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The Development of a U.S. Climatology of Extreme Ice Loads

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The Development of a U.S. Climatology Of Extreme Ice Loads

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Abstract

Ice thickness (and therefore weight) is a key engineering design consideration in the construction of many structures which are subject to outdoor weather. This includes most load-bearing structures, such as cables, towers, wires, etc. Detailed information for engineers regarding ice loads from freezing rain has been sorely lacking, due to a deficiency of site-specific data. Therefore, beginning in 1994, a consortium of individuals and government agencies undertook a project to produce a U.S. climatology of ice thickness due to freezing rain, in the form of an extreme value analysis. This effort, under the auspices of the American Society of Civil Engineers, utilized data modeling techniques to develop such a climatology. This report describes this effort, along with future plans for further development.

1) Introduction

In this report we discuss the development of the map of extreme ice loads with concurrent wind speeds that is included in the latest revision of American Society of Civil Engineers (ASCE) Manual 74 and in ASCE Standard 7. This project is a joint effort of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), the National Climatic Data Center (NCDC), the Air Force Combat Climatology Center (AFCCC), the Bonneville Power Administration (BPA), the Regional Climate Centers, and various state climatologists. The map is based on historical weather data from hundreds of weather stations operated by the National Weather Service (NWS), Department of Defense (DoD), and Federal Aviation Administration (FAA). Equivalent uniform radial ice thicknesses on wires perpendicular to the wind direction in past freezing rain storms were determined from the data at each weather station using ice accretion models. Qualitative damage information was obtained for the storms that appeared to be severe enough to damage trees and power lines. This information was used both to check the modeling algorithms and to group the stations into superstations for the extreme value analysis. Ice thicknesses for long return periods were determined by fitting the generalized Pareto distribution to the sample of largest ice thicknesses for each superstation. Wind speeds concurrent with the extreme ice thicknesses were also calculated. In the West, from the Rocky Mountains to the Pacific, ice thickness zones were extrapolated using qualitative information because extreme ice thicknesses have not yet been calculated from the weather data in this region. For application to overhead electrical wires, the mapped ice thicknesses are adjusted for return period, height above ground, topography, and possibly wire orientation.

Ice and wind-on-ice loads on electric power transmission lines and communication towers are the governing loads (i.e., for engineering design, the key weight factor that must be considered) on these structures in much of the United States. For the 1998 revision of ASCE Standard 7 *Minimum Design Loads for Buildings and Other Structures* (ASCE 2000), the Ice Load Task Committee provided a map of ice thicknesses from freezing rain with concurrent gust speeds for a 50-year return period for the eastern half of the country. This Standard is referenced by other codes, guidelines and standards, including the *National Electrical Safety Code* (NESC), ASCE Manual 74 *Guidelines for Electrical Transmission Lines Structural Loading*, and EIA/TIA 222 *Structural Standards for Steel Antenna Towers and Antenna Supporting Structures*. A revised ice map is provided in the draft of the 2002 revision of ASCE Standard 7, and for the revision of ASCE Manual 74 that is also in progress. The 1998 map was revised based on work done by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) for the American Lifelines Alliance (www.americanlifelinesalliance.org) to analyze weather data in the Plains states, discussions with the Oregon State Climatologist about the map for the Pacific Northwest, and qualitative damage information from *Storm Data* (NOAA 1959–present) west of the Rockies, excluding the Pacific Northwest.

CRREL developed software and algorithms for processing historical data from weather stations with hourly weather data and 6-hourly or daily precipitation data. AFCCC provides researchers at CRREL with the archived data, as part of its support for the US Army. The period of record of the electronically archived data typically begins in the late 1940s for long-established NWS and military stations and around 1973 for most FAA stations. The hourly weather data and precipitation data are then merged into composite observations. (Note that this merging process is no longer necessary, with the availability of the Integrated Surface Hourly (ISH) database (Lott 2001), which provides a composite of the available data.) If hourly precipitation data are not available, accumulated precipitation (e.g., from 6-hourly reports) is prorated to each hour based on the type and severity of precipitation. Freezing rain storms are extracted from these merged data. The accretion of ice, expressed as an equivalent radial thickness, and wind-on-ice loads are modeled for each storm. Both the detailed CRREL ice accretion model (1996b), and the sometimes more conservative Simple model (Jones 1996a,b), are used. The CRREL model does a heat-balance analysis to determine how much of the freezing precipitation impinging on a horizontal cylinder freezes. The Simple model simulates the accretion of ice, assuming that it is cold enough that all the precipitation freezes.

Model results are checked for ice storms with large modeled ice thicknesses using qualitative damage information from *Climatological Data, National Summary* (NOAA 1950–1958) and *Storm Data* (NOAA 1959–present) supplemented by contemporaneous newspaper reports. The damage reports are also used to determine the footprint of damage to overhead lines, telecommunication towers, and trees for each ice storm.

To generate a long period of record for the extreme value analysis of ice and wind-on-ice loads, the weather stations are grouped into superstations. These groupings are based on the frequency of ice storms, the distribution of damaging ice storms, topography, proximity to large bodies of water, etc. Ice thicknesses and wind-on-ice loads for a 50-year return period are determined using the peaks-over-threshold method with the generalized Pareto distribution (Hosking and Wallis 1987). This is a three-parameter distribution, which allows for a heavy tail if the data warrant. The parameters of the distribution are determined, with a threshold chosen to give an occurrence rate of extreme ice thicknesses of up to about 1/year, using the method of probability weighted moments (Wang 1991). Wind speeds concurrent with the 50-year ice thicknesses are back-calculated using the 50-year wind-on-ice load on a 1-in. wire and the 50-year ice thickness. Finally, the ice thicknesses and concurrent gust-on-ice speeds for the superstations are mapped, using 0.25-in. increments in ice thickness and 10 mph increments in gust speed. The maps for the revision to ASCE Manual 74 are shown in Figure 1.

2) **Weather Data in the United States**

In the United States, historical weather data are archived at NCDC and AFCCC. Weather data are reported and provided by the NWS, the Navy, Army and Air Force, the FAA, and other state and federal agencies. At weather stations in the United States, temperatures are considered accurate to the nearest 1°F, wind speeds to the nearest knot, and precipitation amounts to hundredths or tenths of an inch, varying over time and from station to station. Temperature is archived in tenths of a degree Celsius, wind speeds in tenths of a meter per second, and precipitation amounts in millimeters (AFCCC) or hundredths of an inch (NCDC).

