About this Work

GLISA participated in a winter climate adaptation project focused on Chicago, IL (http://glisaclimate.org/project/indicator-suite-and-winter-adaptation-measures-for-the-chicago-climate-action-plan). Freezing-rain events were identified as a weather hazard that is important to city planners and decision makers. As part of the project, GLISA researched how freezing-rain events are expected to change in the future for the city. Although Chicago was the primary geographical focus of this research, most of the research is relevant to the Great Lakes region as a whole.

Executive Summary

Chicago, IL has a unique geography for freezing-rain events. The city's proximity to Lake Michigan and its urban environment have significant impacts on freezing-rain by creating warmer air temperatures that prevent rain from freezing at the surface. Chicago annually has fewer freezing-rain events compared to areas outside of the city, and there is a one-month delay in the timing of the first freezing-rain event for any given year.

Historically, the number of annual freezing-rain events across the Great Lakes has decreased, and Chicago typically experiences some of the fewest events in the region. On average Chicago experiences less than three events per year, and the most events ever experienced in one year was seven.

Looking ahead to how freezing-rain may change in the future, there is consistent evidence to suggest that freezing-rain occurrences will continue to decline for Chicago, IL. There are limited studies on how freezing-rain is represented in models simulating future climate, but one study suggests freezing-rain events will decrease across the eastern half of the United States. There are other pieces of evidence that suggest the prevention of freezing-rain such as warmer winter air and lake temperatures. Warming lake temperatures will extend the effect of the Great Lakes on local weather conditions longer into fall and winter pushing back the first freezing-rain events for the year.
Freezing-Rain Meteorological Definition

Freezing-rain is the term used to describe rain that falls on sub-freezing surfaces and forms an icy layer. It is typically a product of falling precipitation (in frozen form) that travels first through a warm inversion layer in the atmosphere, where it melts, and then a cold atmospheric layer closer to the surface where it is supercooled.¹ A less common mechanism to freezing-rain formation is when supercooled droplets form in a sub-freezing layer and fall but do not travel through a layer cold enough to freeze them.² The precipitation falling at the surface can maintain its liquid state (supercooled droplets) even when temperatures are below freezing if all of the ice crystals melt in the warm layer and there are none left to serve as re-freezing sites at lower atmospheric levels. Objects at the surface that are at temperatures below freezing cause the supercooled droplets to freeze on contact. The difference between freezing-rain and sleet or other wintry precipitation mixes is that freezing-rain droplets have completely melted and do not refreeze in the lower atmosphere, whereas the other forms are a mix of frozen and unfrozen droplets as they reach the surface.

Freezing-Rain Atmospheric Processes

In the Great Lakes region, most freezing-rain events occur when extratropical storm systems move across the region after a polar air mass (cold air) has established itself in the north and warm air from the south advects over the cold surface air.³ "Freezing-rain conditions typically are associated with midlevel short-wave troughs and are found in the northeast quadrant of extratropical cyclones."³ Cyclone climatologies show that there is a higher frequency of cyclones in the east than in the west, which may relate to higher frequencies of freezing-rain events in the east when other conditions, like anomalously warm air over sub-freezing air, exist.³ The paths of cyclones having impact on the Great Lakes region are shown in Figure 1. The most severe winter storms in IL are frequently Type 2 where the storm track runs parallel and to the south of the polar front's preferred position.⁴,⁵ When the storms bring rain but surface temperatures are below freezing, freezing-rain is the result. The atmospheric conditions necessary for freezing-rain events to occur are infrequent, and when freezing-rain does develop it is characterized as "light" 98% of the time.³ The severity of freezing-rain events is typically associated with the duration of an event, not its intensity.

Figure 1
Taken from the Illinois State Water Survey: "Depiction of weather types related to severe winter storms in Illinois"
Distribution of Freezing-Rain in the Great Lakes Region

Most freezing-rain events are reported between December and March\(^3\) and are driven by winter extratropical storm systems passing through the region. There is a general increasing frequency of freezing-rain events in the eastern portion of the Great Lakes region but strong local differences exist (Figure 2). Local variability in the timing and placement of events is important and depends on factors that modify freezing-rain conditions. There are several reasons for the local variation of freezing-rain events including the influence of topography, the presence of large bodies of water, and the impact of urbanization on local weather conditions.

