water is warmer than the surrounding land. Of the 77 events studied, 25 occurred during the month of December. Seventeen events occurred during January, sixteen occurred in February, and nine were in November. The remaining ten were distributed throughout late October, March, and early April. The late October 1954 event began on October 30th and extended into November 1st. Since this event occurred mostly in October it was counted as an October event. Similarly, since most of the snowfall from the late February to early March 2005 event was on March 1st it was counted as a March event.

Beginning in late summer, the average land surface temperature decreases. The temperature of the lake surface typically reaches its maximum a month or two later. Throughout the autumn and early winter, the land surface cools at a faster rate than does the lake surface. The land remains cooler than the water throughout the autumn and winter. This “unstable” season lasts from around late August until middle to late March (Eichenlaub 1979). The difference between the land temperature and lake temperature reaches its maximum in late December to early January (Fig. 15).

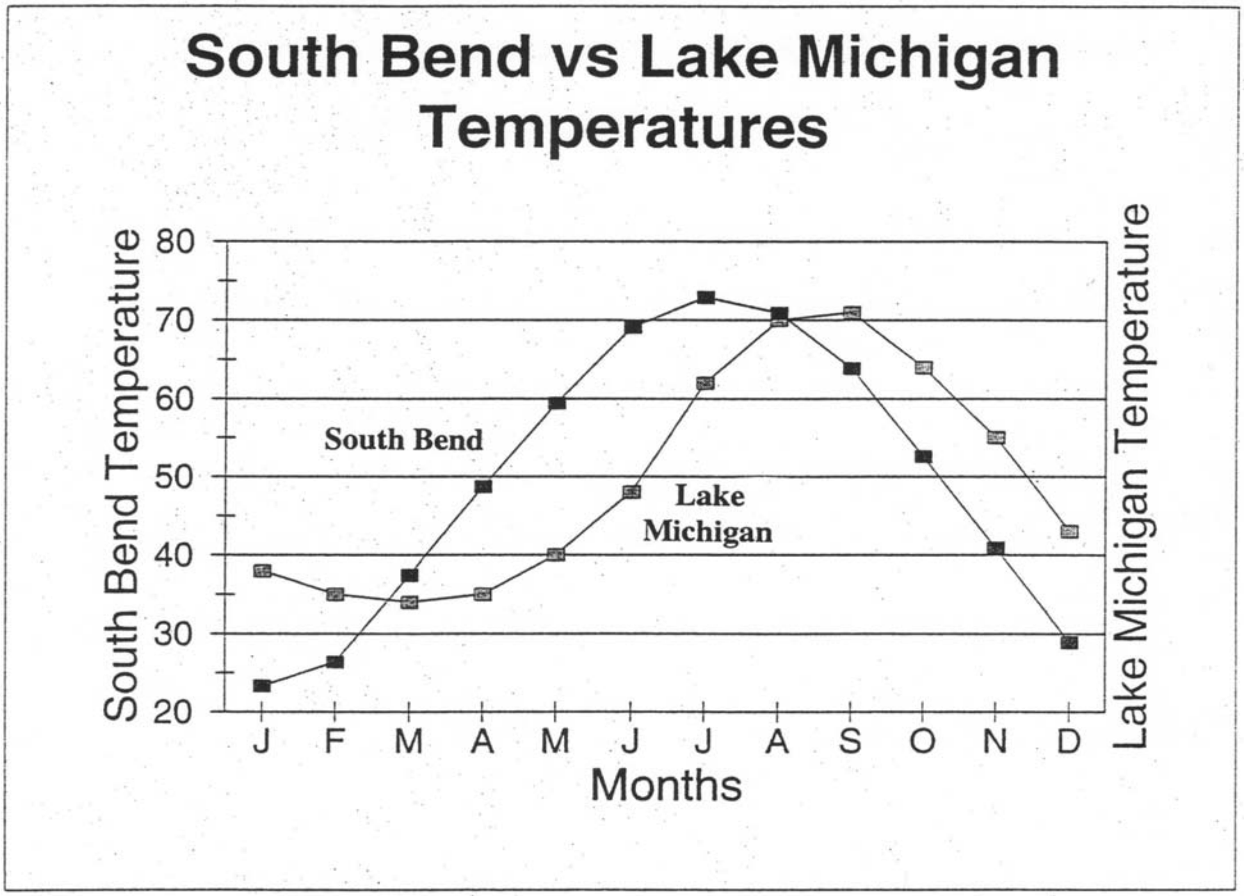

Figure 15. Average temperature (°F) at South Bend, Indiana compared to Lake Michigan surface water temperature (°F) (after Eichenlaub 1979).

A typical lake-effect snow scenario involves the passage of a surface low pressure area or a cold front with northwesterly winds behind the system that move across the lake. As this cold air mass moves across the relatively warm lake surface the lower part of the air mass is warmed. Depending on how cold the air mass is, the lapse rate of its lower layer can approach dry adiabatic. The air mass also picks up moisture from the surface of the lake. This moist unstable air mass can produce clouds downwind of the lake. Vertical speed wind shear, along with orographic lift and frictional effects at the lakeshore, can then help to produce snow showers. Table 4 lists the 77 lake-effect events in this study. The snowfall listed is the total daily snowfall recorded at South Bend for the days of the entire LES event.

Table 4.

Significant Lake-Effect Snow Events
in Northern Indiana
(1949-50 through 2005-06)

Event	South Bend Snowfall (in.)	Event	SouthBend Snowfall (in.)	Event	South Bend Snowfall (in.)
24-25 Dec. 1951	8.9	25-27 Dec. 1970	8.9	14-15 Mar. 1988	8.6
11-12 Jan. 1954	6.8	3-4 Feb. 1972	8.1	15-16 Nov. 1989	7.1
30 Oct.-1 Nov. 1954	7.3	15-16 Dec. 1972	6.5	2-3 Dec. 1989	13.1
19 Dec. 1954	10.3	2-3 Mar. 1975	9.6	15 Feb. 1991	11.5
10-12 Feb. 1955	12.1	13 Jan. 1976	6.7	3-4 Dec. 1991	6.3
10-11 Dec. 1957	7.3	1-2 Feb. 1976	8.2	23-24 Jan. 1992	6.8
1-2 Feb. 1958	8.7	3-4 Nov. 1976	12.2	7-8 Feb. 1992	9.6
15-17 Feb. 1958	11.5	20-21 Dec. 1976	11.1	10-12 Mar. 1992	8.0
7-9 Dec. 1958	6.7	25-27 Nov. 1977	24.3	22-24 Feb. 1993	20.1
15-16 Jan. 1959	16.1	20-21 Dec. 1977	7.8	4-5 Feb. 1995	8.7
5 Mar. 1960	9.0	8-10 Jan. 1978	23.4	7-8 Feb. 1995	12.1
20-21 Jan. 1961	10.2	1-2 Dec. 1978	8.6	25-26 Dec. 1995	6.7
24-25 Feb. 1961	8.2	16-17 Dec. 1979	7.2	30-31 Dec. 1997	6.2
9-11 Dec. 1962	19.8	10-11 Jan. 1981	8.4	9-11 Mar. 1998	15.8
18-20 Dec. 1963	9.5	2 Feb. 1981	6.0	29-30 Dec. 1998	9.4
19-20 Nov. 1964	8.4	8-10 Dec. 1981	9.3	20-21 Jan. 2000	10.6
28-29 Nov. 1965	7.0	18-19 Dec. 1981	16.3	25 Jan. 2000	8.4
7-8 Jan. 1966	8.1	9-10 Jan. 1982	12.3	18-19 Feb. 2000	6.0
29-30 Jan. 1966	6.2	5-6 Feb. 1982	8.4	20-21 Nov. 2000	7.0
28-30 Nov. 1966	7.6	6 Dec. 1984	9.5	11-12 Dec. 2000	12.0
24-25 Feb. 1967	11.0	14-15 Jan. 1985	6.7	29-30 Dec. 2001	11.0
9-10 Feb. 1968	6.1	25 Jan. 1985	9.5	2-3 Mar. 2002	6.6
14 Nov. 1969	7.1	2 Dec. 1985	6.9	22-23 Jan. 2003	6.9
25-26 Mar. 1970	7.9	24 Dec. 1985	9.5	19 Dec. 2004	7.5
1-2 Apr. 1970	7.9	26-27 Jan. 1986	12.9	28 Feb.-2 Mar. 2005	6.7
23 Nov. 1970	9.8	22-23 Jan. 1987	10.8		

Table 5 lists the twenty greatest lake effect events experienced in northern Indiana since 1949.

Table 5.

Greatest Lake-Effect Snow Events
in Northern Indiana
(1949-50 through 2005-06)

	Event	South Bend Snowfall (in.)		Event	South Bend Snowfall (in.)
1.	25-27 Nov. 1977	24.3	11.	3-4 Nov. 1976	12.2
2.	8-10 Jan. 1978	23.4	12.	10-12 Feb. 1955	12.1
3.	22-24 Feb. 1993	20.1		7-8 Feb. 1995	12.1
4.	9-11 Dec. 1962	19.8	14.	11-12 Dec. 2000	12.0
5.	18-19 Dec. 1981	16.3	15.	15-17 Feb. 1958	11.5
6.	15-16 Jan. 1959	16.1		15 Feb. 1991	11.5
7.	9-11 Mar. 1998	15.8	17.	20-21 Dec. 1976	11.1
8.	2-3 Dec. 1989	13.1	18.	24-25 Feb. 1967	11.0
9.	26-27 Jan. 1986	12.9		29-30 Dec. 2001	11.0
10.	9-10 Jan. 1982	12.3	20.	22-23 Jan. 1987	10.8

b. Lake-effect snow forecasting (Review of literature).