Before the data are archived, they are checked using quality control software to correct any data errors that can be automatically corrected and to flag apparent problems that will require a manual check of the data. NCDC does a further manual quality control of NWS and Navy weather records to check and correct data that were flagged and to fill in missing data elements and records if available. AFCCC provides the same level of quality control for the Army and Air Force data. Weather data from the FAA and other agencies, along with international data, do not go through this highest level of quality control, but are quality-controlled using automated QC software. More information on the network of weather stations and data archiving are in Lott and Jones (1998)

For the recent project for the American Lifelines Alliance to extend the mapped region west to the Rockies, both AFCCC data and ISH data from NCDC were obtained through AFCCC. The ISH data files are merged from both the AFCCC and NCDC archives. They include hourly, 6-hourly and 24-hourly precipitation amounts, when reported by the station. As earlier data (typically pre-1948) are digitized from paper records, they will be merged into the ISH database to extend the digital period of record for climatological studies, business interests, and research. This will provide a longer period of record for estimating extreme events. In addition, ISH data have been processed through additional quality control algorithms to make the data more robust. The daily precipitation data are available in a set of *Cooperative Summary of the Day* CDROMs.

The period of record for the electronically archived data begins in the late 1940s at many of the NWS and military weather stations. However, for a number of years, typically 1965 through 1972, but sometimes extending into the early 1980's, weather records were digitally archived only every 3 hours, even though hourly measurements were made. The original handwritten hourly data are available at NCDC, and are expected to be archived electronically and included in the ISH database over the next few years.

The NWS now uses an Automated Surface Observing System (ASOS), which was phased-in nationally during the early to late 1990s. This system is now in use at most hourly reporting stations, which are typically at airports. The system provides a continuous datastream, with generally reliable data for temperature, wind speed and direction, dew point, pressure, and visibility. However, the following elements are somewhat less accurate unless augmented by a human observer, which is done occasionally at selected locations:

- Reports of precipitation type sometimes do not properly show the type of precipitation occurring;

- Precipitation amount from freezing or especially frozen precipitation is problematic and not always reliable in sleet and snow, but usually reliable for freezing rain;
- Clouds are reported up to only 12,000 feet at most stations.

The Rosemount ice sensor has proven to be an excellent addition to the equipment suite at NWS and some FAA stations. It reports the occurrence of freezing rain as soon as it begins. It also has the capability to report:

- Freezing drizzle, for which algorithms are now being developed that will be implemented in the next couple of years;
- Ice thickness, for which algorithms have been developed, and are being tested at selected stations, to report the actual severity of ice accretion in the hourly observation.

The ice thickness capability is very promising for the future, in that utilities, aviation interests, and others will have access to these data in real time, and the archived data for climatological studies. Even without that, the current Rosemount reports of freezing rain have allowed for some continuity in the use of the archived data from the pre-ASOS through ASOS eras.

3) Modeling Ice Accretion in Freezing Rain

The most important parameters in determining ice loads caused by freezing rain from weather data are the precipitation rate and wind speed during the freezing rain storm. Unfortunately, anemometers and precipitation gauges may be adversely affected by accreted ice, and sometimes freezing rain storms cause power outages at weather stations. Thus, the expertise and dedication of the weather observers may have a significant effect on the quality of the recorded wind speed and precipitation amounts. The quality of measurements has varied over time at individual stations and varies from station to station. Furthermore, the quality of the archived data depends on the level of quality assurance that was applied prior to archiving. In analyzing the weather data to estimate ice loads, it is assumed that the data are correct, with the exception of certain known types of errors and shortcomings as mentioned above.

CRREL and Simple Ice Accretion Models

The Simple model determines the equivalent uniform radial ice thickness from the amount of freezing rain and the wind speed:

$$R_{eq} = \sum_{j=1}^{N} \frac{1}{\rho_i \pi} \left[(P_j \rho_o)^2 + (3.6 V_j W_j)^2 \right]^{1/2} , \qquad (1)$$

where

P_j = precipitation rate (amount in mm in the jth hour)

ρ_o = density of water (1 g/cm^3)

ρ_i = density of glaze ice (0.9 g/cm^3)

V_j = wind speed (m/s) in the jth hour

W_j = liquid water content (g/m^3) of the rain-filled air in the jth hour = $0.067 P_j^{0.846}$ (Best 1949)

N = duration of freezing rain storm (hr)

R_{eq} does not depend on the air temperature because it is assumed that all the available precipitation freezes. Then, because the ice is uniformly thick around the wire, R_{eq} does not depend on the wire diameter. Note that the liquid water content W is expressed in terms of the precipitation rate P, implicitly incorporating a fall speed for the raindrops. The relationship used in (1) results in a fall speed $V_T(\text{m/s}) = 4.15P^{0.154}$.

The CRREL model uses a heat-balance calculation to determine how much of the impinging precipitation freezes directly to the wire and how much of the runoff water freezes as icicles. If it is cold enough and windy enough, the ice loads determined by the CRREL and Simple models are the same. However, if the air temperature is near freezing and wind speeds are low, the CRREL model calculates smaller ice loads than the Simple model. In those conditions much of the impinging precipitation may freeze as icicles and some may drip off without freezing. The CRREL model requires the user to specify the diameter of the wire on which the accretion of ice is to be modeled; however, the ice thickness is essentially independent of wire diameter.

The CRREL and Simple models are discussed and compared to each other and to other ice accretion models in Jones (1996a). Comparisons of measured and modeled ice loads on three test spans in Canada are discussed in Newfoundland and Labrador Hydro et al. (1998). Characteristics of a number of models for the accretion of ice in freezing rain that have been used by utilities in the United States and Canada to map ice loads are briefly discussed in Jones and White (2002).

Data–Model Interface

To use historical weather data to determine ice loads, a number of decisions must be made about the data that are separate from the model, but affect the results. These include 1) prorating 6-hourly and 24-hourly precipitation amounts to each hour, 2) deciding how much of the precipitation accretes as ice when there are other types of precipitation, such as rain, snow or ice pellets, mixed with, or alternating with, freezing rain, 3) correcting the measured wind speed from the height above ground of the anemometer to the height of the wire, 4) dealing with wire orientation to the wind and variability in wind direction, 5) interpolating the weather data when they were archived only every third hour, 6) deciding when a freezing rain storm ends. Each of these issues is discussed in this section.

Prorating Accumulated Precipitation

The weighting factors used to prorate 6- and 24-hourly precipitation amounts to each hour are shown in Table 1. These weights were originally chosen to be the typical precipitation rate in mm/hr for each type of precipitation. Table 1 is based on a table provided by Tsoi Yip of Environment Canada (EC). The Canadian table was originally provided in an unpublished report for EC in August 1984. The main difference between Table 1 and the Canadian version is the larger weighting factor for moderate freezing rain, equal to that for moderate rain, here. However, this difference is unlikely to be significant because precipitation in ice storms is often described as light or moderate freezing drizzle or light freezing rain.

