AmericanLifelinesAlliance

A public-private partnership to reduce risk to utility and transportation systems from natural hazards

Extreme Ice Loads from Freezing Rain

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American Society of Civil Engineers

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1.0 Introduction

Ice and wind-on-ice loads on electric power transmission lines and communication towers are the governing loads on these structures in much of the United States. For the 1998 revision of the ASCE 7 Standard *Minimum Design Loads for Buildings and Other Structures*, the Ice Load Task Committee provided a map of uniform ice thicknesses from freezing rain with concurrent gust speeds for a 50-year mean recurrence interval 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 74 *Guidelines for Electrical Transmission Lines Structural Loading*, and EIA/TIA 222 *Structural Standards for Steel Antenna Towers and Antenna Supporting Structures*. The goal of this project is to complete the ice load map.

The Base Region, mapped in Phase I of this project, abuts the region previously mapped. It includes the western Dakotas, Nebraska, Kansas, Missouri, Arkansas, and Louisiana, all of Texas and Oklahoma, Montana and Wyoming, and eastern Colorado and New Mexico. We used weather data from 114 stations in this region and the adjacent region to the east. We also reanalyzed the Piedmont region of the Carolinas, updating data at 3 stations and adding data from 3 additional stations in the eastern Piedmont.

West of the Rockies, ice loads from freezing rain are most significant in the Pacific Northwest. ASCE 7-98 includes a map of ice thicknesses from freezing rain for a 50-yr mean recurrence interval provided by the Bonneville Power Authority for Washington, Oregon, Idaho and western Montana. This map is based on a study done for Bonneville by Meteorological Research Incorporated in 1977. We will use historical weather data from about 180 stations to map ice loads in Alaska and west of the Rockies, including the Pacific Northwest, for Phase II. Mapping of the Pacific Northwest is being done in cooperation with Bonneville Power Authority.

2.0 Background

CRREL has developed software and algorithms for processing historical data from weather stations with hourly weather data and 6-hourly or daily precipitation data. The Air Force Combat Climatology Center (AFCCC) provides us with archived weather and precipitation data. The period of record of the electronically archived data typically begins in the late 1940s for National Weather Service and Navy stations and in 1973 for Army, Air Force and Federal Aviation Administration stations. We first merge the weather and precipitation data and prorate accumulated precipitation to each hour based on the type and severity of precipitation. We then extract freezing rain storms, which are assumed to continue as long as freezing rain is falling and, after freezing rain ends, as long as the air temperature remains below 1^{o}C. The accretion of ice, expressed as the uniform ice thickness, and wind-on-ice loads are modeled for each storm. We use both the detailed CRREL ice accretion model (1996a), which does a heat-balance analysis to determine how much of the freezing precipitation impinging on a horizontal cylinder freezes, and the sometimes more conservative Simple model (Jones 1996a,b), which simulates the accretion of ice at a hypothetical site where it is cold enough that all the precipitation freezes. Model results are checked for ice storms with high-modeled ice thicknesses (at least 13 mm of ice) using qualitative damage information from *Storm Data* (NOAA 1959-present) supplemented by contemporaneous newspaper reports. The damage reports are also used to determine the footprint of damage to power 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 fifty-year mean recurrence interval are determined using the peaks-over-threshold method with the generalized Pareto distribution (Hoskings and Wallis 1987). This three-parameter distribution, which allows for a long tail (negative tail shape parameter *k*) if the data warrants, fits extreme ice thicknesses better than the widely used two-parameter Gumbel distribution. 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 probability weighted moments (Wang 1991), which is unbiased and particularly efficient for $k<0$. Wind speeds concurrent with the 50-yr ice thicknesses are back calculated using the 50-yr wind-on-ice load and the 50-yr ice thickness. Finally, the ice thicknesses and concurrent gust-on-ice speeds for the superstations are mapped, using 0.25-in. increments in uniform ice thickness and 10 mph increments in gust speed.

3.0 Weather Data and Ice Accretion Models

Weather data are used as input to ice accretion models that determine the amount of accreted ice using empirical parameters and a physical model of the ice accretion process. The historical weather data files include documentation of the precipitation type and measurements of the precipitation amount, wind speed, air temperature, dew point temperature and air pressure. The accuracy of the loads determined by an ice accretion model depends on both the quality of the weather data and the quality of the model, as well as the decisions made by the user in applying the model to the data. Because weather instruments may not work well, or at all, in freezing rain, some of the data that determine the accreted ice thickness may be estimated by the weather observers both during and after freezing rain. Owing to spatial variations in precipitation type and intensity, wind speed and temperature, actual accreted ice thicknesses can vary significantly over relatively short distances. Thus, using weather data and an ice accretion model to determine ice thicknesses on wires and conductors supplies only an estimate of the actual ice thickness.

3.1 Weather Data

In the United States historical weather data are archived at the National Climate Data Center (NCDC) and the Air Force Combat Climatology Center (AFCCC). Weather data are collected by the National Weather Service (NWS), the Navy, Army and Air Force, the Federal Aviation Administration (FAA), and other state and federal agencies. At weather stations in the United States, temperatures are measured 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 weather 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. AFCCC provides the same level of manual quality control for the Army and Air Force data. Weather data from the FAA and other agencies do not go through this higher level of quality control. Thus AFCCC archives high quality-controlled Army and Air Force weather data, and lower quality-controlled NWS, Navy and FAA data. NCDC archives high quality-controlled NWS and Navy weather data and lower quality-controlled Army, Air Force and FAA data. For this project we obtained data from AFCCC and NCDC in Datsav3 format. These data files draw from both the AFCCC and NCDC archives and include 6-hourly precipitation data, where it is available. The daily precipitation data are available in a set of *Cooperative Summary of the Day* CDs.

The period of record for the computer-archived data begins in the 1940s at many of the NWS and Navy weather stations. However, for a number of years, typically 1965 through 1972, but sometimes extending into the 1980s, weather records were archived only every 3 hours, even though hourly measurements were made.