Many individuals have conducted valuable studies to learn more about the occurrence and prediction of lake-effect snow. Below are summaries of some of the more well-known studies that have helped to increase our knowledge of this weather phenomenon.

Wiggin (1950).

Over fifty years ago, Wiggin discussed some necessary ingredients in producing lake-effect snow. He stated that cold air aloft producing an adiabatic or greater lapse rate to at least 5000 feet was needed in order to produce heavy lake-effect snow. He also mentioned cyclonic flow aloft as a necessary ingredient. In addition, a large temperature difference between the air and water surface is needed. A long fetch over the lake helps to generate lake-effect snowstorms. And, finally, speed wind shear is needed to produce the longitudinal convective cells that produce lake effect snow showers. These are all ingredients that forecasters would recognize today as being necessary in lake-effect events.

For substantial lake-effect snow, Wiggin noted that the cold air should be relatively deep for snowfall rather than merely cloud production. His study indicated that lake-effect snow is more likely when the air-lake temperature difference is 20^{O}C or greater, and the upper-level wind flow is cyclonic or at least straight. With favorable shear, a lake-effect band will be produced and can remain over one general location for hours. He found these bands to be narrow, usually three to five miles wide and may extend fifteen miles inland from the lakeshore. However, later researchers such as Niziol (see below) have found that too much vertical shear (60 degrees or greater) can actually inhibit snow band formation.

Petterssen and Calabrese (1959).

In this study Petterssen and Calabrese wanted to separate the effects of heating, caused by the relatively warm Great Lakes, from the effects caused by orographic and other motions. They looked at a cold spell which occurred during the second week of February 1958.

The authors referred to previous research done by one of them (Petterssen) in which it was shown how a heat source affects divergence at sea level. With the difference in temperature between a lake surface and the surrounding land, this “would result in horizontal convergence and the development of a cyclonic circulation around the source.”

The authors concluded that “the heat transfer from the Lakes to the air exerts a modifying influence on the motion systems and a dominating influence on the weather systems.” In addition, they found that the maximum relative vorticity and largest drop in sea level pressure should not exceed certain maximum values. They also determined that precipitation amounts were positively correlated with fetch lengths.

Peace and Sykes (1966).

In their classic study of a lake-effect snowstorm over Lake Ontario, Peace and Sykes looked at a number of different parameters. These included radar data, and mesoscale analyses of surface pressure, pressure change, wind direction and speed, and horizontal divergence.

They concluded that the location and movement of snow bands over the lake were most likely controlled by upper-level conditions rather than surface-based processes. However, they pointed out that these surface processes (such as land breezes, shoreline convergence, and orographic effects) could intensify a lake-effect snowstorm. They further emphasized that the orientation of snow bands approximated the direction of the upper-level winds.

Rothrock (1969).

Rothrock observed that “lake snows usually occur during periods of abnormally cold weather.” He went on to state that this often takes place due to the west to northwest flow behind the passage of a low pressure system. In his study, Rothrock wanted to determine which parameters were significant for lake-effect snow to occur and, of the parameters which correlated well to lake-effect snow, what threshold values a forecaster could use. He studied 29 cases during two winters (1965-66 and 1967-68) which seemed to have a significant number of lake-effect snow events.

As a measure of instability Rothrock used the temperature difference between the lake surface and the 850-hPa level. In 28 of the 29 cases the surface to 850-hPa temperature difference was greater than or equal to 13 $^{\circ}$ C. He found this to be the best parameter to use in forecasting significant lake-effect snow. He also found that a threshold of 20 $^{\circ}$ C could be used to predict heavy snow (4 inches or more total snowfall).

Another parameter Rothrock studied was the height of the low-level inversion. He found that the clouds needed to reach a thickness of at least 3,000 feet for significant lake-effect snow to occur. Higher inversion heights were found to correlate to larger snowfall totals. Of the eleven cases during which four inches or more of snow fell, in seven of them the inversion height was at least 6,000 feet.

Rothrock found a negative correlation between positive vorticity advection (PVA) at 500 hPa and the occurrence of lake-effect snow. Of the 29 cases studied, 24 occurred with either negative or neutral vorticity advection. He further noted that, of the eleven cases that had heavy snow, ten of them occurred with negative or neutral vorticity advection at 500 hPa. He stated that this was because the 500-hPa trough was usually east of Lakes Superior and Michigan (the two lakes he studied) and that negative vorticity advection is usually west of the trough axis during lake-effect snow events.

Holroyd (1971).

Weather satellites had been in use for approximately 10 years when Holroyd completed his study. By the late 1960s more detail could be seen in satellite imagery and the author wanted to study the structure of lake-effect cloud bands as seen in this imagery.

In his article, Holroyd first discussed stability relationships associated with lake-effect cloud bands. When these cloud bands were seen in satellite photographs he looked at surface and radiosonde data and determined that the bands almost always occurred when the 850-hPa temperature was more than 13^{O}C colder than the lake surface temperature. He went on to explain that the dry adiabatic temperature decrease from the surface to 850 hPa is approximately 13^{O}C.

In looking at the satellite imagery, Holroyd noticed enlarged cloud bands that were 2.5 times larger than normal lake-effect cloud bands. He suggested two possible mechanisms for the formation of these “enlarged lake storms.” He defined the possible causes as “friction induced convergence” and “thermally induced convergence.”

Since friction will cause air to slow down and be deflected to the left (in the northern hemisphere) Holroyd stated that, if wind flow is parallel to a shoreline of a lake, “convergence will result at or near the shoreline if the land is to the right, divergence and subsidence if the land is to the left.” This friction-induced convergence would then cause a cloud band to form parallel to this shoreline to the right. With thermally-induced convergence the heating experienced over a lake surface, in a dry Arctic air mass, will cause air to converge around the heat source. Stronger wind flow will cause the area of convergence to be displaced downwind of the heat source.

In relation to northwestern Indiana, friction-induced convergence should occur along the southern shore of Lake Michigan with a west wind, but the fetch is very short here. Holroyd found a greater percentage of friction induced convergence along the southwestern shore of Lake Michigan with northerly winds down the long axis of the lake. With thermally-induced convergence Holroyd saw lake storms generated in central and southern Lake Michigan with northerly winds. These are storms which could generate cloud bands that could affect northern Indiana.

Lavoie (1972).

Lavoie noted that the small horizontal extent of lake-effect snowstorms did not allow them to be modeled well by existing numerical models. In this early study Lavoie used a "single-layer numerical model derived to simulate the mesoscale disturbance induced in cold air moving over an unfrozen lake of irregular shape." He used a model that had three layers: a superadiabatic surface layer; a middle layer with little, if any, temperature change through it; and a deep stable upper layer.

The model applied three surface forcing mechanisms (topography, friction, and heating) to Lake Erie. Smoothed topography was added to the model of the lake. Lavoie found that, with respect to topography, upward motion was greatest upwind of elevation barriers. A decrease in relative friction was seen over the lake as wind speeds increased. The maximum wind speed was seen at the downwind shoreline. Finally, to study heat flux from the lake surface, the model was given lake temperatures that were 5^{O}C warmer than the surrounding land. The strongest upward motion was seen near the downwind shorelines, especially in the direction of the longest fetch.

Lavoie found that the mesoscale model provided a "useful first-order approximation to the mesoscale disturbance induced in the planetary boundary layer by pronounced surface features." In his conclusion he mentioned the need for the development of more useful mesoscale predictive models. He understood that the limitations in computer processing at the time affected the extent of meteorological research that could be conducted. Even though he described his model as "a gross simplification of nature," it did show the influence of mesoscale processes on the development and evolution of lake-effect snowstorms.

Dockus (1985).

Numerical forecast models have become indispensable tools used by weather forecasters. The increased resolution of the models, improved physics schemes, better data assimilation techniques, and increased computing power used to run the models have greatly increased the models' accuracy. Interpretation of the models is still needed however, especially during rapidly-evolving mesoscale weather events such as lake-effect snow.

Dockus studied twenty lake-effect snow events from two winters (1983-84 and 1984-85). He used the Limited Fine-Mesh Model II (LFM II) to determine various parameters that could be used in forecasting the occurrence and location of lake-effect snowstorms. He compared these parameters to previously used forecasting rules of thumb and developed a decision tree for use in determining the occurrence of LES.

The results of Dockus's study supported some previously-held rules of thumb and contradicted others.

1. Dockus agreed with Rothrock's findings, of the lake surface-to-air temperature difference of 13^{O}C, but he determined that the critical threshold value was an 850-hPa temperature of -10^{O}C, no matter what the lake surface temperature was. This reflects a dry adiabatic lapse rate from -10^{O}C at 850 hPa to +2^{O}C at the surface. This would help insure snow at 5000 feet reaching the surface as snow instead of changing to freezing rain, ice pellets, or rain.

2. Dockus found that wind flow across a lake fetch of 50 miles produced little, if any, accumulating snow. He felt that 100 miles was the minimum fetch necessary to produce lake effect snow when the 850-hPa temperature was -10^{O}C or colder. (Dockus called this process "lake effect.") A threshold of 40 miles was possible only when there is upper-level PVA and the 850-hPa temperature is less than or equal to -5^{O}C (Dockus referred to this as "lake enhanced.")