Table 1. Weighting factors for prorating 6- and 24-hourly precipitation amounts

Precipitation Intensity/type	*Rain*	*Rain showers*	*Drizzle*	*Freezing rain*	*Freezing drizzle*	*Snow*	*Snow grains*	*Ice pellets*	*Snow showers*	*Snow pellets*	*Hail*
Light	1.8	1.8	0.1	1.8	0.1	0.6	0	1.8	0.6	0.6	1.8
Moderate	5.1	5.1	0.3	5.1	0.3	1.3			1.3	1.3	5.1
Heavy	13.		0.8			2.5					

The weight assigned to each hour in the weather record is determined by the present weather codes for the hour, with the weight set to zero if there is no precipitation. For example, if the only type of precipitation reported in an hour is light freezing rain, the weighting factor for that hour is 1.8. If in the next hour moderate freezing drizzle is reported with light snow, the weighting factor is (0.3+0.6)/2=0.45. The fraction of the accumulated precipitation attributed to each hour is the weighting factor for the hour divided by the sum of weighting factors for the 6 or 24 hours in which precipitation accumulated. This fraction is then multiplied by the accumulated amount to obtain the estimated hourly precipitation amount. Continuing the example above, assume the accumulated precipitation amount in a six-hour period is 4.5 mm. Freezing rain was observed in 1 of these 6 hours and moderate freezing drizzle with light snow was reported in the next hour. The weighting factors for the 4 hours without precipitation is zero, so the sum of the weighting factors for the 6-hour period is 1.8+0.45=2.25. In the hour with freezing rain, 1.8/2.25=80% of the precipitation (3.6 mm) is assumed to have occurred, and the next hour with freezing drizzle and snow has 0.45/2.25=20%, or 0.9 mm, of precipitation. These precipitation amounts are then used in (1) in estimating the increment in equivalent radial ice thickness for those hours.

Mixed Precipitation Types

In freezing rain storms, the type of precipitation varies from hour to hour, and, in any hour, often two or even three types of precipitation will be noted. In the CRREL algorithm, there is no further subdivision of the prorated hourly precipitation amounts. Instead it is assumed that all the precipitation in an hour in which freezing rain falls accretes to the wire as if it were all freezing rain. The models are also allowed to accrete precipitation that was described as rain or drizzle (not freezing) if the air temperature is below freezing. These procedures are intentionally conservative. They allow the modeled ice loads to represent the possibly more severe conditions in the vicinity of the weather station, where all the precipitation is freezing rain rather than the mixture of precipitation types observed at the weather station, or where convective and evaporative cooling are slightly greater than at the weather station. This choice also expresses a reluctance to further subdivide the precipitation amounts based on weighting factors that at best are correct on average, but cannot represent the mix of varying precipitation types in an hour, of which the observers provide only a glimpse in their once per hour observations of the precipitation type.

In both the CRREL and Simple models, ice loads may be determined for two cases: 1) allowing ice to accrete only in hours in which the precipitation type is reported as freezing rain or a combination of freezing rain and other types of precipitation, and 2) allowing ice to accrete also in hours in which the precipitation type is ice pellets. Freezing rain and ice pellets occur in the precipitation-type transition region of winter storms (Stewart 1992), which typically is bounded by snow on one side and rain on the other. Freezing rain and ice pellets develop in the same meteorological conditions, namely a layer of warm air over a layer of cold air. Snowflakes, formed in clouds above the layer of warm air, melt as they fall through the warm air. These water drops then cool while falling through the layer of cold air below. For the right combinations of cold and warm layer thicknesses and temperatures, the raindrops may supercool in the cold air layer, but remain liquid and ultimately freeze on impact with a structure. However, there are two scenarios in which the precipitation falls as ice pellets rather than freezing rain: 1) if the cold air layer is thick enough and cold enough, the rain drops freeze partially or entirely, forming ice pellets, and 2) if the warm air layer aloft is relatively thin or cold, the snowflakes may not melt completely before falling into the cold air layer. In the first case, structures at higher elevations or high enough above ground may be in freezing rain while ice pellets are observed at weather stations. The CRREL ice storm team observed this in a storm in February 1996 in Tennessee where freezing rain damaged trees and power lines on Lookout Mountain, near Chattanooga, while ice pellets were falling at the Chattanooga airport. The inclusion of ice pellets in modeling ice loads at weather stations is intended to estimate ice loads that *may* have occurred on structures at sites where freezing rain occurred while ice pellets were observed at the weather station.

Anemometer and Wire Heights Above Ground

The ice thickness on wires is often calculated at 10 meters above ground, but may be calculated at any height. Because wind speed increases with height above ground through the earth's boundary layer, the ice thickness also increases with height, as shown by (1). Thus, it is important to know how far above ground the wind speed is measured. The anemometer height at any weather station has typically varied over time, and also varies from station to station. The rate of increase of wind speed with height depends on the ground cover, the roughness of the terrain, and the exposure of the site. In this study the wind speed was assumed to be proportional to the 1/7 power of the height, following ASCE Standard 7-93 (1993) for exposure C, which is appropriate at these airport weather stations. Thus

$$V_W = V_A \left(\frac{h_W}{h_A} \right)^{1/7} \tag{2}$$

where V_W and V_A are the wind speeds at the height above ground of the wire h_W and the height above ground of the anemometer h_A, respectively. This formula provides only an estimate of the actual wind profile at any time.

In addition to this anemometer height correction, a correction for hours in which the recorded wind speed is zero is also made. In these hours the wind speed for the previous hour with a non-zero wind speed is used. This is done in case the zero wind is a result of a frozen anemometer. Hours that are actually calm are "corrected" erroneously by this procedure, resulting in modeled ice thicknesses that are too high. On the other hand, if ice accreting on the anemometer has caused erroneously low but non-zero winds for a number of hours, the modeled ice thicknesses will be too low.

Wire Orientation and Wind Direction

Both the CRREL model and the Simple model compute the ice thickness on a wire which reorients as necessary so that it is always perpendicular to the wind to give the largest effect of wind-blown rain. This assumption is conservative for power lines, particularly for line routes that are nearly parallel to the prevailing wind direction in freezing rain storms. To determine the variation in ice thickness with orientation, the ice thickness for a wire that is always parallel to the wind and for wires with fixed orientations from north ranging from 0^{o} to 150^{o} in 30^{o} increments are also computed in the Simple model:

$$R_{eq} = \sum_{j=1}^{N} \frac{1}{\rho_i \pi} \left\{ \left(P_j \rho_o\right)^2 + \left(3.6 V_j W_j \sin[\theta - \phi]\right)^2 \right\}^{1/2} , \tag{3}$$

where θ is the wire direction and ϕ is the wind direction. For the extreme value analysis, only the ice thicknesses on wires that are always perpendicular to the wind direction are used. The results of (3) can be applied in specific locations or for specific storms to determine the variability of ice thickness with wire orientation that is expected.