We obtained weather data sufficient for this application from 114 stations in the region extending from Louisiana to Montana and from six stations in the Piedmont of the Carolinas. The stations are listed in Table 1, with their location, elevation, the period of record for the coop precipitation

Station	State	Latitude	Longitude	Elevation (m)	Coop precip data POR	Hourly weather data POR	3-hourly years	Number of years
EL DORADO/GOODWIN	AR	33.22	92.80	77	40-99	73-99	-	17
FAYETTEVILLE/DRAKE	AR	36.00	94.17	381	7/49-1/82	73-99	-	26.5
FORT SMITH MUNI	AR	35.33	94.37	141	40-99	47-99	65-71	51.5
HARRISON	AR	36.27	93.15	416	9/61-99	73-95 93-99	-	20
LITTLE ROCK AFB	AR	34.92	92.15	95	-	2/56-72, 73-95, 93-99	-	42
LITTLE ROCK/ADAMS	AR	34.73	92.23	79	40-99	11/75-99	-	24
ALAMOSA	CO	37.45	105.87	2299	8/48-96	73-99	-	7
COLORADO SPRINGS	CO	38.82	104.72	1881	8/48-99	9/42-64, 73-81,87-99	-	21.5
DENVER/STAPLETON	CO	39.75	104.87	1625	8/48-10/99	5/40-6/66, 73-2/95	-	40.5
LA JUNTA MUNICIPAL	CO	38.05	103.52	1292	4/45-99	11/42-5/45, 73-99	-	21
LIMON MUNICIPAL	CO	39.27	103.67	1635	3/71-99	73-10/94, 96-99	73-10/86	24
PUEBLO MEMORIAL	CO	38.28	104.52	1439	7/54-99	48-99	65-72	41.5
TRINIDAD/ANIMAS CO.	CO	37.27	104.33	1756	8/48-99	73-99	-	26.5
CONCORDIA(AWOS)	KS	39.55	97.65	452	6/62-99	6/62-72, 73-99	65-72	37
DODGE CITY(AWOS)	KS	37.77	99.97	790	8/48-99	5/43-6/45, 48-72, 73-99	65-70, 72	26.5
GOODLAND/RENNER	KS	39.37	101.70	1124	8/48-99	48-72, 73-99	65-72	51.5
MCCONNELL	KS	37.62	97.27	418	-	12/53-72, 73-4/94, 93-99	-	25.5
RUSSELL	KS	38.87	98.82	568	9/49-99	1/50-4/94, 93-99	-	49.5
SALINA	KS	38.80	97.65	388	52-99	73-4/94, 93-99	-	26
WICHITA/CONTINE	KS	37.65	97.43	408	54-99	73-99	-	26.5
BATON ROUGE/RYAN	LA	30.53	91.15	21	40-99	42-2/45, 7/48-72, 73-99	65-72	51
LAKE CHARLES MUNI	LA	30.12	93.22	10	62-99	5/42-3/63, 73-99	-	28
MONROE REGIONAL	LA	32.52	92.03	24	47-99	73-4/95, 93-99	-	25.5
NEW ORLEANS/MOISANT	LA	29.98	90.25	9	54-99	10/45-99	65-67, 70-71	44.5

SHREVEPORT REGIONAL	LA	32.47	93.82	79	40-99	7/48-72, 73-99	65-69	51.5
JOPLIN	MO	37.15	94.50	299	7/48-99	73-4/94, 93-99	-	26.5
SPRINGFLD MUNI	MO	37.23	93.38	387	7/48-99	48-72, 73-99	65-72	51
BILLINGS/LOGAN INTL	MT	45.80	108.53	1088	7/48-99	5/35-41, 48-72, 73-99	65-72	51.5
GLASGOW INTL ARPT	MT	48.22	106.62	700	11/55-99	43,10/55-72, 73-99	65-72	44.5
GREAT FALLS INTL	MT	47.48	111.37	1115	48-99	48-72, 73-99	65-72	51.5
HAVRE	MT	48.55	109.77	792	2/61-96	73-99	-	24.5
HELENA REGIONAL	MT	46.60	112.00	1188	40-99	48-72, 73-99	65-72	51.5
KALISPELL	MT	48.30	114.27	906	40-96	73-99	-	26.5
LEWISTON MUNI	MT	47.05	109.47	1270	40-99	4/42-11/44, 73-99	-	22.5
MILES CITY	MT	46.43	105.87	801	40-99	48-72, 5/83-99	65-70	40
MISSOULA/BELL FIELD	MT	46.92	114.08	972	7/48-99	48-72, 73-81,87-99	65-72	46.5
BISMARCK MUNICIPAL	ND	46.77	100.75	506	7/48-99	7/36-38, 48-72, 73-99	65-69	51.5
DICKINSON MUNICIPAL	ND	46.80	102.80	789	7/48-99	73-90, 91-99	-	21
FARGO/HECTOR FIELD	ND	46.90	96.80	274	42-99	48-64,73-99	-	43.5
GRAND FORKS AFB	ND	47.97	97.40	278	-	10/59-99	-	26
GRAND FORKS INTL	ND	47.95	97.18	257	8/48-99	73-99	-	26.5
JAMESTOWN MUNICIPAL	ND	46.93	98.68	457	7/48-99	73-5/99	-	21.5
MINOT AFB	ND	48.42	101.35	508	-	10/59-99	-	27
MINOT INTL AIRPORT	ND	48.27	101.28	523	7/48-99	73-99	-	25
WILLISTON/SLOULIN	ND	48.18	103.63	581	7/48-99	67-72, 73-99	67-70	32
GRAND ISLAND	NE	40.97	98.32	566	40-99	2-12/44, 48-72, 73-99	65-72	26.5
NORTH PLATTE	NE	41.13	100.68	849	7/48-99	9/48-10/93, 93-99	65-72	51.5
SCOTTSBLUFF/HEILIG	NE	41.87	103.60	1206	6/48-99	43-9/44, 48-72, 73-99	65-72	51.5
SIDNEY MUNI	NE	41.10	102.98	1312	6/48-86	9/77-99	-	14