3. Dockus found that upper-level (such as at 500 hPa) PVA aids the low-level (below 700 hPa) wind flow across a lake, and increases the snowfall accumulation downwind of the lake. His findings showed that some of the heaviest snowfall results from a combination of this low-level wind flow and upper-level PVA.

4. Dockus found that even relatively light winds (5 to 10 kts) can produce heavy lake-effect snow if the vertical wind shear is minimal. Some earlier researchers felt that wind speeds of at least 15 kts were necessary for significant LES.

In looking at the LFM II Dockus found that diagnosing the following four parameters were "quite valuable" (his words) in forecasting lake-effect snow:

1. 850-hPa temperature isotherm
2. boundary layer wind direction and speed
3. vertical velocity
4. 500-hPa heights and vorticity (areas of PVA)

By using these parameters (along with some others) Dockus developed his "Dockus Decision Tree" (DDT), a flow chart to guide the forecaster through the lake-effect snow decision-making process. (A similar flow chart has been used successfully at both the Indianapolis and Northern Indiana Forecast Offices.).

Niziol (1987).

Niziol reported that Wiggin's conditions for lake-effect snowstorms east of Lake Erie have been modified somewhat by later forecasters at the National Weather Service Forecast

Office in Buffalo, New York. In his article, Niziol describes the synoptic situation that favors lake-effect snow over Buffalo: (1) a 500-hPa low centered over James Bay, (2) strong low-level cold air advection associated with a surface low south of James Bay, and (3) a trough extending south of the surface low which will cause southwesterly winds along the long axis of Lake Erie.

Niziol stated that forecasters at Buffalo found the following parameters to be the most important in forecasting lake effect snow:

1. lake surface to 850-hPa temperature difference
2. wind direction from boundary layer to 700 hPa
3. change in wind direction from boundary layer to 700 hPa
4. height of low-level inversion

Niziol agrees with others (Rothrock, Holroyd) that a surface-850-hPa temperature difference of 13^{O}C is the minimum difference needed for what he calls "pure" LES.

Niziol states that the "wind direction from the boundary layer through 850 mb is the best operational forecast parameter for general snowband orientation and location."

According to Niziol, forecasters at Buffalo through the years noticed that a change in wind direction of greater than 30 degrees with height seems to inhibit storms' organization. This may be due to the shearing effects of this change in wind direction. With this wind shear Niziol states that single snow bands tend to divide into multiple bands and, with directional shear of greater than 60 degrees, snow bands are not sustainable.

Finally, the height of the low-level inversion limits the depth of the clouds. Niziol points out that this has a direct effect on precipitation rate. He states that the inversion is generally found within the lowest 2 km of the surface, but that more intense convection can occur with an inversion height above 3 km.

Other considerations in forecasting LES events include: The existence of cyclonic vorticity advection at 500, 700, and 850 hPa; the amount of ice cover on the lakes upwind; and elevation effects downwind of the lakes that would increase LES intensity and accumulation.

Niziol, Snyder, and Waldstreicher (1995).

This is an excellent overview of the state of lake-effect snow forecasting in the mid 1990s. The authors first summarize the climatology of lake-effect snowfall. They then describe five different types of lake-effect snow bands. In a third section they discuss the use of operational models, satellite and radar technology, and forecast techniques used at the National Weather Service Forecast Offices at Buffalo and Albany, New York. Finally, they discuss some future prospects for improving LES forecasting.

Northern Indiana's proximity to the southeastern shore of Lake Michigan allows all five types described by Niziol, Snyder, and Waldstreicher. “Type I” snow bands are bands that form when the upper-level wind flow is generally parallel to the long axis of the lake. A narrow snow band often forms under these conditions. “Type II” snow bands are also parallel with the wind flow but are directed across the shorter axis of the lake. In this situation multiple less intense snow bands form due to the weaker convergence over the lake.

“Type III” snow bands are a combination of Types I and II. These bands form over lakes that are upstream and then redevelop over the second lake. The authors describe the situation in which lake-effect snow bands form over Lake Huron, are carried south, and then redevelop over Lake Erie. In northern Indiana a similar situation can occur in which snow bands form over Lake Superior, move across the upper peninsula of Michigan, and then reform over Lake Michigan and, with the northerly flow along the lake’s long axis, can reach northwestern Indiana. This trajectory from Lake Superior may have more of an effect on precipitation and stability parameters at locations near the northern part of Lake Michigan than at locations farther south (Sousounis and Mann 2000).

According to the authors, “Type IV” snow bands are also called “shore parallel bands”...but are primarily a result of a land breeze generated in a very cold environment with a weak synoptic-scale pressure gradient. Snowfall is usually less with this type due to the subsidence associated with the Arctic high pressure over the region.

Finally, the authors state that “Type V” snow bands (also called “mesoscale vortices”), like Type IV snow bands, often form under stable conditions. The authors describe the vortices that develop due to the circular, bowl-shaped shoreline of the lake. They further state that these events are more common on the Upper Great Lakes than on Lakes Erie and Ontario. In fact, these vortices have been detected on the Northern Indiana WSR-88D radar over southern Lake Michigan.

c. Lake-effect snow forecasting in northern Indiana.

Prior to the existence of the Northern Indiana National Weather Service Forecast Office (WFO) forecasts for northern Indiana were issued from the WFOs in Indianapolis and Chicago. Forecasters at the Northern Indiana office use forecast techniques that have been tested and found reliable at other offices. Many of these techniques (such as modifications of the Dockus Decision Tree) have proven useful in forecasting lake-effect snow in northern Indiana.

With its location at the southeastern shore of Lake Michigan northern Indiana experiences lake-effect snow from only a small range of wind directions. North winds down the long axis of Lake Michigan can deposit large snowfall totals over northwestern Indiana. In northern Indiana La Porte and St. Joseph counties can experience heavy snowfall. With strong enough winds, snowfall can be carried into Starke and Marshall Counties.

Winds from the northwest can create snow bands that affect northwestern Indiana, but especially north-central parts of the state. The same counties that are affected by northerly winds are also affected with winds from the northwest, but with the addition of Elkhart County. West winds produce snow bands over southwestern lower Michigan. The fetch is also much shorter with westerly and northwesterly winds than it is with northerly winds. This can negatively affect the available moisture from the surface of Lake Michigan.

As a result of past research (some of it referred to above), the lapse rate from the surface of the lake to a height of 5,000 feet has been found to be very important in generating lake-effect cloud bands. The traditional temperature difference threshold of 13^{O}C seems to work well in northern Indiana. A temperature difference of greater than 20^{O}C adds even more instability to the air mass and can produce even larger snowfall totals.

As mentioned in relation to wind direction above, fetch length is also extremely important. For fetch lengths of less than around 50 miles, significant upward vertical motion at 700 hPa seems to be necessary to produce accumulating snow. Westerly winds that cross southern Lake Michigan at the latitude of northern Indiana result in a fetch length of less than 50 miles. For fetch lengths of greater than 50 miles, northwesterly, or especially northerly winds, must occur.

Another parameter forecasters must consider is the base of the middle-level inversion. An inversion base below around 3,000 feet will inhibit the vertical growth of cloud bands. For larger amounts of snowfall to be produced the inversion base must be above 3,000 feet. An inversion base above 7,000 feet can allow clouds bands to grow to significant thicknesses and thus generate copious amounts of snow.

Lake Michigan rarely freezes over completely (Assel et al. 1979). Because of this, lake-effect snow can occur in northern Indiana throughout most winters. Another parameter that can affect lake-effect snowstorms is topography. Increases in elevation can enhance snowfall rates. Hjelmfelt found that changes in elevation of as little as 100 to 300 feet can double the snowfall rate of a lake-effect storm (Hjelmfelt 1992). Much of northern Indiana is 100 to 150 feet higher than the surface of Lake Michigan. This is enough change in elevation to increase snowfall rates over the region.

5. Ice Events

For the purpose of this study, icing events were identified in *Storm Data* (NOAA 1959-2006). Sounding data were acquired from the "Radiosonde Data of North America" CD ROM set produced by Forecast Systems Laboratory (FSL) and the National Climatic Data Center (NCDC) (FSL and NCDC 1996). Table 6 below lists the dates and locations of the thirty-five cases identified in *Storm Data*.

Table 6.

Greatest Icing Events in Indiana
(1959 through 2005)

Event	Location in Indiana	Event	Location in Indiana
27-30 Jan. 1962	Central	18 Mar. 1992	Northern
23 Feb. 1962	Southeast	11-12 Feb. 1993	Northern
23-24 Jan. 1965	Northern	16-17 Jan. 1994	Southern
26-27 Jan. 1967	Northern	8-9 Feb. 1994	Central and Southern
5 Mar. 1967	Central, northern half	27-28 Feb. 1995	Northwest
8 Jan. 1969	Northern and Central	6-7 Mar. 1996	Southeast
12 Dec. 1972	Northwest third	15 Jan. 1997	Southern
10 Jan. 1974	Western and Southern	21 Dec. 1998	Southwest
*4-5 Feb. 1976	Central	8-9 Jan. 1999	Southern
24-25 Mar. 1978	North and Central	14 Jan. 1999	Central and Eastern
6 Jan. 1981	Southern and Central	17 Jan. 2000	Southwest
20 Dec. 1981	South and South-central	13 Dec. 2000	Southern and Central
23 Jan. 1982	Northeast and Central	31 Jan. 2002	Northern
3 Mar. 1985	Northwest	25-26 Mar. 2002	Central
3-4 Mar. 1988	Central	15-16 Feb. 2003	Southern and Central
**14-15 Feb. 1990	Northern and Central	25 Jan. 2004	Southern and Central
22 Dec. 1990	Statewide	5-6 Jan. 2005	Northern and Central
12-13 Mar. 1991	Northern		

* This storm was considered the worst ice storm "in memory" (*Storm Data* 1976)

** This storm was considered the worst in Northeast Indiana since 1976 (*Storm Data* 1990)

Sounding data from 1962 until 1995 were used. During that time, many upper-air sites changed locations and location identifiers. Table 7 lists the locations and identifiers of upper-air sites before and after the NWS modernization during the mid 1990s. The period of record was obtained from the National Climatic Data Center.

