Forecasting Lake Effect Snow off of Southern Lake Michigan

A Primer

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January in The Great Lakes: its typical ingredients include bouts of heavy snow, waves of arctic cold, and bursts of biting wind. It's a particularly brutal winter, and The Great Lakes Region is experiencing frequent winter storms. Yet another potent mid-latitude cyclone pulls northeast into Canada. Cities such as Chicago and Milwaukee, now covered in a clean and deep blanket of snow, are beginning to clear out as cold, Canadian High Pressure slowly noses into The Northern Plains. Yet, as some folks enjoy a brief respite from winter's snowy grasp, residents of cities such as Gary and Valparaiso, Indiana, are wondering: "When is this snow going to end?" Unfortunately, it isn't simply a matter of residual flurries; rather, it is just the beginning of a significant, northerly flow lake effect snow (LES) event over Northwest Indiana. In this paper, I will begin by presenting a basic overview of LES climatology in The Great Lakes region. Next, I will offer a brief review of parameters which are favorable for its generation and sustenance. Finally, I will utilize two case studies: December 20th, 2004 and February 3rd and 4th, 2009, both significant LES events for Northwest Indiana (a region which I will more precisely define later on), as windows into particular patterns which lead to significant LES accumulations off of Southern Lake Michigan.

In a nutshell, lake effect snow occurs when Continental Polar (cP) air blows across relatively mild lake waters. As dewpoints increase and clouds form, lake effect precipitation begins to form. As ice crystals and water droplets continue to collect, gravity pulls precipitation down to ground level, where it eventually accumulates on windward shorelines (1). Thus, LES events tend to occur between November and March, as cold, Canadian air makes its presence known across The Great Lakes Region (2). However, it is important to note that significant LES can occur at unexpected points as evidenced by Lake Storm Aphid, which pounded Buffalo with nearly 18” of snow on October 12th and 13th, 2006 (3). In rare cases, a late season LES event can occur as an anomalously cold airmass descends from Canada, and moves over slowly moderating lake waters.

Geographically, LES occurs most frequently on windward (downwind) shores of The Great Lakes, in regions known as snowbelts. Snowbelt regions average significantly higher snowfall over an entire season when compared to areas at a similar latitude, which are located further inland. This makes for a relatively easy identification process on snowfall climatology maps. Snowbelts exist downwind of all five Great Lakes. The heaviest seasonal snowfalls tend to occur off of Lakes Ontario and Superior, where in excess of 200 inches may fall in a given year (4). The presence of extremely cold cP airmasses coupled with a favorable orientation relative to prevailing wind patterns, leads to such heavy seasonal snowfalls. Still, locations off of Lakes Erie, Huron, and Michigan, frequently pick up in excess of 100 inches of snowfall in a given season (4). LES is extremely localized in nature so while a snowbelt region may be quite broad, individual locales vary widely in terms of how much snow actually accumulates. It is important to remember: LES can occur off of any one of the five Great Lakes given significant instability, a favorable wind direction, and little to no vertical wind shear.

When attempting to diagnose Lake Effect Snow Potential, a well-rounded forecaster must consider a wide variety of ever-changing parameters including instability, wind, moisture, and lake ice coverage. LES is an extremely complex and intricate process, and a minute shift in even a single, relevant parameter can have a profound impact on overall snowfall potential.

Instability results from pronounced cooling as one ascends vertically in the atmosphere. For significant LES to unfold, a difference of at least 13 degrees C should exist between lake water temperatures and 850mb temperatures (5). Ideally, a Lake-850mb Delta T of between 15° and 20° C should be in place (6). If Delta T's exceed 25°C, heavy LES becomes less likely, simply because such cold 850mb temperatures may prove unfavorable for dendritic growth. Delta T's of slightly less than 13° C may produce LES, but a significant degree of synoptic forcing must be present in order to boost snowfall totals (5). Often, such scenarios are referred to as "Lake Enhanced", and not purely "Lake Effect" in nature.

Wind direction and speed are very important parameters to consider when forecasting for an LES event. Fetch refers to how far air travels over a body of water (5). Naturally, significant LES accumulations become increasingly likely when air travels across a lake's long axis as such a path increases available moisture, moisture which may fall as lake effect precipitation on a lake's windward shore. A fetch of one hundred kilometers is generally considered necessary for significant LES, with > 200 km being particularly conducive to heavy snowfall amounts (5). Vertical wind shear presents a significant obstacle to heavy lake effect snowfalls. If vertical wind shear becomes too pronounced, LES cannot become organized into well-developed bands. To assess vertical wind shear, a forecaster may look at sfc-700mb wind direction. If sfc-700mb wind direction varies by 60 degrees or more, only a few snow showers are likely (5). When vertical wind shear is between 30 and 60 degrees, weaker bands are a distinct possibility (5). Ideally, vertical wind shear will be 30 degrees or less, which is conducive to very well-organized, persistent banding (5). Wind speed plays a less important role, but nonetheless an important one. Strong wind speeds may carry LES well inland, but if wind speeds become too strong or significant speed shear is present, bands may be torn apart before attaining organization.