VALENTINE	NE	42.87	100.55	792	6/48-99	77-10/93, 93-99	-	19.5
ALBUQUERQUE INTL	NM	35.05	106.62	1620	40-99	12/41-99	-	54.5
CANNON AFB/CLOVIS	NM	34.38	103.32	1309	-	43-99	-	26
CARLSBAD/CAVERN CTY	NM	32.33	104.27	1004	7/48-99	9/42-54, 73-99	-	29.5
HOLLOMAN AFB	NM	32.85	106.10	1248	-	9/42-70, 11/81-99	-	18
ROSWELL/INDUSTRIAL	NM	33.30	104.53	1118	12/72-99	8/42-2/67, 5/74-99	-	23
ALTUS AFB	OK	34.67	99.27	420	-	2/43-4/45, 9/53-99	-	26.5
FORT SILL	OK	34.65	98.40	362	-	9/39-99	-	26
GAGE/SHATTUCK	OK	36.30	99.77	678	48-99	8/46-64, 73-99	-	36
HOBART MUNICIPAL	OK	34.98	99.05	477	48-99	73-99	-	20.5
MC ALESTER REGIONAL	OK	34.88	95.78	235	6/53-99	7/53-54, 73-99	-	24.5
OKLAHOMA CITY/WILL ROG	OK	35.38	97.60	397	48-99	12/41-64, 73-99	-	43.5
PONCA CITY MUNI	OK	36.73	97.10	307	3/48-99	8/46-54, 73-99	-	27
TINKER AFB	OK	35.42	97.38	394	-	73-99	-	25.5
TULSA INTL ARPT	OK	36.20	95.90	206	48-99	47-99	65-71	50.5
VANCE AFB/ENID	OK	36.33	97.92	398	-	42-99	-	24.5
ABERDEEN REGIONAL	SD	45.45	98.43	396	40-99	48-54, 11-12/56, 7/64-72, 73-99	65-69	19
ELLSWORTH AFB	SD	44.15	103.10	999	-	2/39-99	-	28
HURON	SD	44.38	98.22	393	5/48-99	1/40-10/93, 93-99	65-1/81	52
PIERRE	SD	44.38	100.28	531	48-99	1/48-8/93, 93-99	65-80	51.5
RAPID CITY REGIONAL	SD	44.05	103.07	966	5/48-99	73-99	-	26.5
SIOUX FALLS/FOSS	SD	43.58	96.73	435	48-99	8/48-10/93, 93-99	65-74, 80	46
ABILENE MUNICIPAL	TX	32.42	99.68	546	48-99	8/46-99	65-71	49.5
AMARILLO ARPT	TX	35.23	101.70	1099	48-99	3/43-99	65-72	51
AUSTIN/MUELLER MUNI	TX	30.30	97.70	189	40-99	73-99	-	26.5

BEAUMONT/PORTARTHUR	TX	29.95	94.02	7	10/47-99	7/48-72, 73-99	65-72	51
BROWNSVILLE INTL	TX	25.90	97.43	6	48-99	47-99	65-72	50.5
CARSWELL AFB	TX	32.77	97.45	198	-	12/42-99	-	28.5
CHILDRESS MUNICIPAL	TX	34.43	100.28	595	48-99	2/43-54, 73-99	-	26
COLLEGE STATION	TX	30.58	96.37	98	8/51-99	73-99	-	24.5
CORPUS CHRISTI INTL	TX	27.77	97.50	13	48-99	8/46-99	-	50.5
DALHART MUNICIPAL	TX	36.02	102.55	1216	12/48-99	73-99	-	20
DALLAS/FT WORTH	TX	32.90	97.03	182	74-99	73-99	-	26.5
DALLAS/LOVE FIELD	TX	32.85	96.85	148	48-99	7/46-5/99	65-72	51.5
DEL RIO INTL(AUTOB)	TX	29.37	100.92	307	5/51-8/57, 3/63-99	8/46-8/57, 3/63-99	3/63-1/64(no ZR), 65-72	27
DYESS AFB/ABILENE	TX	32.43	99.85	545	-	12/43-45, 4/56-99	-	26.5
EL PASO INTL ARPT	TX	31.80	106.40	1194	48-99	4/41-4/66, 9/72-99	-	43.5
FT HOOD/GRAY AAF	TX	31.07	97.83	309	-	10/50-99	-	26.5
~~FT HOOD AAF/KILLEEN~~	~~TX~~	~~31.15~~	~~97.72~~	~~283~~	~~-~~	~~3/61-99~~	~~-~~	~~5~~
FORT WORTH/MEACHAM	TX	32.82	97.37	216	9/46-6/53, 3/92-99	8/46-4/53, 73-99	-	19.5
GALVESTON/SCHOLES	TX	29.30	94.80	16	9/46-99	11/43-9/63, 73-99	-	38
HONDO MUNICIPAL	TX	29.35	99.18	283	3/75-99	5/84-99	-	9.5
HOUSTON/INTERCON	TX	29.97	95.35	33	6/69-99	73-99	-	26.5
HOUSTON/WILL HOBBY	TX	29.65	95.28	14	11/41-99	8/46-99	65-69	49.5
~~JUNCTION~~	~~TX~~	~~30.50~~	~~99.77~~	~~522~~	~~40-11/57 4/69-12/96~~	~~12/74-10/96~~	~~-~~	~~0~~
KELLY AFB	TX	29.38	98.58	210	-	9/37-99	-	26
LAREDO INTL AIRPORT	TX	27.55	99.47	155	1/44-10/65	43-99	-	19.5
LUBBOCK INTL ARPT	TX	33.65	101.82	988	40-99	47-99	-	44.5
LUFKIN/ANGELINA CO.	TX	31.23	94.75	88	40-99	73-99	-	22.5
MCALLEN/MILLER INTL	TX	26.18	98.23	33	61-99	73-99	-	26.5