Table 7.

Site ID	**Period of Record**
PIA (Peoria, IL)	September 12, 1956 to February 14, 1995
SLO (Salem-Leckrone, IL)	April 16, 1954 to November 28, 1988
DAY (Dayton, OH)	December 1, 1951 to September 29, 1995
ILX (Lincoln, IL)	February 11, 1995 to present
ILN (Wilmington, OH)	September 29, 1995 to present

Data were collected from the CD ROM set and then analyzed using the Skew-T/Hodograph Analysis and Research Program (SHARP) (Hart and Korotky 1991). After the cases were analyzed, an average sounding was created (Figure 16).

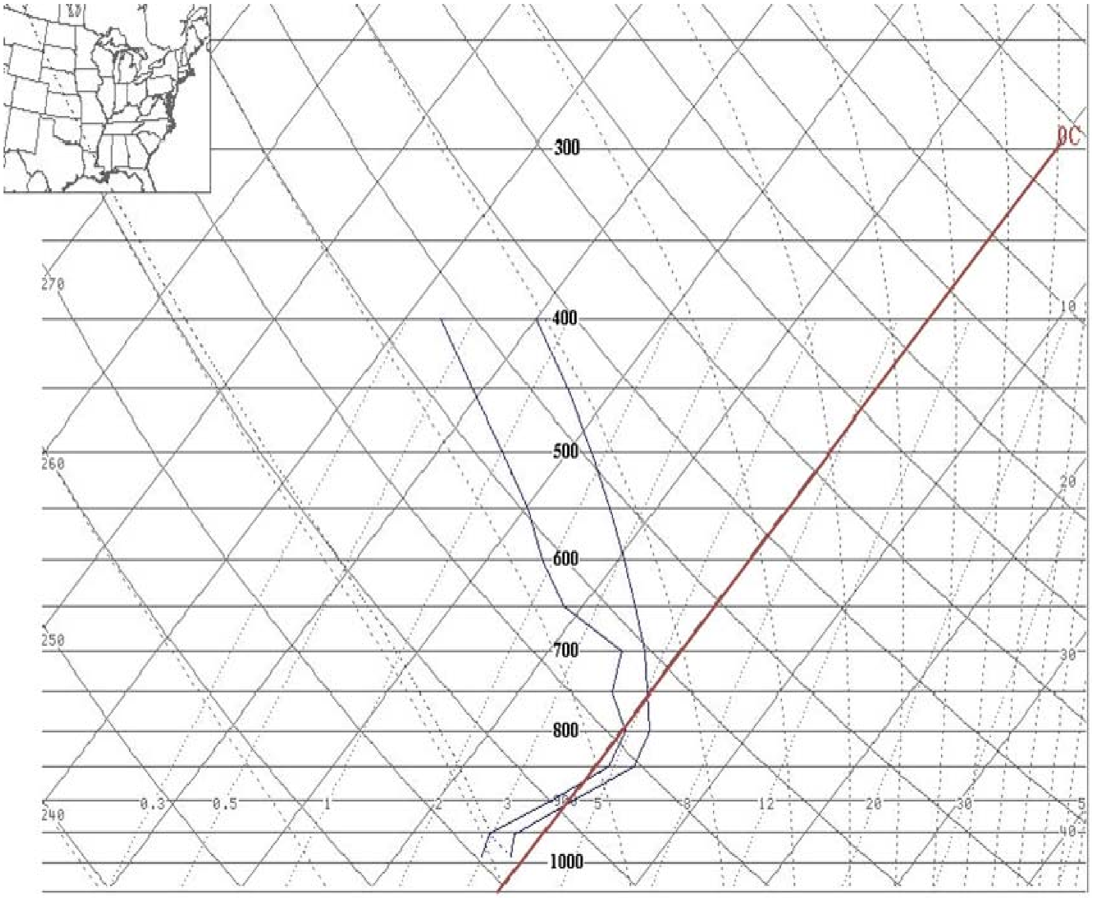

Figure 16. Composite sounding of icing events analyzed.

Precipitation-type forecasting poses significant challenges. Several studies have identified parameters that can be used in making a judgment on precipitation type (Bocchieri 1980, Stewart and King 1987, Heppner 1992, Bourgouin 2000). This average sounding displayed characteristics that are "typical" of a freezing rain event as identified by various studies (Bocchieri 1980, Cortinas 2000). Using Baumgardt's "A Wintertime Cloud Microphysics Review" (Baumgardt 1999) as a guide, the following information was extracted from the average sounding data.

The classic freezing rain sounding consists mainly of freezing or slightly below freezing temperatures at the surface, an elevated warm layer, and saturation indicating the presence of clouds. Beginning in the upper troposphere, assessing whether ice will be introduced into the cloud is the first step in diagnosing precipitation type. Research has shown that a saturated cloud layer should have a temperature of -10°C or colder in order for ice crystallization to begin in a cloud. At temperatures of -20°C ice crystallization is almost certainly initiated. Reviewing the average sounding created from the cases analyzed, the saturated layer is generally not cold enough for ice to be introduced from above and therefore must rely on other physical processes for freezing precipitation production.

Assessing the warm layer is the next step in determining precipitation type. The temperature and the depth of the warm layer play a role. Research has shown that with ice introduced in the upper cloud layer, several different scenarios could result. If the warm layer maximum temperature is less than 1°C, snow is most likely; at temperatures from 1°C to 3°C a mix and/or sleet is probable; and if the temperature is greater than 3°C, freezing rain/drizzle will be the most likely precipitation type. If ice is not introduced into the cloud, freezing rain/drizzle will almost always be the result. The influence of the depth of the warm layer was studied by Czys et al. (1996). Figure 17 is a reproduction of their isonomogram comparing mean warm layer temperatures to the layer depth and the resultant precipitation type.

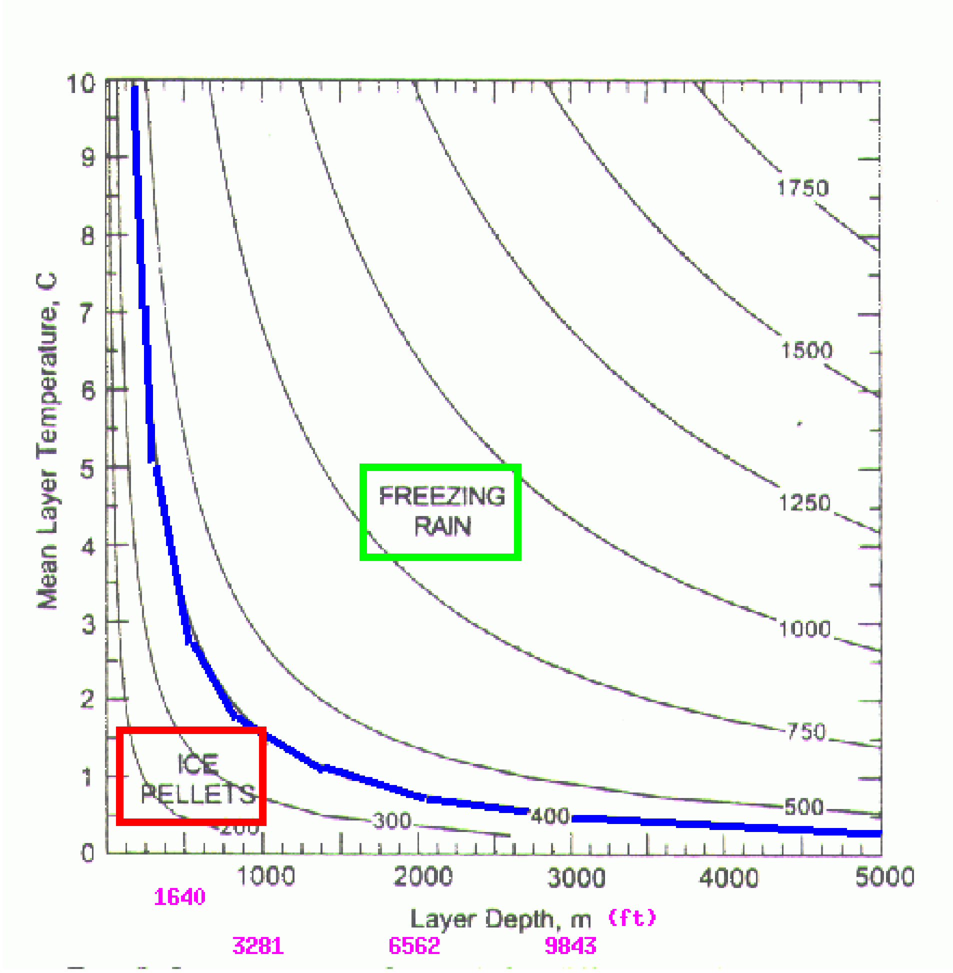

Figure 17. Isonomogram comparing mean warm layer temperatures to the layer depth, and the resultant precipitation type (from Czys et al. 1996).