Interpolating 3-Hourly Data

At NWS stations, from about 1965 to about 1972 or later, weather data were digitally archived only every 3 hours, even though measurements were made every hour. During those years, all weather elements were archived electronically at 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 Universal Coordinate Time (UTC) only. These gaps in the data are dealt with by assuming that the weather was the same as the archived hour in the two hours following. For example, the wind speed at 0400 and 0500 is assumed equal to the archived wind speed at 0300. However, the precipitation totals for the full period are available (i.e., for the entire event), so there is no loss of data in regard to precipitation accumulation. Also, with freezing rain generally being non-convective, there is less variation in conditions from hour to hour than during many other weather events. As a result, we found the level of verification with qualitative information (e.g., *Storm Data*) to be just as high as for events with hourly data available.

Storm End

An important aspect of pre-processing the weather data before running ice accretion models is deciding when a freezing rain storm ends. That choice affects both the maximum wind-on-ice load and the maximum ice thickness at the end of the storm. The maximum wind-on-ice load may occur following the freezing rain, if a cold front accompanied by higher winds moves into the storm area as freezing rain ends. In the models, storms are ended at the first hour after freezing rain ends when the air temperature rises above 1^{o}C. This choice sometimes results in ice accreting on top of previously accreted ice that is many days or even weeks old. Ideally, one would model the melting and sublimation of accreted ice. However, that process is more complex and locally variable than modeling the accretion of ice because melting by direct or reflected solar radiation and ice shedding before complete melting are both significant.

4) Damage Information

For the purposes of this qualitative investigation, a storm is defined as beginning when freezing rain begins at any station in the study region and continuing as long as freezing rain events continue to occur, with an event beginning at one station before one at another station has ended. A storm may be as short as a few days or as long as many weeks in regions where cold winters are typical.

Four criteria were checked in choosing the storms to investigate:

1) At least 13 mm of ice from the CRREL model, accreting freezing rain only, at one or more stations;
2) At least 13 mm of ice from the Simple model, accreting freezing rain only, at one or more stations, that is also at least 6 mm more than the CRREL freezing rain only result;
3) At least 13 mm of ice from the CRREL model, accreting both ice pellets and freezing rain, at one or more stations, that is also at least 6 mm more than the CRREL freezing rain only result;
4) At least 13 mm of ice from the Simple model, accreting both ice pellets and freezing rain, at one or more stations, that is also at least 6 mm more than the CRREL freezing rain only result.

Storms chosen, based on the first and second criteria, help to determine if the CRREL model should be used rather than the Simple model. Those chosen by the third and fourth criteria help to determine if freezing rain often occurs in the region while ice pellets are observed at the airport sites.

The storms that are investigated are test storms that *may* be damaging ice storms. In these storms, reports of downed trees and outages in the power distribution system, and perhaps in the power transmission system, are expected to have occurred where ice thicknesses are significant. However, it must be kept in mind that damage to overhead lines in ice storms is not necessarily caused by ice thicknesses exceeding the design value. Typically, most of the damage in ice storms is caused by ice-covered branches and trees falling on distribution lines. However, there are often reports that the weight of the ice on the wires of power, phone, cable TV, or telegraph lines caused outages by breaking wires and poles. High winds, galloping (conductor movement causes line to swing in a sine wave pattern), transformer problems, wet ground, frozen switches, broken ground wires, structures falling on wires, cars hitting poles, repairs not completed from prior storms, prior lightning damage, cracked arresters, defective components, and touching wires are sometimes mentioned as causing outages. There may also be regions with significant icing where there is little or no damage to trees and power lines. This is most likely to occur where there are few trees or an effective hazard-tree program, where the overhead lines are designed for relatively high ice loads and there is an effective line maintenance program, or where the power distribution system is underground. Thus, information on damage to overhead lines provides only an indication of significant icing.

For each storm, information from *Storm Data* (NOAA 1959–present) and *Climatological Data, National Summary* (NOAA 1950–1958) is compiled. This information was supplemented by newspaper reports from cities where the modeled ice thickness is at least 6 mm. The region in which damage to trees, power, phone, telegraph, and cable TV lines was reported is outlined on a map of each storm. Regions where only slippery roads, school closures, flooding or damaging snow accretions were reported are not included in this storm footprint.

Typically, storms chosen based on the first and second criteria are damaging ice storms, while those chosen on the third and fourth criteria are not. However, the information obtained for all of these test storms helps in constraining the ice thickness estimates from the models and identifying patterns of damaging storms. In addition, based on these investigations, we have tightened the criteria for allowing the accretion of ice (Jones 1998), which in turn has reduced the differences between the ice thicknesses determined by the CRREL and Simple models in some storms.

5) Extreme Value Analysis

The modeled ice thicknesses at the weather stations were used to estimate ice thicknesses for a 50-year return period. Both the peaks-over-threshold method (e.g., Hosking and Wallis 1987, Wang 1991, Abild et al. 1992, and Simiu and Heckert 1995) and the concept of superstations (Peterka 1992) were used in the extreme value analysis.

Superstations

The superstation concept is described in Peterka (1992) for extreme wind speeds. The 50-year return-period wind map in the 1993 revision of ASCE Standard 7 shows small regions in the Midwest with high winds. Peterka argued that these small-scale variations in the extreme wind speed were not real but were due to sampling error from determining the parameters of the extreme value distribution from relatively short data records. He suggested that the records of extreme winds, from different weather stations with the same wind climate, could be appended to each other to form a superstation with a much longer period of record. The long period of record of a superstation supplies many more extremes to use in the extreme value analysis and thus produces better estimates of the parameters of the extreme value distribution. The limitation on forming the superstation is the requirement that the maximum annual winds from the different stations in the superstation should be uncorrelated. If extreme winds at two stations are correlated, then including the second station supplies no new information on the extreme wind climate.

Sampling errors in the estimation of extremes can be significant for the electronic data records of weather stations, which vary from less than 20 years up to about 50 years in length. At any weather station, the probability that the 50-year return-period ice thickness has occurred increases as the period of record increases. However, a large ice thickness with a long return period may have occurred at a station with a short period of record, and, conversely, only short return-period ice thicknesses may have occurred at a station with a longer period of record. Thus, the ice thickness estimate for a 50-year return period, which is calculated from the available sample, may change significantly as additional years of data are added to the historical record. This variability decreases as the period of record increases.

In grouping stations into superstations, a number of factors were considered, including 1) the number of damaging storms at each station, 2) the number of times adjacent stations were in the same damaging storm, 3) the frequency of ice storms causing at least 1 mm of ice at each station, and 4) station elevation, along with latitude, proximity to water, and relief. A balance was sought between grouping only stations likely to have the same severe icing climatology against the desire to generate as long a period of record as possible to reduce sampling error.

Correlation Between Stations

If the ice thicknesses (and wind on ice) at pairs of stations in a superstation are correlated in time, then the concatenation of data from those stations does not supply new information and the apparently long period of record for the superstation is not real. However, if the correlation between stations is low, the stations are essentially independent.