MIDLAND REGIONAL	TX	31.95	102.18	872	6/48-99	4/40-99	65-72	49.5
PALACIOS MUNICIPAL	TX	28.73	96.25	5	2/43-99	4/49-54, 73-99	-	26
RANDOLPH AFB	TX	29.53	98.28	232	6/48-9/51	4/38-99	-	26.5
REESE AFB/LUBBOCK	TX	33.60	102.05	1017	-	3/42-70 82-2/97	-	15.5
SAN ANGELO/MATHIS	TX	31.37	100.50	582	9/46-99	7/41-99	65-72	51.5
SAN ANTONIO INTL	TX	29.53	98.47	242	9/46-99	9/46-99	65-10/67 7/69-72	52.5
STEPHENVILLE/CLARK	TX	32.22	98.18	402	7/41-99	6/84-3/94	-	10
VICTORIA REGIONAL	TX	28.85	96.92	36	7/61-99	7/64-99	65-72	26.5
WACO-MADISON COOPER	TX	31.62	97.22	155	40-99	5/42-8/68, 73-99	-	47.5
WICHITA FALLS/SHEP	TX	33.98	98.50	314	40-99	4/42-64 73-99	-	47
WINK/WINKLER CO.	TX	31.78	103.20	859	40-99	8/46-54, 73-99	-	27.5
CASPER/NATRONA INTL	WY	42.92	106.47	1612	8/48-99	40-64, 73-99	-	41
CHEYENNE/WARREN AFB	WY	41.15	104.82	1872	40-99	48-99	-	49.5
LANDER/HUNT FIELD	WY	42.82	108.73	1694	8/48-99	62-72, 73-99	65-72	37
LARAMIE/GEN. BREES	WY	41.32	105.67	2218	8/48-99	73-99	-	19.5
ROCK SPRINGS	WY	41.60	109.07	2060	8/48-99	73-99	-	22.5
SHERIDAN CO. ARPT	WY	44.77	106.97	1209	8/48-99	48-72, 73-99	65-72	46
CHARLOTTE	NC	35.22	80.93	234	9/48-99	1/48-4/95, 10/95-99	66-72	51
FT. BRAGG	NC	35.13	78.93	74	-	7/61-12/70, 1/73-99	-	35.5
GREENSBORO	NC	36.08	79.95	270	1/40-99	7/48-99	66-69	51
HICKORY	NC	35.73	81.38	362	1/49-99	1/73-99	-	24
RALEIGH	NC	35.87	78.78	134	8/48-99	7/48-99	66-71	51
SPARTANBURG	SC	34.90	82.22	296	11/62-99	10/62-4/95, 10/95-99	66-81	37

Table 1. Stations Used to Extend the Ice Load Map

data, the period of record for the hourly weather data, years with 3-hourly data, the total number of year with usable weather data, and comments on the data, including missing years in the precipitation or weather data, years with part-time data, and data errors.

3.2 Ice Accretion Models

The most important parameters in determining ice thicknesses from weather data are the precipitation rate and wind speed during the freezing rainstorm. Unfortunately, anemometers and precipitation gauges may be adversely affected by accreted ice, and sometimes freezing rainstorms 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 data. We do not know how much the quality of weather measurements has varied over time or how much it varies from station to station.

The Simple model determines the 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 amount (mm) in the jth hour

ρ_o = density of water (1 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 = $0.067P_j^{0.846}$ (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 Eq. 1 results in a fall speed V_T(m/s) = $4.15P^{0.154}$.

The CRREL model is similar to the Simple model, but 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 thicknesses 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 thicknesses 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 and Simple models are discussed and compared in Jones (1996b).

3.3 Data-model Interface

To use historical weather data to determine ice thicknesses, 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) at NWS stations, interpolating the weather data when it was archived only every third hour, 6) deciding when a freezing rain storm ends. Each of these aspects of determining ice thicknesses from weather data is discussed in this section.

3.3.1 Prorating Accumulated Precipitation

The weighting factors used to prorate 6- and 24-hourly precipitation amounts to each hour are shown in Table 2. These weights were originally chosen to be the typical precipitation rate in mm/hr for each type of precipitation. 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 six or 24 hours in which precipitation accumulated. This fraction is then multiplied by the accumulated amount to obtain the estimated hourly precipitation amount. Table 2 is based on one provided by Tsoi Yip of the Atmospheric Environment Service (AES), which was originally from an unpublished report by MEP for Environment Canada in August 1984. The main difference between Table 2 and the Canadian version is the larger weighting factor for moderate freezing rain, equal to that for moderate rain, here.

3.3.2 Mixed Precipitation Types

In freezing rainstorms the type of precipitation varies from hour to hour, and in any hour there will often be two or three types of precipitation. We do not attempt a further subdivision of the prorated hourly precipitation amounts, but instead assume that all the precipitation in an hour in which freezing rain falls accretes to the wire as if it were freezing rain. This ignores the lower collision efficiency and smaller sticking fraction of snow and the tendency for ice pellets to bounce when they hit. The models are also allowed to accrete precipitation that was described as rain or drizzle (not freezing) if the air temperature was freezing or below. These assumptions are conservative. They allow the modeled ice thicknesses to represent the possibly more severe conditions in the vicinity of the weather station, where perhaps all the precipitation is freezing rain rather than the mixture of precipitation types observed at the weather station.

3.3.3 Anemometer and Wire Heights Above Ground

Ice thicknesses on wires are often calculated at 10 m 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 in Equation 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 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. Equation 2 provides only an estimate of the actual wind profile.

3.3.4 Wire Orientation and Wind Direction

Both the CRREL model and the Simple model compute the uniform ice thickness on a wire whose orientation changes 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 for freezing rainstorms. To determine the variation in uniform ice thickness with orientation, the uniform ice thickness for wires with fixed orientations from north ranging from 0^o to 150^o in 30^o increments:

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

where θ is the wire direction and ϕ is the wind direction, are also computed in the Simple model.

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		0.8			2.5					

Table 2. Weighting Factors for Prorating 6- and 24-hourly Precipitation Amounts

3.3.5 Interpolating 3-hourly Data

At NWS stations, from about 1965 to about 1972 or later, weather data were archived only every 3 hours at 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 Greenwich Mean Time (GMT) even though weather measurements were made every hour. We deal with these gaps in the data by assuming that the weather was the same as the archived hour in the hours immediately before and immediately after. For example, the wind speed at 0200 and 0400 is assumed equal to the archived wind speed at 0300. We investigated the sensitivity of the modeled ice thicknesses to this interpolation scheme by comparing the ice thicknesses obtained using interpolated weather data and the original hourly data for one severe freezing rain storm at Springfield, Illinois, in

1978. The hourly and interpolated 3-hourly uniform radial ice thicknesses differed by only 1 mm, or 2% of R_{eq}. The original handwritten hourly data are available at NCDC, so one could use these complete weather records if it were considered worthwhile to take the time to manually enter the missing data.