LES can occur under a variety of synoptic patterns; but, certain patterns are particularly conducive to LES formation. Cold air advection (CAA) is frequently associated with LES. Given significant CAA, low-level instability increases as cold 850mb readings pour southeast out of Canada across relatively mild lake waters. Additionally, cyclonic vorticity advection aloft may enhance LES potential by lifting the capping inversion (5). This allows for higher cloud tops and a deeper, moister column. High values of RH should be present as particularly low values prevent condensation from even occurring. One pattern which absolutely inhibits LES formation is a strong anticyclone parked directly overhead. In such a case, strong subsidence limits instability, prevents rising motion, and leaves an area clear and bitterly cold.

One interesting, more localized factor involved in forecasting LES events surrounds lake ice coverage. As lake ice coverage increases, less and less moisture remains available for evaporation. Thus, many significant LES events occur between November and January, before lake ice coverage increases substantially. Once ice coverage becomes significant, heavy amounts of LES become less likely, but a significant event can still occur. Once lake ice begins to dissipate and waters gradually warm, a late season, heavy LES event may occur if particularly cold air happens to emerge from Canada.

The meteorological parameters discussed above possess a great deal of relevance in forecasting for an LES event off of any lake at any point. They are quite general in nature. The focus of this particular study is on Southern Lake Michigan LES events, and how such events impact Northwest Indiana. It is important to classify exactly what is meant by Southern Lake Michigan and Northwest Indiana. I will define Southern Lake Michigan as the region of Lake Michigan south of a line from Port Washington, Wisconsin to Muskegon, Michigan (roughly S of 43.5° N in latitude). This encompasses Lake Michigan's entire "Bowl Shaped" region. This area's geographical features may actually affect LES behavior in this region as I will point out later. I will define Northwest Indiana as Lake, Porter, and Laporte Counties. I have selected such a narrow region because I hope to focus primarily on northerly or north-northwesterly LES events. It is such events which are capable of dropping prodigious snowfall amounts on NW Indy residents.

Two recent LES events stand out as particularly significant in NW Indiana history: December 20th, 2004 and February 3rd and 4th, 2009. Both are classic, northerly flow LES events, which left excessive snowfall amounts across northwest Indiana. Totals exceeded 20" in both cases (albeit in localized areas), and snowfall rates eclipsed 3" per hour at times. Both events were well-observed and well-sampled. Thus, they will serve as excellent windows into features, ingredients, and parameters which are common to significant lake effect snowfalls off of Southern Lake Michigan.

December 19-20, 2004 featured a particularly significant LES event over Northwest Indiana. A powerful cold front blasted SE out of Canada, and significant CAA accompanied its passage across the Great Lakes region. As NW winds shifted northerly, a dominant, single band of lake effect snow begin organizing over a relatively mild Lake Michigan. This northerly wind direction resulted in a band of LES extending the entire length of Lake Michigan (7). The band remained nearly stationary, leading to excessive snowfall amounts across a small area in Northwest Indiana. Totals ranged from 6-12" across much of Porter and Laporte counties, with

15-25” across eastern Porter and western Laporte counties. The highest snowfall total came from Michigan City, IN, where 26” of snow was recorded (7). So, exactly what meteorological variables led to such a heavy LES event for NW Indy?

Being late December, Lake Michigan was still relatively mild when compared to what it might be in late January or February. As 850mb readings of around -20C poured across above freezing lake waters, delta T’s exceeded 22°C (8). This led to extreme instability over Lake Michigan. Such a pronounced increase in low-level instability was instrumental in leading to significant snowfall amounts over NW Indy as it allowed for very heavy snowfall rates in excess of 2-3” per hour at times.

Perhaps even more important was wind direction. As a cold 1032mb high pressure cell nosed into central Minnesota, winds quickly shifted from NW to due north across all of the Great Lakes Region (8). This northerly wind direction, nearly 360°, led to an incredibly long fetch over Lake Michigan. As cold air blew due south out of Canada and across Lake Michigan’s long axis, evaporated moisture continued to increase. Furthermore, sfc-850mb winds were nearly unidirectional, with only a slight backing between 850mb and 700mb (8). With Vertical Wind Shear of < 30°, well-organized LES bands could be expected, with single band formation likely. Additionally, wind speeds were not overly strong leading to a hospitable environment for LES formation in that bands had a chance to form without being torn apart.