The correlation between each pair of stations in each superstation was calculated as follows. For each pair, storms that overlapped in time were paired. If the ice thickness for either or both of these storms exceeded the threshold value for the superstation, that pair of ice thicknesses was included in determining the correlation for the station pair. The sample of extreme ice thicknesses is bounded from below by the threshold, so it is not normally distributed. Therefore, the non-parametric Spearman rank-order correlation coefficient r_s (Press et al. 1987) was used, rather than the commonly used Pearson correlation coefficient. The strength of the association between stations is given by the square of r_s. Stations that were correlated were not simultaneously included in the superstation. In this case, two versions of the superstations were analyzed, each including one of the correlated stations and the uncorrelated stations.

Peaks-over-threshold Method

The peaks-over-threshold (POT) method was used to estimate ice thicknesses for long return periods. This is different from the epochal method (fitting a distribution, often Gumbel, to the annual maxima) and is a better approach for freezing rain storms because:

- At a given location, freezing rain storms occur infrequently and some winters have no measurable freezing rain. In those years the maximum ice thickness is zero, which would have to be considered part of the extreme population in the epochal method;
- In other years there is more than one severe ice storm, each of which may cause larger ice thicknesses than the most severe storms in milder years. The epochal method does not include these large, but not worst-that-year, ice thicknesses in the estimation of the parameters of the extreme value distribution.

These problems are avoided using the POT method because values are chosen as members of the sample population if they exceed a specified threshold. The excess of the value over this threshold is used to determine the two additional parameters of the generalized Pareto distribution:

$$\begin{aligned} F(x) = P(X \le x \mid x \ge u) &= 1 - \left[1 - \frac{k(x-u)}{\alpha}\right]^{1/k} \qquad k \ne 0 \\ &= 1 - \exp\left[-\frac{x-u}{\alpha}\right] \qquad k = 0 \end{aligned} \tag{4}$$

The threshold is u, the shape parameter is k, and α is the scale parameter. The cases $k = 0$, $k < 0$, and $k > 0$ correspond to the extreme value distribution types I (shortest infinite tail), II (longer infinite tail), and III (finite tail length, $x < \alpha/k$). Typically, k ranges between –0.5 and 0.5.

The method of probability weighted moments (Abild et al. 1992, Wang 1991, Hosking and Wallis 1987) was used to determine the distribution parameters k and α. Estimates of the distribution parameters (Wang 1991) are provided by:

$$k = \frac{4b_1 - 3b_0 + u}{b_0 - 2b_1}$$

$$\alpha = (b_0 - u)(1 + k)$$

where (5)

$$b_0 = \frac{1}{l} \sum_{i=1}^{l} x_{(i)}$$

$$b_1 = \frac{1}{l} \sum_{i=1}^{l} \frac{i-1}{l-1} x_{(i)}$$

where the $x_{(i)}$ are the ordered sample, $x_{(1)} \le x_{(2)} \le \ldots \le x_{(l)}$ of values greater than the threshold u. Note that b_0 is the mean of the ice thicknesses in the sample and b_1 is a weighted mean.

A variety of methods can be used to define the threshold u. It should be high enough that only true extremes are used to estimate the parameters of the distribution, but low enough that there are sufficient data so sampling error is not a problem. For determining ice thickness extremes, the threshold thickness is chosen so that the occurrence rate of the sample extremes is about 1/year, except in the southern states where ice storms occur more infrequently. There the occurrence rate varied from about 1 in 2 years to 1 in 10 years.

Once the parameters of the distribution have been determined, the ice thickness x_T corresponding to a specified return period T is calculated from

$$x_T = u + \frac{\alpha}{k}\left[1 - (\lambda T)^{-k}\right] \qquad (6)$$

where λ is the occurrence rate (number per year) of values exceeding the threshold.
The estimation of extremes is discussed further in Jones and White (2002).

Wind-on-ice Speeds

The amount of ice that accretes on a wire is affected by the speed of the wind that accompanies the freezing rain. Wind speeds during freezing rain are typically moderate. However, the ice that accretes on a wire may last for days or even weeks after the freezing rain ends, as long the weather remains cold. Thus, the ice-laden wires may be exposed to high winds that occur after the storm. The wind speeds to use in combination with the extreme ice thicknesses were determined from the modeled wind-on-ice loads on a 1-in. wire.

The summary information for each freezing rain storm includes the maximum wind-on-ice load that occurred at any time during the storm. The parameters of the distribution of extreme wind-on-ice loads for the superstations were calculated by the peaks-over-threshold method described above. Assuming that the maximum wind-on-ice load in each storm occurs with the maximum ice thickness, we can calculate the concurrent wind-on-ice speed V_C from the wind-on-ice load F_{50} and the ice thickness $R_{\mathrm{eq}50}$ for a 50-year return-period:

$$V_C = \sqrt{\frac{2F_{50}}{\rho_a C_D (D + 2R_{eq50})}}\,, \tag{7}$$

where ρ_a is the density of air, D is the diameter of the bare wire, and the drag coefficient is C_D. V_C is the wind speed that, when used in combination with the 50-year return-period ice thickness, gives the 50-year return-period wind-on-ice load. It is used to characterize the 50-year wind load rather than using F_{50} directly because F_{50} applies only to a 1-in. diameter wire. Furthermore, if the concurrent wind speed is calculated for other return periods, it is found to be essentially constant. Therefore, the wind speed to be applied concurrently with the extreme ice thickness does not increase with return period.

V_C is an hourly wind speed, rather than a 3-s gust speed or a fastest-mile wind speed. It is obtained from the 1- or 2-minute average wind speeds that are reported each hour at the weather stations. Gust speeds are recorded at most first-order airport weather stations in the United States whenever there is a rapid change in wind speed with at least a 10-knot difference between the high and low speeds. In a previous study, these gust wind speeds at a number of Army and Air Force weather stations were used to calculate the 50-year return-period gust-on-ice speed G_C and the ratio between G_C and V_C:

$$f_{gust} = G_C / V_C = 1.34. \tag{8}$$

f_{gust} was used to estimate G_C from V_C for each superstation. This concurrent gust-on-ice speed G_C is mapped in Figure 1 with the 50-year equivalent radial ice thickness R_{eq50}.

6) Ice Thickness Estimates in the Western U.S.

From the Rocky Mountains to the West Coast, excluding the Pacific Northwest, extreme ice thicknesses have not yet been calculated from the weather data. In this region ice thickness zones with concurrent wind speeds were extrapolated based primarily on information from *Storm Data* (NOAA 1959–present). The information in *Storm Data* is sorted by state and includes the date the storm began, a list of the forecast zones within each state that were affected, and a brief narrative describing the storm and the resulting impact.