3.3.6 Storm End

An important aspect of pre-processing the weather data before running ice accretion models is deciding when a freezing rainstorm ends. That choice affects both the maximum wind-on-ice load and the maximum ice thickness for the storm. The maximum wind-on-ice load may occur following the ice storm, if a cold front accompanied by higher winds moves into the storm area as freezing rain ends. We end storms at the first hour after freezing rain ends when the air temperature goes above 1^{o}C. This choice sometimes results in ice accreting on top of previously accreted ice that is many days or weeks old. For example, in newspaper reports on ice storms in North Dakota, utility spokespeople often mentioned that they had line crews out breaking the ice off their wires and that if they didn't the ice would remain the entire winter. Ideally, one would model the melting and sublimation of accreted ice; however, that is more difficult than modeling the accretion of ice. Melting by direct or reflected solar radiation and ice shedding before complete melting may be significant at many locations.

4.0 Storms

To balance these inherent uncertainties in modeled ice thicknesses and to provide a qualitative description of historical freezing rain storms to better understand the climatology of these storms in the region, we also compile information from newspaper accounts of damaging freezing rain storms, (NOAA, 1959-1999), and other publications. These sources are not expected to supply quantitative information on ice thicknesses, but they do provide crucial information on the severity and extent of storms.

We chose storms in the Base Region, based on the modeled ice thicknesses, and obtained qualitative information on these storms. We use three criteria for choosing these storms: 1) the accretion of 13 mm or more of ice from freezing rain only by the CRREL model, at one or more stations, or 2) the accretion of at least 13 mm of ice from freezing rain only by the Simple model, which is also at least 6 mm more than the CRREL model result, at one or more stations, or 3) the accretion of at least 13 mm of ice from freezing rain or ice pellets by either the CRREL or Simple models, which is also at least 6 mm more than the freezing rain only result, at one or more stations. The second criterion is used to investigate the justification for using results from the more conservative Simple model, rather than the CRREL model, in the extreme value analysis. The third criterion is used to investigate the justification for allowing ice pellets to accrete as well as freezing rain, to pick up storms in which there may be a band of freezing rain that is not observed at the weather stations. In these storms descriptions we expect to see many reports of downed trees and outages in the power distribution system, and perhaps in the power transmission system, if the actual ice thicknesses were as high as the modeled ice thicknesses. Thus these are test storms that *may* be damaging ice storms.

We identified 125 storms in the Base Region for which we mapped the modeled ice thicknesses and determined the footprint of the storm using information we compiled from *Storm Data* and newspaper articles from cities in the affected region. Based on this compilation, we ultimately used the Simple model results for freezing rain only in mapping ice thicknesses throughout the Base Region. The storm footprints were also compiled to determine regions with similar icing climatologies for forming superstations for the extreme value analysis.

5.0 Extreme Ice Thicknesses and Concurrent Wind-on-ice Speeds

We used the modeled ice thicknesses at the weather stations in the Base Region to determine ice thicknesses with a 50-yr mean recurrence interval. We found both the peaks-over-threshold method (Simiu and Heckert 1995, Hoskings and Wallis 1987, Walshaw 1994, Wang 1991, Gross et al. 1994, and Abild et al. 1992) and the concept of superstations (Peterka 1992) to be useful in the extreme value analysis.

5.1 Superstations

The superstation concept is presented in Peterka (1992) for extreme wind speeds. The 50-yr wind map in the 1993 revision of ASCE 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 prediction of extreme loads can be significant for the electronic data records of weather stations in the Base Region, which range up to about 50 years in duration (see Table 1). At any weather station the probability that an ice thickness with a 50-yr mean recurrence interval has occurred increases as the period of record increases. However, a high ice thickness with a long mean recurrence interval may have occurred at a station with a short period of record, and conversely, only short recurrence interval ice thicknesses may have occurred at a station with a longer period of record.

5.2 Peaks-over-threshold Method

Researchers often use the epochal method to determine the parameters of an extreme value distribution. They pick the maximum value for each year in the period of record, and then use these annual maxima to determine the parameters of a type I (Gumbel), II (Frechet) or III (reverse Weibull) extreme value distribution. We think that the peaks-over-threshold (POT) approach is better for dealing with ice thicknesses for the following reasons:

- At a given location freezing rainstorms occur infrequently and some winters will 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 will be more than one severe ice storm, each of which may generate larger ice thicknesses than the most severe storms in milder years. The epochal method would not include these severe but not worst-that-year storms in the estimation of the parameters of the extreme value distribution.

- Because the calendar year ends in the middle of the freezing rain storm season one could argue that it make more sense to choose maximum ice thicknesses for the season rather than for the calendar year. In one study the parameters of the extreme value distribution depended on whether the calendar or seasonal year was used (Laflamme 1993).

These problems are avoided using the POT method because loads are chosen as members of the extreme 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 (GPD):

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

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. If the data are correctly described by a GPD, then k is not dependent on the value chosen as the threshold, as long as the threshold is chosen high enough.

We used probability weighted moments (Abild et al. 1992, Wang 1991, Hoskings and Wallis 1987) to determine the distribution parameters k and α. This method is unbiased and particularly efficient for distributions with $k < 0$, which seems to be generally true of the extreme ice thickness data. Estimates of the GPD parameters are provided by:

$$
\begin{aligned}
k &= \frac{4b_1 - 3b_0 + u}{b_0 - 2b_1} \\
\alpha &= (b_0 - u)(1 + k)
\end{aligned}
$$

where

$$
\begin{aligned}
b_0 &= \frac{1}{l} \sum_{i=1}^{l} x_{(i)} \\
b_1 &= \frac{1}{l} \sum_{i=1}^{l} \frac{i-1}{l-1} x_{(i)}
\end{aligned}
\tag{5}
$$

(Wang 1991), where the $x_{(i)}$ are the ordered sample, $x_{(1)} \le x_{(2)} \le \ldots \le x_{(l)}$ of loads greater than the threshold u.

A variety of methods can be used to define *u*. It should be high enough that only true extremes are used to estimate the parameters of the GPD, but low enough that there are sufficient data so sampling error is not a problem. Some authors specified the threshold as a percentile of the number of cases. For example, Walshaw (1994) used a threshold at about the 95th percentile of his 10 years of hourly maximum wind gusts. Sometimes the threshold is determined on a physical basis (Abild et al. 1992). For the Base Region, we used a threshold ice thickness to give an occurrence rate of the extremes of about 1/year. In the far southern portion of the region, where ice storms are relatively infrequent, a threshold corresponding to occurrence rates of between one storm in two years and one storm in ten years was used.