The composite sounding created from the cases in this study revealed an average warm layer depth of 1530 meters and an average maximum temperature of 3°C. Plotting these values on the isonomogram in Figure 17 correlates well with the freezing rain threshold. Given below-freezing temperatures at the surface, and recalling the minimum cold layer temperature is warmer than -10°C, further supports the freezing rain precipitation type.

Using the Daily Weather Maps produced by NOAA’s National Climatic Data Center and the NOAA/NWS's Hydrometeorological Prediction Center (HPC) some general conclusions can be drawn with regard to the surface pattern in place during the aforementioned analyzed events. Nearly half of the analyzed cases had a high pressure system located in the vicinity of Hudson Bay that moved south or southeast into the Great Lakes region. Some of these were preceded by cold frontal boundaries that passed through the region near the time of the onset of the precipitation event. A few cases had surface lows originating from the southern or central Rockies which moved east toward the Great Lakes, with either a stationary boundary or a warm frontal boundary over northern and central Indiana. In these situations, warm air is transported vertically as well as horizontally, providing the warm layer above the surface. This is better known as "overrunning."

In summary, it was found that significant icing events in northern and central Indiana follow patterns that have been discovered by researchers who have studied icing events in the past. No deviation from these generalities was uncovered.

6. Frost / Freeze conditions.

Central and northern Indiana experience growing seasons that last almost six months each year. The growing season can be defined as the period between the last occurrence of frost in the spring and the first occurrence of frost in the fall (Trewartha and Horn 1980). The growing season in Indiana consists, on average, of approximately 150 days in northern Indiana to around 200 days in the southwestern corner of the state (U.S. Dept. of Commerce 1988). Due to the moderating influence of Lake Michigan, the growing season in the northwestern corner of Indiana extends later in the fall than it does at locations farther inland at a similar latitude.

The term "growing season," however, may be more accurately referred to as the "frost-free" season. The actual growing season for different types of plants may be of quite shorter length than the frost-free season (Oliver and Hidore 1984). Plants begin growing when the temperature reaches certain levels. Crops such as wheat and oats can begin growing when the temperature rises to just above freezing. Other crops such as sorghum do not start to grow until the temperature reaches approximately 60^{O}F (Oliver and Hidore 1984). Thus the "growing season" is different for various types of plants.

However, for our purposes, we can use these terms interchangeably since the public generally accepts the growing season as the frost-free period during the warmer half of the year. Many flowers and ornamental plants may be damaged or killed by frost, so members of the public who have these types of plants are interested in when it may be necessary to protect plants in the fall, or when it might be safe to begin growing plants in the spring.

Plants can be damaged whether frost forms on them or not. If the surface air temperature falls below freezing over a widespread area for a climatologically significant length of time it is defined as a "freeze" (Glickman 2000). If the dew point is low enough so that water vapor does not sublimate directly into ice crystals on a plant surface as the air temperature drops below freezing, the water inside of a plant may freeze. This is defined as a "black frost" (in reference to the color of the plants' leaves after this happens) (Glickman 2000). Conversely, if the dew point is relatively high, and the air temperature drops to equal the dew point, frost may form on plant surfaces. Tender plants may be killed by just a light freeze or deposition of light frost. A frost or freeze that lasts long enough to kill most vegetation and thus end the growing season is called a "killing frost" or a "killing freeze." This situation can also delay the start of the growing season in the spring.

Air temperatures are usually measured at a height of approximately six feet above ground level. Because of radiational cooling, the air at ground level can be 32^{O}F or cooler while the air above is warmer. This is why a temperature of 36^{O}F is sometimes used to predict the occurrence of frost if strong radiational cooling is expected.

Frost and freeze conditions do not just affect plants. The freezing of soil tends to occur much later in the season than the freezing of vegetation. Plants may be damaged when the air temperature falls to below freezing and remains there for a few hours. The soil temperature however is typically still much above freezing, perhaps at a temperature of 50^{O}F to 60^{O}F. As the atmosphere continues to cool, water at or just below the surface of the soil will freeze as the temperature drops below freezing. This typically occurs for a short period of time at night during the early fall. The ice then melts during the day as the temperature rises to above freezing.

Water in the soil freezes from the top down. The water freezes in layers called "ice lenses" (Anderson et al. 1984). Since water expands as it freezes, an ice lens will displace soil upward in a process called "frost heaving." As the soil freezes, colder temperatures are translated downward and water continues to freeze at deeper levels as the winter progresses. During a typical winter in the southern Great Lakes region, soil freezes to a depth of 8 to 10 inches. However, during a very cold winter, soil can freeze to levels as deep as one and one half feet. During the spring the soil thaws from the top, and it can take weeks for the frozen soil to completely thaw.

Frozen soil and frost heaving is mainly an engineering concern, but it can also be a hydrological problem. As the soil freezes throughout the winter, permeability decreases. This can pose problems during the spring if there is significant snow cover. The soil may stay frozen for a longer period of time in the early spring as its top layer is not exposed to the warmer air temperatures. This can cause flooding problems if snow cover melts rapidly or if excessive rainfall is deposited over a small area. Any water that cannot be absorbed by the soil will become runoff. This can contribute to flooding if rivers and streams cannot accept and discharge all of this runoff. During relatively cold winters, ice may begin to form on rivers. On occasion, ice breakage can lead to an "ice jam," resulting in upstream flooding.

As mentioned above, the public often inquires when frost can be expected during the fall and spring. It is generally not a concern once the growing season ends. The date given for the first frost in the fall and the last frost in the spring is usually the "average" date. This is defined as the date when there is, climatologically, a 50 percent chance of frost occurring before this date and a 50 percent chance of frost occurring after this date. The average date of frost can be determined using NWS official 30-year temperature averages or by using averages determined from even longer periods.

As might be expected, the dates of first and last frost have remained relatively stable over the years. In fact, Easterling (2002) found that there has been very little change in the number of frost days in the southern Great Lakes region from 1948 through 1999. Freeze / frost data for Indiana show that the average date of first frost (50 percent probability) during the fall ranges from early October in the northeastern part of the state, to late October in southwestern Indiana. The average date of last frost in the spring ranges from mid-April in southern Indiana to early May in northern Indiana (U.S. Dept. of Commerce 1988). Visher found similar results for Indiana when he examined data from the last quarter of the nineteenth century through 1940 (Visher 1944).

The average date of first or last frost may be beneficial for many users. However, some users may ask how early they can plant in the spring or how late they can leave plants out in the fall before there is a "high chance" of frost occurring. Dates of 90 percent probability of frost occurrence may be of more use to these customers. These are the dates that frost can be expected with a high degree of certainty.

Many frost climatologies use probabilities to describe the chance of frost by or after certain dates and for the resulting frost-free periods (U.S. Dept. of Commerce 1988; Thom and Shaw 1958). For example, if the 90 percent probability level for 32^{O}F at a location falls on March 15th, this means that in 9 out of 10 years (90 percent of the time) a temperature of 32^{O}F or lower can be expected to occur <u>after</u> March 15th. Similarly, if the 90 percent probability level for 32^{O}F falls on October 15th, this means that 9 years out of 10 a temperature at or lower than 32^{O}F can be expected to occur <u>before</u> October 15th (U.S. Dept. of Commerce 1988). This can give forecasters a better idea of when frost will be fairly common. It can help to increase a forecaster's confidence in a prediction of frost.

Figure 18 shows the average dates (50 percent probability) of first occurrence of a temperature of 32^{O}F in the fall. Figure 19 shows the dates before which there is a 90 percent probability that a temperature of 32^{O}F will occur in the fall. Figure 20 shows the average dates (50 percent probability) of the latest occurrence of a temperature of 32^{O}F in the spring. Figure 21 shows the dates after which there is a 90 percent probability that a temperature of 32^{O}F will occur in the spring. Temperature data are from the period 1951-80 (latest available). (Data used in figures are from U.S. Dept. of Commerce 1988).