The Appalachian Mountain Range provides many low-lying valleys where cold air collects and remains during freezing-rain events.\(^3\) When cold surface air is trapped by the mountains, and warm, moist air travels over, the conditions are right for freezing-rain.\(^6\) Two different interactions with cold air trapped by the mountains can lead to freezing-rain - the source of the warm air is either from Atlantic cyclones or an eastward-moving continental cyclone.\(^6\)

Lakes experience fewer freezing-rain events, because the warm lake waters raise the temperature of the cold-air masses passing over them enough to prevent freezing of the droplets.\(^6\) This influence of the lakes is mainly observed during early winter when the lake waters are unfrozen. When the lakes are frozen over the frequency of freezing-rain events is similar for lake-side and inland locations.\(^3\)

Urban modification of local weather can also be important to freezing-rain events. The urban heat island effect is a localized warming of the surface air temperature due to urban-related activities that give off heat and the retention of heat by the materials used to construct the urban environment. Similar to the lake-effect, the urban heat island effect warms the local surface air temperature enough to prevent the freezing of droplets.\(^7\) The urban heat island effect is, however, four times as effective at reducing the chance of droplet freezing, and is responsible for 12-31% decreases in freezing-rain occurrences.\(^7\) Similarly, the urban heat island effect is also responsible for local decreases in snowfall.\(^7\)

The Great Lakes are also known to modify precipitation patterns and intensity. Regions along the western coasts of Lake Michigan, Lake Huron, Lake Erie, and southwest of Lake Ontario have fewer freezing-rain events each year compared to locations farther inland.\(^3\) Locations that experience modification of their air temperature by the
Figure 2 taken from Cortinas, 2000: "Frequency (×100%) of hourly freezing-rain reports relative to the number of available hourly observations in the research dataset from 1976 to 1990. To estimate the expected number of freezing rain observations per year, multiply the values by 0.876. Contours were drawn objectively using an objective analysis scheme described by Koch et al. (1983)"

**Chicago, IL Freezing-Rain Climatology**

Storms that bring icy conditions to Illinois are most common in the central part of the state, with less events annually in the far north and far south (Figure 3). The pattern across IL is consistent with the contour lines in Figure 2 and Figure 3 over Illinois. Chicago, IL is located in a region with fewer freezing-rain events annually, and it is unique because it is influenced by both the lake-effect and urban heat island effect. The city's urban heat island and lake-effect environment act together to delay the timing and lessen the occurrence of freezing-rain events. Observations between 1945-2000 show that Chicago experiences on average 2.7-2.9 freezing-rain days annually compared to 3.1-4.6 days at nearby stations (Figure 4). The influence of Lake Michigan is greatest in early winter when the relatively warm surface waters raise local air temperatures above freezing and delay the first freezing-rain event by one month compared to areas farther inland. Even during years that had a maximum number of freezing-rain events, Chicago experienced less freezing-rain days than the surrounding area and it was the only location to experience a first freezing-rain event as late as December.

The average number of freezing-rain days has fluctuated over the 1948-2000 time period. The Chicago area experienced the most freezing-rain days during the first third of the period (about 5 days annually), the least during the second third (1-2 days annually), and the average rebounded during the last third (around 4 days annually). Over the entire period, significant downward freezing-rain trends were found in several regions of the US, including the Midwest.

Figure 3 taken from the Illinois State Water Survey: "Average annual number of days with freezing rain"
The Future of Freezing-Rain Events

Several questions are posed to synthesize a storyline about the future of freezing-rain in Chicago and the Great Lakes region. If there is a consistent message across all components there is greater evidence in support of the storyline.

1. **Is there a climate change signal in the historical observations?**

An overall decreasing trend in the number of freezing-rain days between 1948 and 2000 has been identified in the Midwest, but dividing that time into three periods revealed a high-low-medium pattern for freezing-rain days, respectively. The lack of a consistent trend of decreasing freezing-rain days in each successive period provides less evidence that future years will continue the downward trend.

2. **If there is a signal in the observations, is it consistent with basic theory?**

With a decreasing trend of freezing-rain days one would expect to see other changes related to winter precipitation such as more rain (snow) if air temperatures are increasing (decreasing) or fewer winter storms moving across the region. Observations point to a combination of events occurring that are consistent with less freezing-rain. The Chicago area has experienced decreased snowfall by a few inches on average, but the state of IL has only had small, statistically insignificant increases in winter precipitation and air temperatures since 1895. We would expect decreasing snowfall to be replaced by increasing winter rainfall if precipitation totals are staying the same or slightly increasing. However, discussion of observed winter rainfall trends are scarce in the literature. There is evidence for a decrease in the number of extratropical cyclones (storms) passing over the Great Lakes which is the main mechanism for producing wintertime precipitation. So, if precipitation totals are staying fairly constant but the number of opportunities for producing precipitation (i.e., storms) are decreasing, winter precipitation must be coming in more intense events. There is a finding that extreme precipitation events have increased in the Great Lakes, but most of
the trend was due to increases during the warm-season.