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

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

where λ is the occurrence rate (number per year) of values exceeding the threshold.

5.3 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, ranging between 3 and 8 m/s. 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. We have determined the wind speeds to use in combination with extreme ice thicknesses from the modeled wind-on-ice loads at the weather stations in this region.

The summary information for each freezing rainstorm includes the maximum wind-on-ice load at the maximum uniform ice thickness (a conditional maximum) as well as the maximum wind-on-ice load that occurred at any time during the storm (the absolute maximum). We use the peaks-over-threshold method to calculate the parameters of the distribution of extreme wind-on-ice loads for the superstations. By assuming that the maximum wind-on-ice load in each storm occurs with the maximum ice thickness, which is somewhat conservative, the wind-on-ice speed V_{50} can be calculated from the 50-yr wind-on-ice load W_{50} and the ice thickness R_{eq50} for a 50-yr mean recurrence interval:

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

where ρ_a is the density of air, D is the diameter of the bare wire, and C_D is the drag coefficient. V_{50} is the wind speed that when used in combination with the ice thickness for a 50-year mean recurrence interval gives the wind-on-ice load for a 50-year mean recurrence interval. Wind loads are calculated using a drag coefficient $C_D = 1$ in both models, however the computation of the load is done differently in the two models. The Simple model wind load is based on the compact wire plus ice diameter, equal to $D + 2R_{eq}$. The CRREL model wind load is based on the average cross-sectional dimension of the ice-covered wire, taking into account the spacing (45 icicles/meter), length L_i and diameter D_i of the icicles. The cross-sectional area of icicles is $45D_iL_i$ in each meter so the cross-sectional width used in the wind load calculation is $D + 2t + 0.45D_iL_i$, where t is the uniform thickness of the ice that freezes immediately to the wire. This is larger than $D + 2R_{eq}$ when there are icicles. Thus, for the CRREL model, V_{50} accounts crudely for the increase in wind drag on the iced wire because of icicles, while retaining an ice thickness expressed in terms of the equivalent uniform radial ice thickness.

V_{50} 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 military 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 G_{50}, the gust-on-ice speed with a 50-yr mean recurrence interval. The ratio between G_{50} and V_{50} was then calculated:

$$f_{gust} = G_{50} / V_{50} = 1.34. \quad (8)$$

We use f_{gust} to estimate G_{50} from V_{50} for each station and superstation in the Base Region.

6.0 Results

The results of this analysis are shown in Figure 1, with the map insert for the Lake Superior region shown as Figure 2. These maps show uniform ice thicknesses from freezing rain and concurrent gust speeds at 10 m above ground for a 50-year mean recurrence interval. The weather stations used in mapping these ice thicknesses are shown in Figure 3.

In the Base Region the 1-in. ice thickness zone extends into most of Arkansas, eastern Oklahoma and southeastern Kansas. The large 0.75-in. zone covers southern Arkansas, northern Louisiana, the northern half of Texas including the eastern South Plains and Panhandle, the rest of Oklahoma except the far western Panhandle, and most of Kansas. The 0.5-in. zone covers the rest of Texas to the Gulf Coast, except the southernmost and westernmost portions of the state, far western Kansas and far eastern Colorado, central Nebraska, and almost all of South Dakota. Far southern Louisiana and Texas, a portion of west Texas extending north into eastern New Mexico and Colorado, far western Nebraska and South Dakota, all except central Wyoming, and all of Montana are in the 0.25-in. zone. West of that zone in the remainder of the Base Region, the ice thicknesses from freezing rain for a 50-year mean recurrence interval are essentially zero. However, in this region icing from supercooled clouds may be significant on well-exposed, elevated terrain. Icing from supercooled fog also appears to contribute to ice loading during freezing rainstorms in the Texas Panhandle and South Plains and may be the most significant ice loading mechanism in eastern Colorado and New Mexico. In Arizona, New Mexico and the Panhandles of Texas and Oklahoma, the U.S. Forest Service specifies design ice thicknesses from in cloud icing for towers constructed at specific mountaintop sites (USFS 1994).

The reanalysis of the Piedmont Region of the Carolinas showed that this region should be included in the 0.75-in. zone. Furthermore, the results for Ft. Bragg, the station closest to the Atlantic coast in this group, indicate that the 0.5-in. boundary could perhaps be moved farther inland. This boundary was originally established using data summaries from NCDC, studies of a 1994 ice storm in the Southeast (Lott and Sittel 1996), and information in a report by the Southeastern Regional Climate Center (Davis and Gay 1993). Adjustments to this boundary and the boundary of the 0.25-in. zone in Florida await an extreme value analysis of modeled ice thicknesses at weather stations in this region.