The evaluation process began by separating freezing rain storms from the snow and in-cloud icing events that can cause the same type of damage. The identification of freezing rain storms from the storm description was sometimes difficult, particularly along the eastern slopes of the

Rockies in Colorado and New Mexico where severe in-cloud icing apparently occurs with only a small contribution from freezing rain to the ice thickness.

For each of the freezing rain events that were identified, ice thicknesses and the associated wind speed were estimated based on the extent of damage to power and telephone lines and communication towers, the financial impact of ice and wind damage, duration of power outages, comparisons to previous ice storms, and reported ice thickness and wind speed. After all the ice storms were processed, they were plotted on a map by intensity and by location within each state. Ice thickness and concurrent wind speed zones were based on this information. Two of the authors (Jones and Thorkildson) established these zones independently, discussed differences, and ultimately came to an agreement on the zone boundaries.

Additional guidance for the extrapolations was provided by two papers on freezing rain in the United States (Bernstein and Brown 1997 and Robbins and Cortinas 1996). Both of these publications characterize the frequency of freezing rain across the United States, but neither contains information on the duration, precipitation amounts, or accumulated ice thicknesses. A narrative describing the distribution of freezing rain throughout the western United States by Kelly Redmond, Deputy Director of the Western Regional Climate Center, was also helpful. Finally, climatologists from these states reviewed the map and it was revised based on their comments and suggestions.

7) Site-Specific Issues

A number of factors contribute to differences in the equivalent radial thickness of ice on different wires of the same span and wires of different spans in a freezing rain storm. While the amount of freezing rain has an obvious effect on the accreted ice thickness, other factors are also important. The importance of wind speed and direction, air temperature, and Joule heating are discussed in this section.

Wind-blown rain may contribute significantly to the ice thickness on a structure. The wind flux term in (1) is comparable to the falling rain term at a wind speed of about 5 m/s. More ice will accrete on wires of spans at windy locations than on wires that are sheltered from the wind, if the other conditions are the same. Because wind speed typically increases with height above ground, more ice is expected to accrete on ground wires than on the conductors of the same span, and on the highest conductor in a vertical configuration than on the lower conductors. On the other hand, the ice thickness on wires of spans that are parallel to the wind direction will be less than the Simple model estimates in (1) and no increase in ice thickness with height above ground is expected.

The air temperature may vary at any location during an ice storm and across the region affected by the storm. At near-freezing temperatures, even small variations in temperature can have a significant effect on the fraction of the impinging precipitation that freezes to a wire and on the rate of freezing, which controls the shape of the accretion. At relatively higher temperatures, icicles may account for a large portion of the accreted ice. At lower temperatures, on the other hand, the impinging precipitation tends to freeze where it hits, accumulating in an eccentric accretion, which would cause torsionally flexible ground-wires and single conductors to rotate, with the ice eventually forming a cylindrical sleeve around the wire. At intermediate temperatures the impinging water flows before freezing, resulting in thicker ice on the sides or bottom of a wire than on the top. The shape of the accreted ice affects the drag coefficient and the actual wind-on-ice load.

Following an ice storm the temperature may remain below freezing longer at higher elevations than at the airports where the weather data are recorded. Where it remains cold, structures may see higher wind-on-ice loads than are obtained from the concurrent wind speeds on the map in Figure 1. Joule heating from the current in conductors may have a significant effect on the amount of ice that accretes. For the impinging precipitation to freeze to a conductor, the heat of fusion must be removed, typically by convective and evaporative cooling. If sufficient heat is generated in the conductor, it will remain ice free. Although this is unlikely, the amount of heat generation in the conductor may be enough to decrease the initial rate of freezing and make more water available for icicle formation. This larger volume of dripping water affects the aspect ratio of the icicles, with long, thin icicles occurring with lower freezing rates and short, fat icicles with high freezing rates. The shape of the accretion ultimately affects both the further accretion of ice and the rate of ice shedding when the storm ends and the weather warms.

8) Current Work

CRREL and the Bonneville Power Administration (BPA) are working to remap ice thicknesses in the Pacific Northwest. In addition to mapping extreme ice thicknesses from freezing rain, this project also includes the testing of an accretion algorithm for in-cloud icing. The map in Figure 1 is based on detailed maps provided to BPA by Meteorological Research Inc. (MRI) in 1977. The map of ice thicknesses from freezing rain that was compiled from these maps for ASCE Standard 7-98 (2000) was revised for the current revisions of that standard and ASCE Manual 74 based on discussions with the Oregon State Climatologist. When MRI originally mapped the region, they used weather data through 1964 at most of the stations in the region, a different model was used to estimate accreted ice thicknesses than has been used for the rest of the country, and extremes were calculated using Weiss (1955), who developed nomograms based on the Gumbel fitting method.

As a follow-on to the project to map extreme ice thicknesses in the Plains states for the American Lifelines Alliance, CRREL is analyzing weather data in the rest of the western states and Alaska. The in-cloud ice accretion algorithm tested in the Pacific Northwest will be applied in this region if it is successful.

9) Acknowledgments

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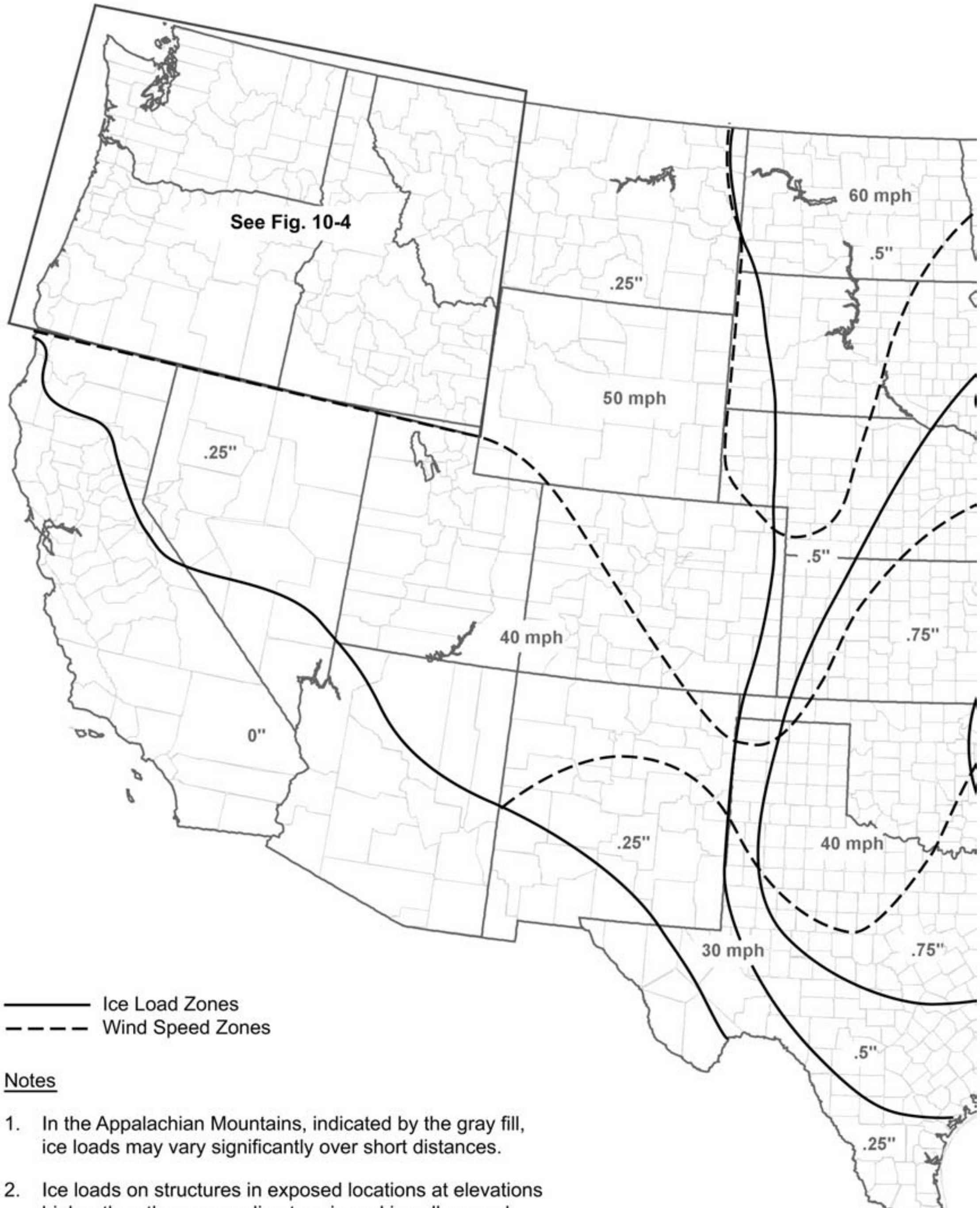
11) Symbols and Acronyms