Synoptically, in addition to a well-developed high pressure center over the Northern Plains, a 1004mb low pressure center was exiting the Great Lakes region, as it moved from northern Lake Huron into upstate New York. Aloft, a well-developed 500mb trough axis shifted gradually eastward across Michigan (8). Accompanying its passage was a region of cyclonic vorticity advection, which further enhanced lift and aided in squeezing out available moisture.

In addition to broader, synoptic features, several local features also helped contribute to significant snowfall amounts over extreme northwest Indiana. Given a favorable wind direction, an upwind, unfrozen lake can act as a significant, positive feedback in relation to overall LES amounts in a downstream region (5). Intuitively, one can see how such a process manifests itself as moisture is picked up, advected by broader flow patterns, and essentially added to moisture already available via a downwind lake. The "Lake Superior Connection" acts as a prominent example of such a setup. As cold, northerly winds blow south across a wide region of Lake Superior, quite a bit of water vapor is condensed, moisture which moves south across Lake Michigan, where even more liquid is added to the mix. December 19^{th}-20^{th}, 2004 was a classic case of a "Lake Superior Connection" as it was relatively early in the season, and both Lakes Superior and Michigan were relatively mild. Furthermore, nearly 360° sfc-850mb wind fields allowed for an incredibly long fetch across both lakes.

Another factor which likely contributed to heavy LES amounts over NW Indy on December 19^{th}-20^{th} of 2004, can be seen by carefully examining a daily weather map. The surface map from 12/19/04 at 1200z indicates northwest winds all across Wisconsin and Illinois, on Lake Michigan's western shoreline. Yet, when one looks on Lake Michigan's eastern shoreline, light NE winds are indicated. Such a wind field allowed for significant, mid lake convergence. This convergence led to an upswing in rising motion, which allowed for stronger updrafts and heavier precipitation.

December 19^{th}-20^{th} of 2004 was a significant LES event for NW Indiana, one which will not soon be forgotten. Yet, on February 3^{rd} and 4^{th}, 2009, another crippling lake effect snowstorm blasted across Lake, Porter, and Laporte counties. As a powerful coastal storm moved away from New England, a cold, 1036mb high begin to build south into the Northern Plains states. The high brought bitterly cold Canadian air down with it, dropping 850mb readings down to around -18°C. Once again, NW winds turned northerly, allowing for weak, multiple bands to consolidate into a well-developed, single band over Lake Michigan (9). This band oscillated back and forth over Lake, Porter, and Laporte counties between February 3rd and 4th. However, it eventually became focused on Porter County, IN as well as extreme western Laporte County, IN. Snowfall amounts in excess of 6" were common across Porter and Laporte counties, with a maxima of approximately 19", about ½ mile SSW of Valparaiso, IN (9). So, once again, it must be asked: Exactly what meteorological parameters led to such significant LES amounts? And, we can now ask: How was Feb, 3rd-4th, 2009 different from Dec. 19th-20th, 2004?

Despite Lake Michigan being notably colder than it might be in December, sufficient instability was present for heavy amounts of LES. Bitterly cold 850mb readings between -18° and -20°C allowed for delta T's of well above -13°C (8). This led to plentiful low-level instability all across Lake Michigan, which allowed for heavy, convective snowfall rates to materialize. Similar to December 19th-20th of 2004, snowfall rates exceeded 2" per hour, even approaching 4" per hour at a couple of points.

Once again, a cold, Canadian high pressure system nosed into The Northern Plains. This allowed for NW winds to shift northerly, providing a long fetch over Lake Michigan. This 340°-360° flow blew from Manistique, MI to Michigan City, IN, picking up an abundance of moisture and energy from a relatively balmy Lake Michigan. Sfc-850mb winds were nearly unidirectional, with only a slight degree of backing noted as 340° surface winds shifted to nearly 360° at 850mb

(8). Nonetheless, sfc-700mb vertical wind shear remained below 30°, allowing for very well organized, single bands of lake effect snow to form. Additionally, wind speeds were quite light, with only 20 knots noted at 850mb, and 15 knots noted at 700mb (8). This further contributed to LES band formation in that bands were not torn apart before growing into well organized structures.

Synoptically, a significant difference existed between December 19th-20th, 2004 and February 3rd-4th, 2009. The former featured a well-developed low pressure system, which was moving northeastward from Lake Huron into Canada. The latter did not exhibit such a low pressure system in close proximity to the Great Lakes region, with only weak cyclonic flow around a departing Nor'easter (8). Looking aloft, a 500mb trough axis was present as in the case of Dec. 19th and 20th, with cyclonic vorticity advection noted across the Great Lakes. This once again helped contribute to an upswing in vertical motion, which enhanced precipitation rates.