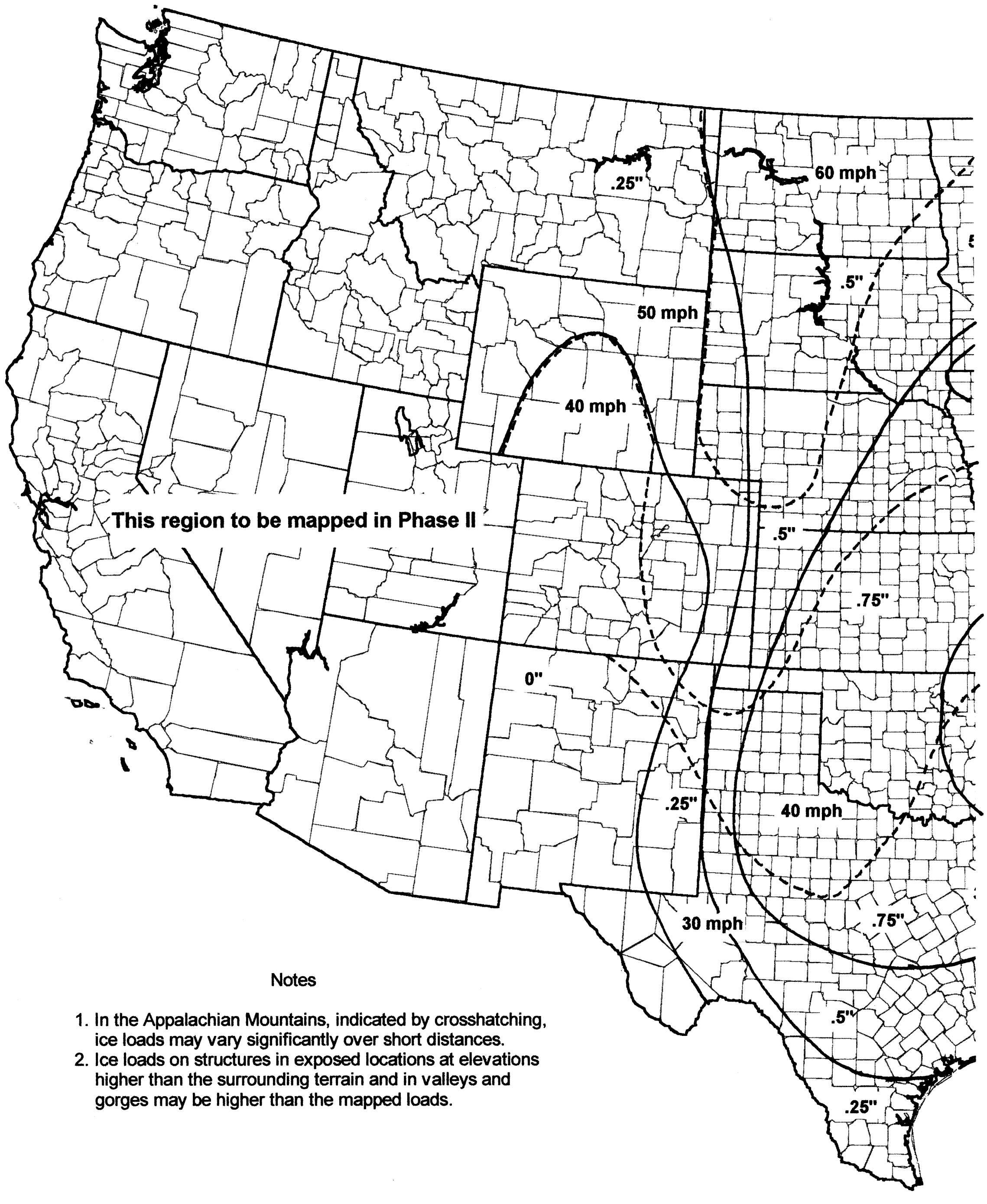

Figure 1. Uniform Ice Thicknesses Due to Freezing Rain with Concurrent 3-sec Gust Speeds for a 50-yr Mean Recurrence Interval: Contiguous 48 States.

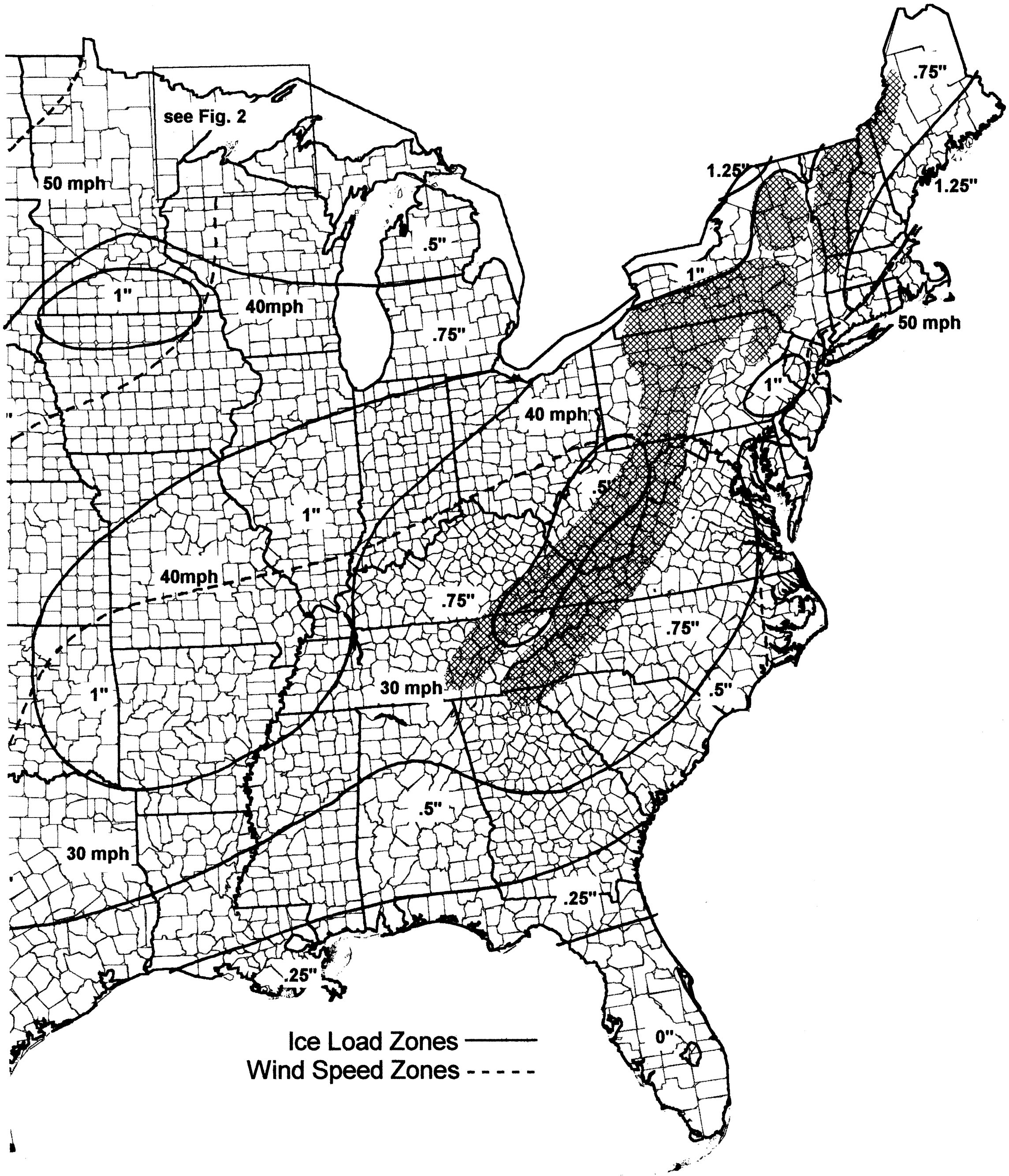

Figure 1. (cont'd)