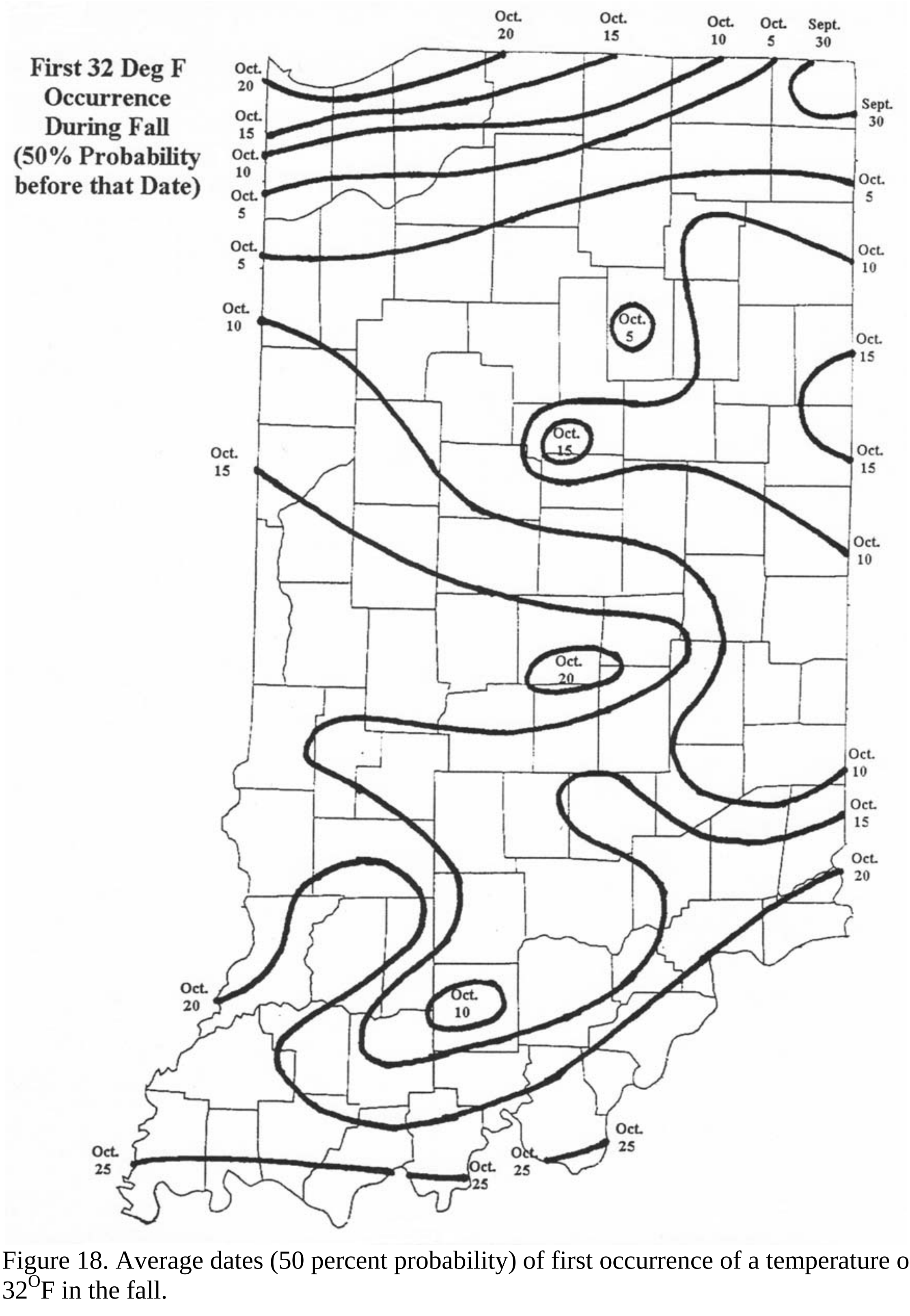

Figure 18. Average dates (50 percent probability) of first occurrence of a temperature of 32^{O}F in the fall.

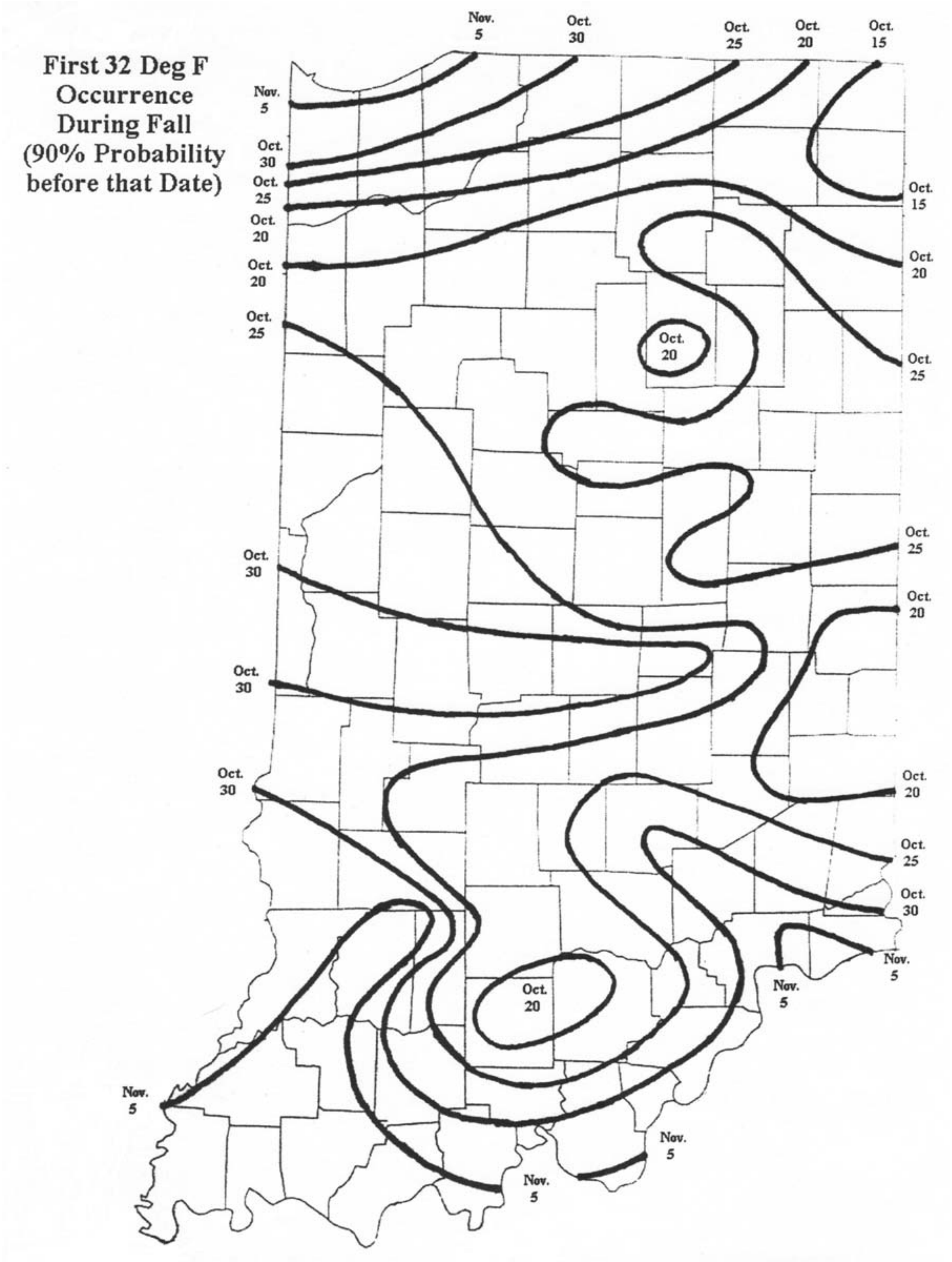

Figure 19. Dates before which there is a 90 percent probability that a temperature of 32^{O}F will occur in the fall.

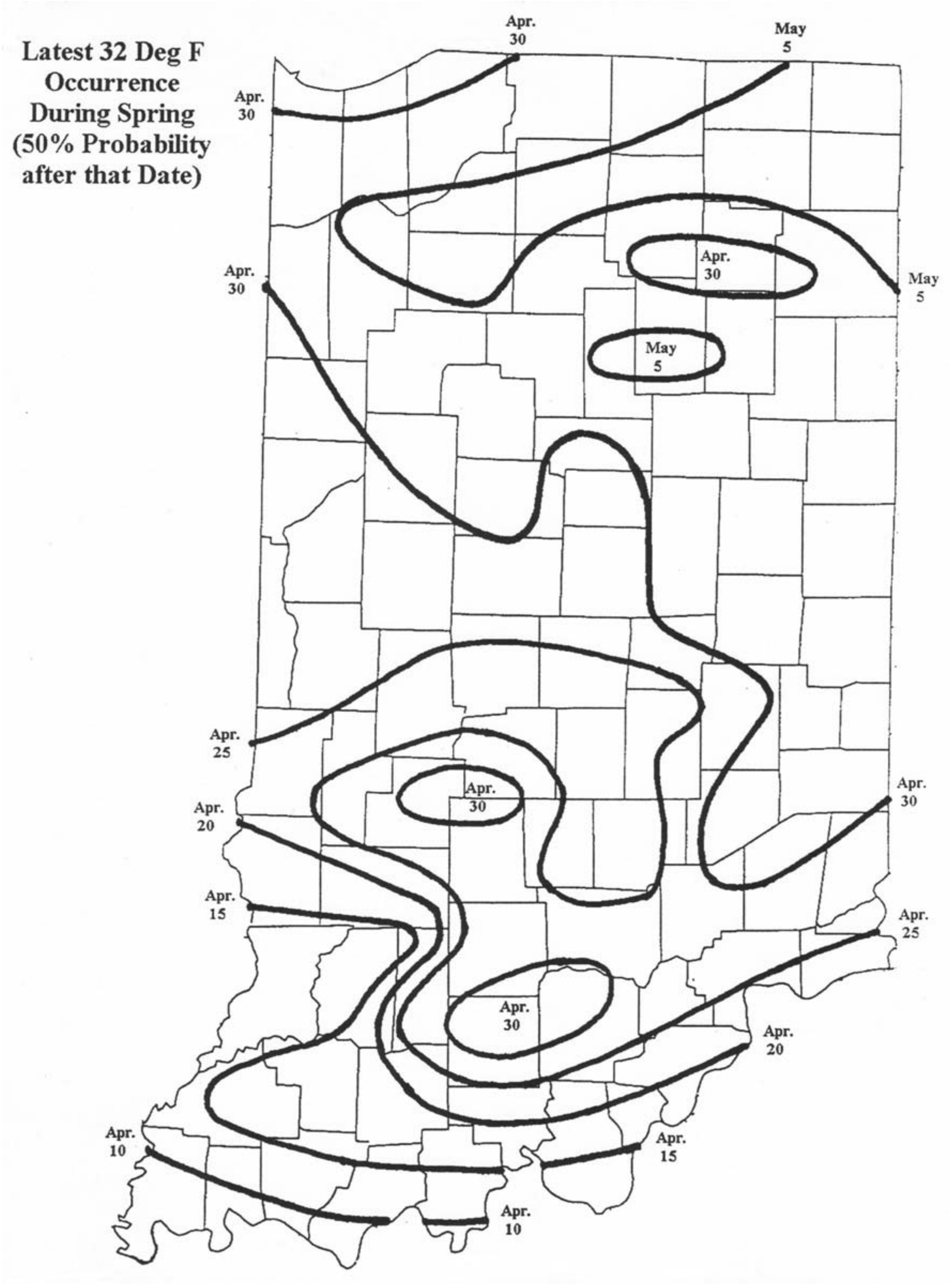

Figure 20. Average dates (50 percent probability) of the latest occurrence of a temperature of 32^{O}F in the spring.