Once again, local features also played a significant role in allowing for such prodigious LES amounts over NW Indy. The "Lake Superior Connection" undoubtedly played a role, albeit a less significant one than in December of 2004, simply because Lake Superior was colder and becoming increasingly ice covered. The effects of mass, mid-lake convergence can once again be noted. Looking at SPC's Mesoanalysis for February 3rd, 2009 at 22z, one notices a light NNW wind off of Lake Michigan's western shore, with a light N or NE wind from Muskegon, MI south to Grand Rapids, MI. However, in this case, different from in December of 2004, an additional feature was present, which played a unique role in this particular LES event: a mesolow.

A mesolow is simply a small-scale low pressure center, which can be formed as a result of mesoscale contrasts in a variety of meteorological variables. Mesolows can occur in all four seasons as a result of lake effect processes, severe convection or other mesoscale processes. In LES events, such a low tends to form under weak synoptic flow on a bowl-shaped body of water such as Lake Huron or Lake Michigan (10). While a mesolow itself may not produce particularly heavy snowfall amounts due to its transient nature; it creates a dynamic environment favorable for single band development and stationarity on its western flank. February 3rd-4th, 2009 featured a mesolow structure over southern Lake Michigan. The NWS WSR-88D radar image from 02/03/09 at 18z indicated a cyclonically curved trajectory to the primary LES band (11). Additionally, wind observations supported its presence, with light NW winds from Sheboygan to Milwaukee, WI, and light NNE winds along SW Michigan's coastline. Furthermore, different from December 19th-20th, 2004, synoptic flow was quite a bit weaker, since no well-developed low pressure system existed in close proximity to Lake Michigan (8). This pattern also supports mesolow formation. The mesolow's cyclonic flow pattern forced a strong single band of LES slightly westward, shifting it over eastern Porter and western Laporte counties as opposed to Laporte and St. Joseph counties, further east. Had such a mesolow not been present, LES amounts likely would have been greatest further east across eastern Laporte and western St. Joseph counties in Indiana.

December 19th-20th of 2004 and February 3rd-4th of 2009 represent classic examples of a pattern which is favorable for significant LES amounts over extreme Northwest Indiana. However, many similar events have undoubtedly occurred, each of which is unique in its form and impact. The process of Lake Effect Snow is well understood overall; yet, it is still quite difficult to forecast its intensity and placement in an operational setting. However, certain key parameters exist, which are instrumental in beginning to assess LES potential.

To review, instability is a necessity if significant LES is to occur. Given Delta T's of < 10°C, significant LES is simply not likely to occur. Ideally, Delta T's should be > 13°C for significant snowfall accumulations. However, if Delta T's are too high, say > 25°C, due to a particularly cold and dry airmass, significant LES may not occur simply because dendritic growth is not favored. A lack of significant sfc-700mb vertical wind shear is also an essential component of a heavy LES event. If vertical wind shear is > 60°, only a few light snow showers can be expected. With vertical wind shear between 30° and 60°, moderate accumulations as a result of multiple bands are likely to occur. With vertical wind shear under 30°, single band formation is likely. Synoptically, strong CAA is usually associated with significant LES as well as cyclonic vorticity advection aloft. For significant amounts in NW Indiana, a cold, Canadian high pressure center nosing into the Northern Plains can often be seen on a surface weather chart. This helps shift low-level flow to a more northerly direction, leading to a more favorable fetch over Lake Michigan's long axis. In addition, high values of sfc-700mb RH are also important.

On a local scale, one must consider lake ice coverage. Significant ice coverage may decrease available moisture, and reduce snowfall amounts. For NW Indiana, "The Lake Superior Connection" is also important. If Lake Superior isn't significantly ice covered yet, and winds are nearly northerly, additional moisture may be available in addition to Lake Michigan's, further increasing snowfall amounts. Finally, one must remain alert for mesolow formation. If synoptic flow is weak, as it was on February 3rd and 4th of 2009, a mesolow may form. This is especially true on southern Lake Michigan, with its bowl-shaped orientation. Such a mesolow may force a single band westward, leading to copious amounts of snow just west of its landfall location.

Lake Effect Snow will always present a challenge for an operational forecaster. Its behavior is governed by an intricate mixture of variables which interact in ways we are only beginning to fully understand. As an operational forecaster, one must constantly be aware of changes in synoptic and mesoscale patterns which may play a role in an evolving LES event. Thus, while lake effect snow will always be somewhat mysterious in its nature, it presents an exciting opportunity for forecasters to work as a unit in hopes of discovering more about its dynamic nature.

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I am currently studying Meteorology at Valparaiso University in Indiana. I will be a Junior in Fall 2009. My interests within Meteorology are mainly in mesoscale processes, especially severe convection. I am also interested in wintertime mesoscale processes such as lake effect snowfall. Feel free to contact me with any questions regarding my work.

Sincerely,

Anthony P. Acciaioli