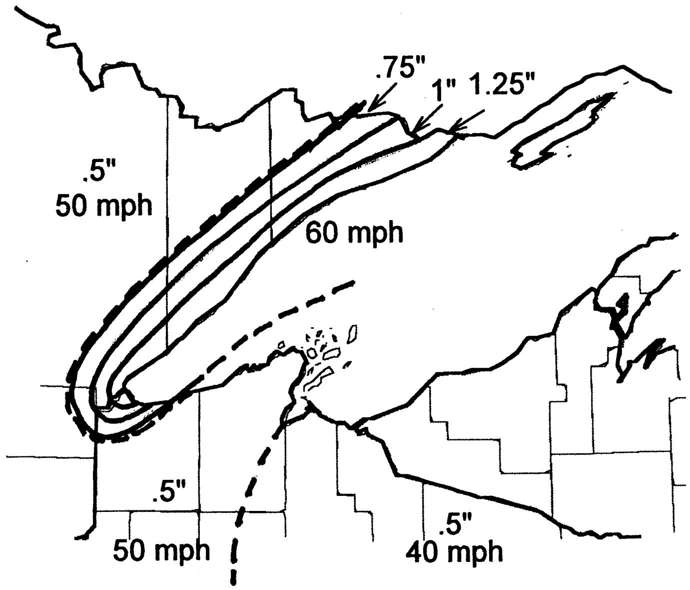

Figure 2. Uniform Ice Thicknesses Due to Freezing Rain with Concurrent 3-sec Gust Speeds for a 50-yr Mean Recurrence Interval: Lake Superior.

Figure 3. Weather Stations for Ice Load Map.

(Stations in red were added or extended for this project.)

References

Abild, J., E.Y. Andersen and L. Rosbjerg (1992) The climate of extreme winds at the Great Belt, Denmark, *J. of Wind Engineering and Industrial Aerodynamics*, 41-44, pp 521-532.

ASCE (1993) *Minimum Design Loads for Buildings and Other Structures*, ASCE Standard 7-93, New York, 134 pages.

Best, A.C. (1949) The size distribution of raindrops. *Q. J. Royal Met. Soc*., 75, pp 16-36.

Gross, J., A. Heckert, J. Lechner and E. Simiu (1994) Novel extreme value estimation procedures: Application to extreme wind data, *Extreme Value Theory and Applications*, J. Galambos et al. (eds.), pp 139-158, Kluwer Academic Publishers, Netherlands.

Hoskings, J.R.M., and J.R Wallis (1987) Parameter and quantile estimation for the generalized Pareto distribution, *Technometrics***,** 29, no. 3, pp 339-349.

Jones, K.F. (1996a) Ice accretion in freezing rain, CRREL Report 96-2, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Jones, K.F. (1996b) A simple model for freezing rain ice loads, *Proceedings of the 7th International Workshop on Atmospheric Icing of Structures*, Chicoutimi, Canada, pp 412-416.

Lott, N. and M. Sittel (1996) The February 1994 Ice Storm in the Southeastern U.S., *Proceedings of the Seventh International Workshop on Atmospheric Icing of Structures.*

Laflamme, J. (1993) Spatial variation of extreme values in the case of freezing rain icing, *Proceedings of the Sixth International Workshop on Atmospheric Icing of Structures*, Budapest, Hungarian Electrotechnical Association, pp 19-24.

NOAA (1959-1999) *Storm Data*, National Climate Data Center, Asheville, NC.

Peterka, J.A. (1992) Improved extreme wind prediction for the United States, *J. of Wind Engineering and Industrial Aerodynamics*, 41-44, pp 533-541.

Simiu, E. and N.A. Heckert (1995) *Extreme wind distribution tails: A "Peaks over Threshold" Approach*, National Institute of Standards and Technology Building Science Series 174, U.S. Government Printing Office, Washington D.C., 72 pages.

USFS (1994). Forest Service Handbook FSH6609.14 Telecommunications Handbook, R3 Supplement 6609.14-94-2 Effective 5/2/94, United States Forest Service, Washington, D.C.

Walshaw, D. (1994) Getting the most from your extreme wind data: A step by step guide, *J. of Research of the National Institute of Standards and Technology*, 99, pp 399-411.

Wang, Q.J. (1991) The POT model described by the generalized Pareto distribution with Poisson arrival rate, *J. of Hydrology*, 129, pp 263-280.

Newspapers from the Plains (various dates)

Amarillo Daily News

Amarillo Globe News

Arkansas Democrat Gazette

Austin American-Statesman

Beaumont Enterprise

Bismarck Tribune

Brownsville Herald

Carlsbad Current-Argus

Clovis News Journal

Corpus Christi Caller-Times

Daily Oklahoman

Dallas Morning News

Denver Post

Dodge City Daily Globe

Fargo-Morehead Sun

Ft. Worth Star-Telegram

Grand Forks Herald

Hollis News

Houston Chronicle

Laredo Morning Times

Lubbock Avalanche-Journal

Mcalester News-Capital and Democrat

Midland Reporter Telegram

Minot Daily News

Monroe News-Star World

Northwest Arkansas Times

Roswell Daily Record

San Antonio Express News

Shreveport Times

Sioux Falls Argus-Leader

Southwest Times-Record

Springfield News-Leader

The Aberdeen American News

The Baton Rouge Advocate

The Lawton Constitution

The McAllen Monitor

The Salina Journal

The Sheridan Press

The Wichita Eagle

Tulsa World

Wichita Falls Times Record News

Woodward News

Wyoming Tribune-Eagle

Newspapers from the Carolinas (various dates)

Greensboro Daily News

Greenville News

Hickory Daily Record

The Charlotte Observer

The Fayetteville Observer

The Raleigh News and Observer

The Raleigh Times