3. Is there a climate change signal in the GCMs?

There is very little information about freezing-rain in climate models presumably because models do not simulate freezing-rain directly. Models simulate precipitation and then an algorithm must be applied to the precipitation output to estimate the precipitation type (i.e., rain, snow, freezing-rain, sleet, etc). Several algorithms exist and each has its own strengths and weaknesses.² There are a few studies that have concluded general decreases in freezing-rain events over the eastern United States and potentially slight increases over northeast Canada.² However, the Lambert and Hansen (2011) study only examined freezing-rain from one climate model (CGCM3) run under one emissions scenario (A2), which is only a sample of the models and scenarios that are available. By the end of the 21st century Lamber and Hansen predict that freezing-rain activity will decrease by two events per year at most in the eastern United States and by about one event per year near Chicago, IL.

4. Are the projections reliable?

The reliability of the projections is a complex matter that will be determined differently by each application that uses their information. In the Lambert and Hansen (2011) study on freezing-rain only one GCM was used to show a decrease in freezing rain the eastern United States. There are very few studies to date that discuss model projections for freezing-rain, so freezing-rain projections are lacking. Putting aside the limitations to only using one model for information about future climate, there are some general statements of quality about GCMs for the Great Lakes region that can inform how reliable the information is that they could provide. These statements are directly relevant to the collection of GCMs known as CMIP3, which includes the model used by Lambert and Hansen (2011).
• GCMs simulate large-scale processes mainly responsible for wintertime precipitation better than convective precipitation mechanisms.
• GCMs have relatively large spatial resolutions (2.8 degrees lat x lon for the Lambert and Hansen (2011) study) that do no distinguish small-scale (i.e., city-scale) differences.
• Lake-effects are not represented in the GCMs because the lakes are not simulated (important for modifying the timing of Chicago freezing-rain events).
• The urban heat island effect is not represented in GCMs (important for modifying the frequency of Chicago freezing-rain events).
• GCMs do not directly simulate freezing-rain, so freezing-rain projections are dependent on various algorithms\(^2\) that must interpret the type of precipitation simulated.
• Freezing-rain events typically occur on the order of a few hours but the models were sampled twice daily.\(^2\)

**Synthesis**

There is a level of agreement amongst all pieces of evidence (observations, climate models, and theory) to suggest that Chicago, IL will experience less freezing rain events in the future. Freezing-rain events have decreased across the Midwest from 1948 to 2000, and the western Great Lakes region (including Chicago, IL) experiences less freezing-rain than the eastern Great Lakes. Chicago, IL receives a minimum amount of freezing rain compared to the entire Great Lakes region because it is affected by Lake Michigan and its own urban heat island effect. Lake Michigan maintains a warmer air temperature near Chicago in early winter that can prevent the formation of freezing-rain. Once the lake is frozen over it no longer modifies the near-lake air temperature, therefore its influence is greatest in early winter. Chicago's urban heat island effect is four times stronger than its lake-effect and modifies freezing-rain throughout the extent of winter. The frequency of freezing-rain in Chicago is notably less than freezing-rain events just outside of the city.

According to the Lambert and Hansen (2011) study, the number of freezing-rain events in the eastern United States is expected to decrease by 2100. Additional studies are required to make stronger statements about future freezing-rain projections. Based on the limited climate model information we have, decreases in freezing-rain are predicted near the eastern U.S. coastline (-2 freezing-rain events annually) with smaller decreases of about one less freezing-rain event per year for the Chicago, IL area. However, the information the model provided about freezing-rain did not take into account the lake- and urban-effects for Chicago, which we can not assume will remain constant over time. In particular, lake-ice on Lake Michigan has decreased\(^11\), which could mean a greater lake-effect on freezing-rain (less freezing-rain) in the future if the downward trend continues.

Since the observations and model projections converge to the same
conclusion that freezing-rain is decreasing in the Chicago area, there should be other detectable changes to confirm the trend. For freezing-rain to decrease there must be a change in the mechanisms responsible for freezing-rain. Changes are either related to the form of precipitation (i.e., freezing-rain, snow, or rain) that is falling, the amount, or a combination of both. Observations indicate that is the "combinations of both" scenario that is occurring. Snowfall has decreased in Chicago but the number of storms passing over the Great Lakes has also decreased. At the same time total precipitation in IL has not changed significantly, so we expect more winter precipitation to be falling as rain and in potentially heavier storm events.
Footnotes and References

All references are available on the Chicago project page (http://glisaclimate.org/project/indicator-suite-and-winter-adaptation-measures-for-the-chicago-climate-action-plan) or via GLISA’s Resource Portal (http://glisaclimate.org/search) - search by resource title or author name.