C_D	drag coefficient of ice-covered wire
D	diameter of wire
f_{gust}	G_{50}/V_{50}
$F(x)$	cumulative distribution of x
F_{50}	50-year return period wind-on-ice load on a 1-in. wire
G_{50}	gust speed equivalent to V_{50}
h_A	height of anemometer above ground
h_W	height of wire above ground
k	shape parameter for generalized Pareto distribution
N	number of hours
P	precipitation rate
R_{eq}	equivalent uniform radial ice thickness
R_{eq50}	50-year return period equivalent uniform radial ice thickness
r_s	Spearman rank order correlation coefficient
T	return period
u	threshold for generalized Pareto distribution
V	wind speed
V_A	wind speed at height of anemometer
V_T	terminal velocity of raindrops
V_W	wind speed at height of wire
V_C	1-min hourly wind speed associated with R_{eq50} and W_{50}
$x_{(i)}$	ith extreme value
x_T	T-year return-period value
W	liquid water content
α	scale parameter for generalized Pareto distribution
λ	occurrence rate of extreme loads

π	3.14159
ρ_a	density of air
ρ_i	density of glaze ice
ρ_o	density of water

AFCCC	Air Force Combat Climatology Center
ASCE	American Society for Civil Engineering
ASOS	Automated Surface Observing System
BPA	Bonneville Power Administration
CRREL	Cold Regions Research and Engineering Laboratory
EC	Environment Canada
FAA	Federal Aviation Administration
ISH	Integrated Surface Hourly data
MRI	Meteorological Research, Inc.
NCDC	National Climatic Data Center
NWS	National Weather Service
POT	Peaks over threshold
UTC	Universal Coordinate Time



Notes

1. In the Appalachian Mountains, indicated by the gray fill, ice loads may vary significantly over short distances.
2. Ice loads on structures in exposed locations at elevations higher than the surrounding terrain and in valleys and gorges may be higher than the mapped loads.

Figure 1. Uniform radial ice thicknesses due to freezing rain, with concurrent 3-s gust speeds, for a 50-year return period a) western United States