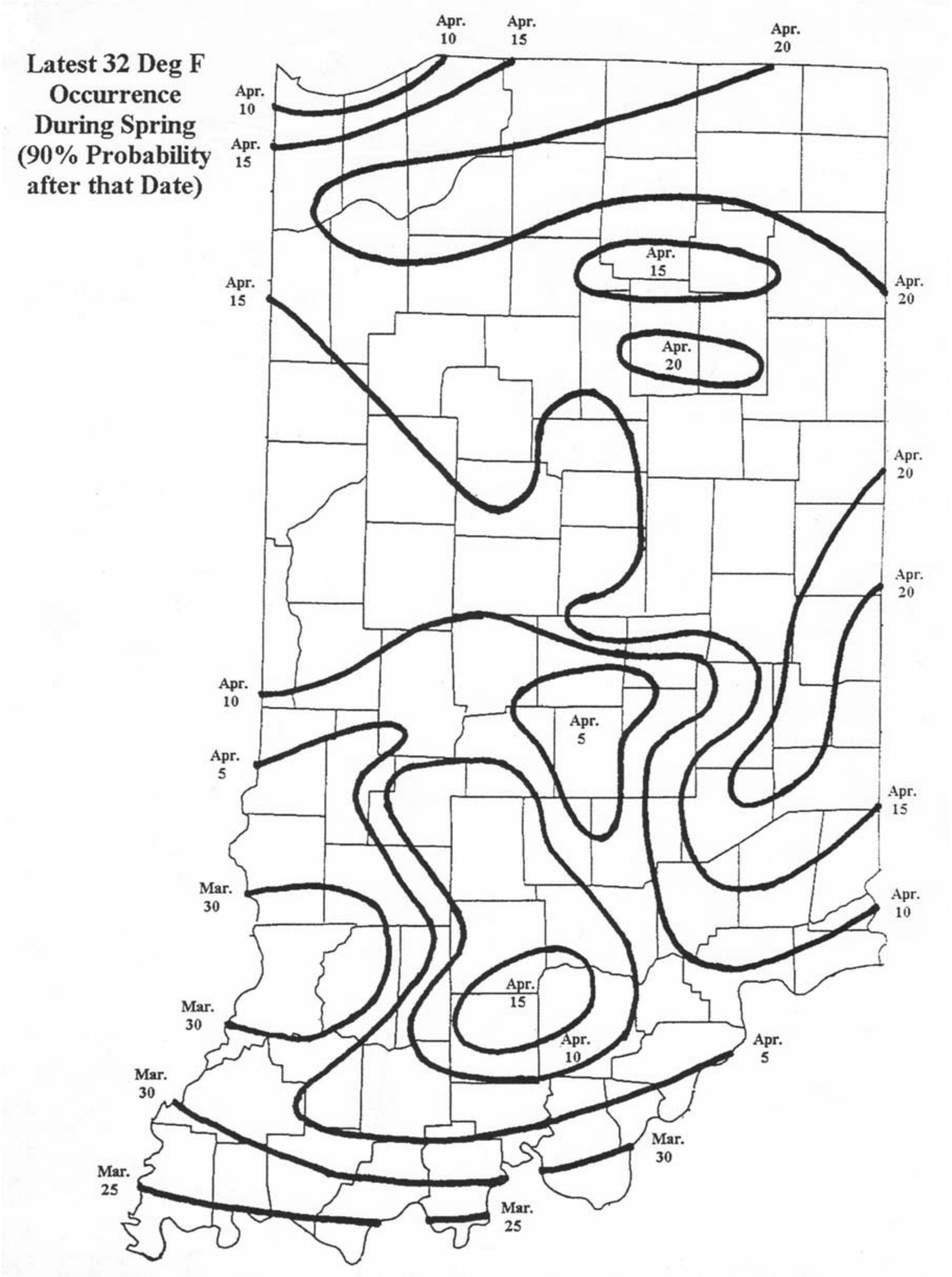

Figure 21. Dates after which there is a 90 percent probability that a temperature of 32^{O}F will occur in the spring.

7. Extreme Cold.

Extended outbreaks of temperatures well below normal are not only a nuisance, but can be a public health hazard. Hypothermia and frostbite are the most common cold weather-related health hazards. Hypothermia is defined as a lowering of the core body temperature to 95^{O}F (32^{O}C). According to the Centers for Disease Control and Prevention (CDC), from 1979 to 1992 a total of 10,550 people in the United States died from hypothermia. Locally, from 1979 to 1998, only five Indiana counties reported deaths due to hypothermia for a total of nine deaths statewide. Not surprisingly, Marion County (highest population) was the leader with five deaths for the period.

Frostbite is defined as damage to the skin and underlying tissues caused by extreme cold. Although death from frostbite does not occur, injury to extremities can be serious enough to require amputation. Other indirect health impacts from extreme cold are the increase in influenza, pneumonia, and other respiratory illnesses.

An analysis of cold outbreaks at South Bend, Fort Wayne, and Indianapolis was conducted. The period studied was from 1950 to 1999 during the months of October through April. The normals were obtained from the LCDs for each station. A cold outbreak was defined as daily average temperatures 10^{O}F or more below normal. The data were further divided into groups of 10 to 19 degrees below normal for 1 day or longer, 20 to 29 degrees below normal for 1 day or longer, 30 to 39 degrees below normal for 1 day or longer, and 40 to 49 degrees below normal for 1 day or longer. No daily average temperature colder than 49 degrees below normal was observed for the period studied. An analysis of the data revealed the following:

The 10 to 19 degrees below normal category was the most frequent occurrence.

For Indianapolis, the 1970s have the most occurrences of below normal temperatures compared to other decades in the study. The 1990s have the fewest occurrences of below normal temperatures compared to other decades. There were four occurrences of daily average temperatures 40 to 49 degrees below normal - the most of the three stations studied.

For South Bend, the 1960s have the most occurrences of below normal temperatures compared to other decades. The 1980s have the fewest occurrences of below normal temperatures compared to other decades. There were no occurrences in the 40 to 49 degree below normal category.

For Fort Wayne, the 1960s have the most occurrences of below normal temperatures compared to other decades. The 1990s have the fewest occurrences of below normal temperatures compared to other decades. There were two occurrences of daily average temperatures 40 to 49 degrees below normal.

8. Conclusions.

Synoptic snow.

One hundred systems affected northern and central Indiana during the 57 years of this study, which is an average of about 1.8 storms per year.

Most significant systems that affect Indiana originate in the Rockies and travel through the central and southern Plains, gaining substantial low-level moisture from the Gulf of Mexico prior to arriving in the Great Lakes region.

The strongest systems develop a neutral to negative tilt at in the trough axis at 500 hPa.

Forty-six of the 100 systems studied developed a closed circulation at 500 hPa.

There is less correlation between significant snowfall and the intensity of the surface low pressure. The main importance seems to be the upper dynamics (500-hPa tilt) and advection of Gulf moisture ahead of the system.

Lake-effect snow.

Seventy-seven significant lake-effect snow events occurred during the 57 years of this study. This results in an average of 1.4 events per winter snowfall season.

Lake-effect snow occurs mainly from mid-November through February, with a maximum in December. The twenty largest events had snowfall totals of over 10 inches at South Bend. Seventeen of these events occurred during the depth of winter (being evenly distributed among the months from December through February).

Icing events.

Significant icing events in northern and central Indiana follow patterns that have been discovered by researchers who have studied icing events in the past. No deviation from these generalities was uncovered.

Frost / freeze conditions.

The first 32°F temperatures during the fall in central and northern Indiana generally occur in October and have not shown any variation throughout the 20th century.

The last 32°F temperatures are typically seen in late April to early May, and these dates have also been consistent during the past 100 years.

The shortest frost-free period is in northeastern Indiana (approximately 5 months).

The frost-free period is extended in northwestern Indiana due to the influence of Lake Michigan. It is also longer in southwestern Indiana, and along the White River valley, where the growing season is 6 months or greater.

Extreme cold temperatures.

Average daily temperatures of 30 to 40 degrees below normal are extremely rare during the winter. For example: Average daily temperatures of 30 to 39 degrees below normal have occurred only 5 to 6 days per decade. Average daily temperatures of 40 degrees or more below normal occurred only twice at both Fort Wayne and Indianapolis in the last 50 years (40 below normal on both Dec. 24, 1983 and Jan. 20, 1985). South Bend did not experience any days during the winter when the average temperature was 40 or more degrees below normal.

Average daily temperatures of 20 to 29 degrees below normal occur four to five times during the 6 months from October through March.

No major difference is seen between extreme cold temperature departures from normal at South Bend and those departures experienced farther inland at Fort Wayne and Indianapolis. Temperatures this cold are usually the result of a synoptic regime (not mesoscale or local) and affect the entire region.

Acknowledgments.

The authors would like to thank Rich Grumm, Science and Operations Officer at the National Weather Service Forecast Office at State College, Pennsylvania, for running the algorithm he created to determine the relative strength of the surface lows (surface pressure anomalies) for the synoptic events listed in Table 1. The authors also wish to thank John Kwiatkowski, Science and Operations Officer at the NWS Forecast Office at Indianapolis, Indiana, for reviewing the manuscript. And the authors would especially like to thank Jeff Manion of the Meteorological Science Division at NWS Central Region Headquarters. His thorough review made this a much better document.

References.

Anderson, Duwayne M., Peter J. Williams, Gary L. Guymon, and Douglas L. Kane, 1984: Principles of Soil Freezing and Frost Heaving. In *Frost Action and Its Control*, Richard L. Berg and Edmund A. Wright, eds. New York, NY, Amer. Soc. of Civil Engineers, 1-21.

Angel, James R., 1996: *Cyclone Climatology of the Great Lakes.* Misc. Pub. 172. Champaign, IL, Illinois State Water Survey, 122 p.

Assel, R. A., D. E. Boyce, B. H. DeWitt, J. Wartha, and F. A. Keyes, 1979: *Summary of Great Lakes Weather and Ice Conditions, Winter 1977-78.* NOAA Tech. Memo. ERL GLERL-26, 123 p.

Auer, August H., Jr., 1987: An Aid to Forecasting Heavy Snowfall Episodes. *Nat. Wea. Dig.*, **12**, 11-14.

Baumgardt, Dan, 1999: Wintertime Cloud Microphysics Review, NWS Central Region website, http://www.crh.noaa.gov/arx/micrope.html.

Black, Robert E., 1971: *A Synoptic Climatology Of Blizzards On The North-Central Plains Of The United States*. Kansas City, MO, Nat. Wea. Service, NOAA Technical Memorandum NWS CR-39, 38p.

Bocchieri, Joseph R., 1980: The Objective Use of Upper Air Soundings to Specify Precipitation Type. *Mon. Wea. Rev.*, **108**, 596-603.

Bourgouin, Pierre, 2000: A Method to Determine Precipitation Types. *Wea. Forecasting*, **15**, 583-592.

Browne, Richard F. and Russell J. Younkin, 1970: Some Relationships Between 850-Millibar Lows and Heavy Snow Occurrences Over the Central and Eastern United States. *Mon. Wea. Rev.*, **98**, 399-401.

Carlson, T. N., 1980: Airflow Through Midlatitude Cyclones and the Comma Cloud Pattern. *Mon. Wea. Rev.*, **108**, 1498-1509.

Cook, Billie J., 1980: A Snow Index Using 200mb Warm Advection. *Nat. Wea. Dig.*, **5**, 29-40.

Cortinas, John, Jr., 2000: A Climatology of Freezing Rain in the Great Lakes Region of North America. *Mon. Wea. Rev.*, **128**, 3574-3588.

Czys, Robert R., Robert W. Scott, K. C. Tang, Ronald W. Przybylinski, and Michael E. Sabones, 1996: A Physically Based, Nondimensional Parameter for Discriminating between Locations of Freezing Rain and Ice Pellets. *Wea. Forecasting*, **11**, 591-598.

Dockus, Dale A., 1985: Lake-Effect Snow Forecasting in the Computer Age. *Nat. Wea. Dig.*, **10**, 5-19.

Doesken, Nolan J. and Arthur Judson, 1996: *The Snow Booklet: A Guide to the Science, Climatology, and Measurement of Snow in the United States*. Fort Collins, CO, Colorado State Univ. Dept. of Atmos. Science, 84 p.

Easterling, David R., 2002: Recent changes in frost days and the frost-free season in the United States. *Bull. Amer. Meteor. Soc.*, **83,** 1327-1332.

Eichenlaub, Val L., 1979: *Weather and Climate of the Great Lakes Region*. Univ. of Notre Dame Press, 335 p.

FSL and NCDC, 1996: Radiosonde Data of North America (1946-1995), Version 1.0.

Garcia, Crispin, Jr., 2000: *Forecasting Snowfall Using Mixing Ratios on an Isentropic Surface: An Update*. Kansas City, MO, CRH SSD NOAA Technical Memorandum NWS CR-116. 14 p.

Glickman, Todd S., ed., 2000: *Glossary of Meteorology,* 2nd ed. Boston, MA, Amer. Meteor. Soc., 855 p.

Gordon, John D., 1997: *A Comprehensive Winter Weather Forecast Checklist*. CR Applied Research Papers, Vol. 18, Dec. 1997, 59-66.

Goree, Paul A. and Russell J. Younkin, 1966: Synoptic Climatology of Heavy Snowfall Over the Central and Eastern United States. *Mon. Wea. Rev.*, **94**, 663-668.

Grumm, Rich, 2000: personal communication.

Hart, John A., and W.D. Korotky, 1991: *The SHARP Workstation – Version 1.50.* A Skew-T/Hodograph Analysis and Research Program for the IBM and Compatible PC User's Manual, 62 p.

Heppner, Paul O. G., 1992: Snow versus Rain: Looking beyond the "Magic" Numbers. *Wea. Forecasting,* **7**, 683-691.

Hjelmfelt, Mark R., 1992: Orographic Effects in Simulated Lake-Effect Snowstorms over Lake Michigan. *Mon. Wea. Rev.*, **120**, 373-377.

Holroyd, III, Edmond W., 1971: Lake-Effect Cloud Bands as Seen From Weather Satellites. *J. Atmos. Sci.*, **28**, 1165-1170.

Isard, Scott A., James R. Angel, and Geoffrey T. VanDyke, 2000: Zones of Origin for Great Lakes Cyclones in North America, 1899-1996. *Mon. Wea. Rev.*, **128**, 474-485.

Kocin, Paul J. and Louis W. Uccellini, 1990: *Snowstorms Along the Northeastern Coast of the United States: 1955 to 1985*. Boston, MA, Amer. Meteor. Soc., 280 p.

Lavoie, Ronald L., 1972: A Mesoscale Numerical Model of Lake-Effect Storms. *J. Atmos. Sci.*, **29**, 1025-1040.

National Centers for Environmental Prediction, 1996: *N-AWIPS User's Guide Version 5.4.*

NOAA, NCDC, 1959-2006: *Storm Data*. National Climatic Data Center, Asheville, NC. **1-48**, Nos. 1-12.

Niziol, Thomas A., 1987: Operational Forecasting of Lake Effect Snowfall in Western and Central New York. *Wea. Forecasting*, **2**, 310-321.

__________, Warren R. Snyder, and Jeff S. Waldstreicher, 1995: Winter Weather Forecasting throughout the Eastern United States, Part IV: Lake Effect Snow. *Wea. Forecasting*, **10**, 61-77.

Oliver, John E. and John J. Hidore, 1984: *Climatology*. Columbus, OH, Charles E. Merrill, 381 p.

Panofsky, Hans A. and Glenn W. Brier, 1958: *Some Applications of Statistics to Meteorology.* University Park, PA, The Pennsylvania State University, 224 p.

Peace, Jr., R. L. and R. B. Sykes, Jr., 1966: Mesoscale Study of a Lake Effect Snow Storm. *Mon. Wea. Rev.*, **94**, 495-507.

Petterssen, S. and P. A. Calabrese, 1959: On Some Weather Influences Due to Warming of the Air by the Great Lakes in Winter. *J. of Meteor.*, **16**, 646-652.

Rothrock, H. J., 1969: *An Aid in Forecasting Significant Lake Snows*. Kansas City, MO, Weather Bureau Central Region Technical Memorandum WBTM CR-30, 12 p.

St. Jean, Dan, 1998: *GEMCD3 User's Guide*.

Sousounis, Peter J. and Greg E. Mann, 2000: Lake-Aggregate Mesoscale Disturbances. Part V: Impacts on Lake-Effect Precipitation. *Mon. Wea. Rev.*, **128**, 728-745.

Stewart, Ronald E. and Patrick King, 1987: Freezing Precipitation in Winter Storms. *Mon. Wea. Rev.*, **115**, 1270-1279.

Thom, H. C. S. and R. H. Shaw, 1958: Climatological Analysis of Freeze Data for Iowa. *Mon. Wea. Rev.*, **86**, 251-257.

Trewartha, Glenn T. and Lyle H. Horn, 1980: *An Introduction to Climate.* New York, NY, McGraw-Hill, 416 p.

U. S. Dept. of Commerce, 1988: *Climatography of the U.S., No. 20, Supplement No. 1: Freeze / Frost Data*. Asheville, NC, NCDC, 186 p.

__________, 2008: *WFO Winter Weather Products Specification*, National Weather Service Instruction 10-513, 57 p.

Univ. of Washington and National Center for Atmospheric Research, 1996: *National Meteorological Center Grid Point Data Set, CDROM: Version III, General Information and User's Guide*.

Visher, Stephen S., 1944: *Climate of Indiana*. Bloomington, IN, Indiana Univ., 511 p.

Weber, Eugene M., 1978: Major Midwestern Snowstorms. *Preprints, Conference on Weather Forecasting and Analysis and Aviation Meteorology*, Silver Spring, MD, Amer. Meteor. Soc. and Nat. Wea. Assoc., 30-37.

Wiggin, B. L., 1950: Great Snows of the Great Lakes. *Weatherwise*, **3**, 123-126.