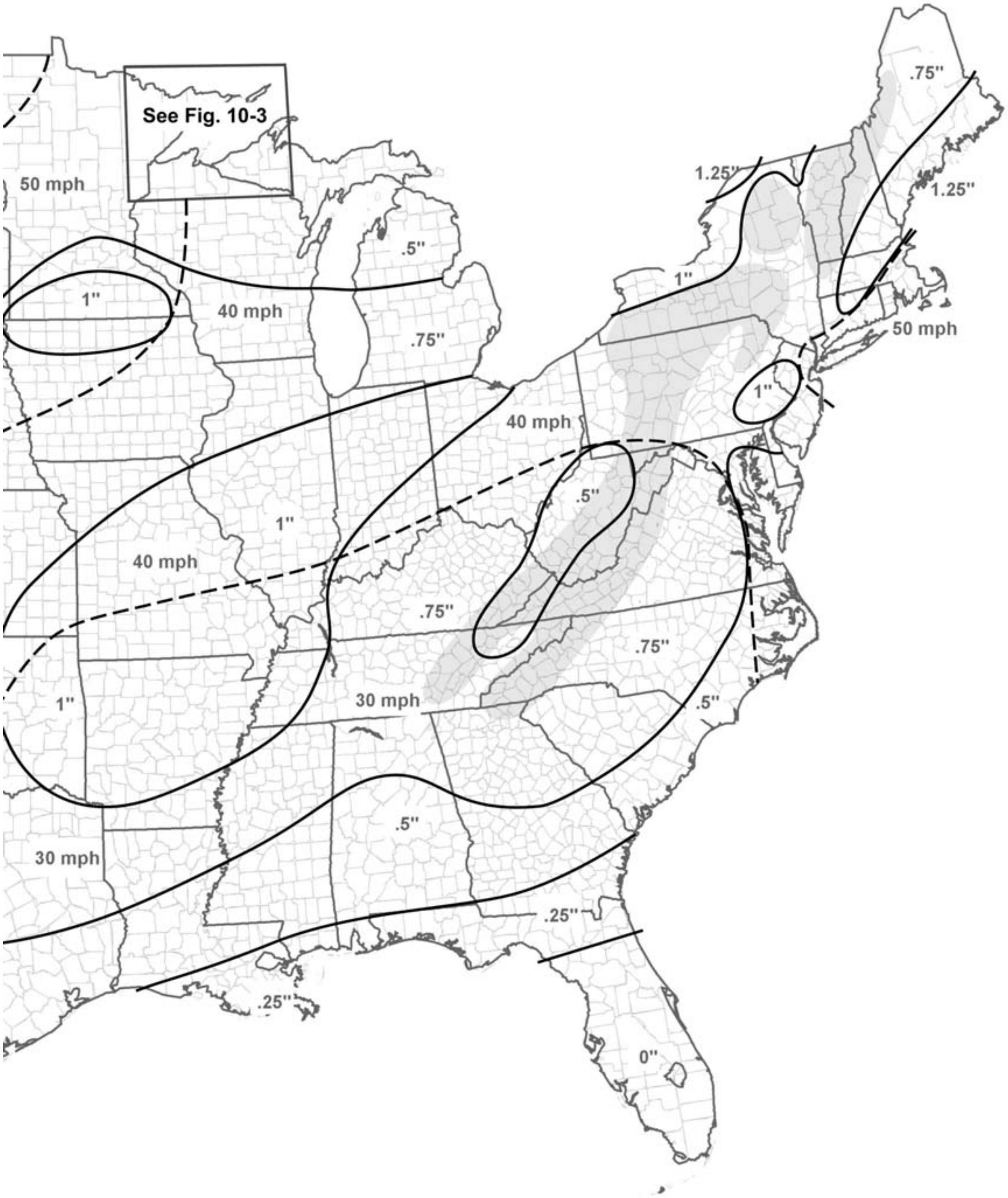
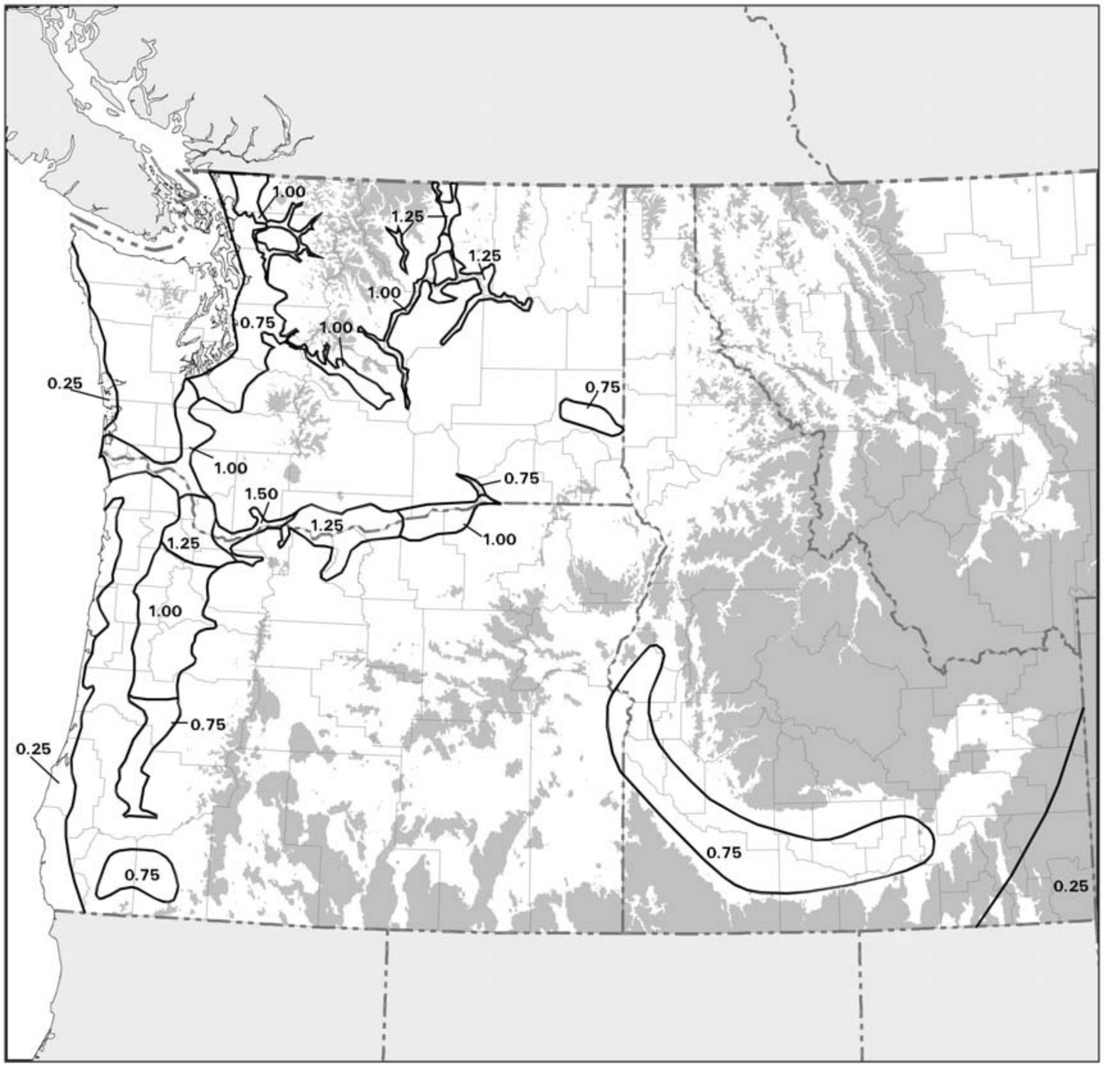


Figure 1 (cont). Uniform radial ice thicknesses due to freezing rain, with concurrent 3-s gust speeds, for a 50-year return period b) eastern United States



Notes:

1. Ice thickness is shown in inches.
2. Unless otherwise specified use 0.50 inch ice thicknesses.
3. Freezing rain is unlikely to occur in the shaded mountainous regions above 5,000 feet. ▨
4. Apply a concurrent 3-sec gust of 50 mph to the appropriate ice thicknesses.

Figure 1 (cont). (Referenced above as inset 10-4, from ASCE Manual 74) Uniform radial ice thicknesses due to freezing rain, with concurrent 3-s gust speeds, for a 50-year return period c) Pacific Northwest

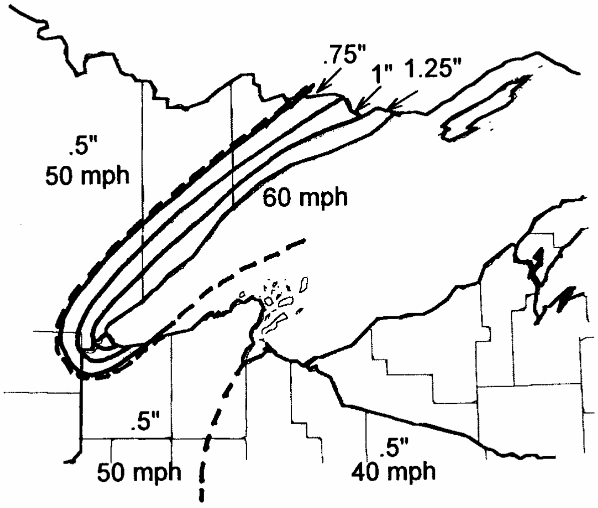


Figure 1 (cont). (Referenced above as inset 10-3, from ASCE Manual 74) Uniform radial ice thicknesses due to freezing rain, with concurrent 3-s gust speeds, for a 50-year return period d) Lake Superior