USING U.S. WEATHER DATA FOR MODELING ICE LOADS FROM FREEZING RAIN

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Abstract

In the last few years a number of researchers have developed models for determining the amount of ice accreted on structures in freezing rain storms. However, little attention has been paid to the weather data that drives these models. We have an ongoing project to determine design ice loads for structures throughout the United States, for which we are using historical weather data. In this paper we describe in detail the weather data that are collected by agencies in this country, focusing on the weather elements that are significant in modeling ice loads in freezing rain. We discuss the meteorological instruments, data accuracy and problems, data archival, and decisions that must be made by users of the data in modeling ice loads.

1. Introduction

The amount of ice accreted in freezing rain storms is not a standard measurement made by the National Weather Service, other federal agencies, or public or private utilities in the United States. However, power lines, communication towers and highway signs are all designed to withstand extreme ice loads. There is an ongoing effort to map extreme ice loads in the United States using weather data and ice accretion models. The models for ice accretion in freezing rain require hourly weather data with at least 1) information on whether freezing rain is occurring, 2) precipitation rate, 3) wind speed, and 4) air temperature. The models either assume a relative humidity or use dew point data.

A number of recent papers (Jones 1996, Makkonen 1996, Yip 1993) have compared results from different models. In this paper we focus on the input to these models. We describe the weather data that are collected by a number of agencies in this country. We discuss the meteorological instruments that have been used, the accuracy of the data, variations in the way the data are collected, and difficulties in making these measurements during freezing rain. We also discuss the period of record of the archived weather data, along with the changes in the way data have been archived over the years. Finally, we discuss decisions that must be made by researchers or engineers in using these data to estimate historical ice loads using any of the ice accretion models for freezing rain.

2. Hourly Station Network

Hourly weather data are observed and reported by the National Weather Service (NWS), the Department of Defense (Navy, Army, and Air Force), the Federal Aviation Administration (FAA), and other state and federal agencies. There are approximately 1400 active hourly weather stations in the U.S., most of which are at airports. Over 800 of these are full-time stations with observations normally reported 24 hours/day--Figure 1 shows their locations for the continental U.S. Some of these are automatic stations (which may not record present weather), while some do not report the precipitation amount. At many stations where precipitation is measured, accumulated precipitation is measured every six hours or once a day rather than hourly. The National Climatic Data Center's World Wide Web site (http://www.ncdc.noaa.gov) has inventories of the U.S. and global data for users to peruse and determine data availability for their application. Approximately 500 stations across the country have the necessary reporting frequency and data elements for modeling ice loads from the weather data.

3. Archived Data

Historical weather data are archived at the Federal Climate Complex (FCC) in Asheville, North Carolina, consisting of the National Climate Data Center (NCDC) and the Air Force Combat Climatology Center (AFCCC). These data originally took the form of paper records of the hourly observations, typically on one page per day. As we entered the “computer age,” these records were key entered into digital files for storage on magnetic tape. The key entry of these old records reached back in time to include data generally from the 1930s or 1940s forward. Then, in the 1970s, electronic transmission of data gradually took over, and most data were archived directly from the digital data received from each station.

Digital data coming into the FCC contain numerous errors due to observers’ typographical errors, instrumentation problems, communication problems, etc. Therefore, before the data are archived, they are checked using quality control software to correct any 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. However, weather data from the FAA and other agencies do not go through this higher level of manual quality control; thus, more errors are left uncorrected in the data from these stations. Overall, better than 99% of the errors are eliminated from the database of hourly surface weather observations.

4. Weather Elements

The measurement of the crucial weather elements for modeling ice accretion in freezing rain is described in this section. Present weather, wind speed and temperature are observed every hour, usually between 10 minutes before the hour and ten minutes after the hour. Reported values are point measurements rather than averages for the hour.

The present weather indicator records the existence of different kinds of precipitation, fog, dust and sand, drifting or blowing snow, thunderstorms and funnel clouds at the time of the observation. Present weather is best recorded by human observers. Typically, one, two or three present weather indicators are reported for each hour. Thus, light snow, ice pellets and fog in one hour may be followed by moderate snow and blowing snow the next hour, then by light rain and ice pellets, and finally by fog alone.

Automatic stations typically do not have the instruments necessary to distinguish the different types of precipitation; thus, hourly data from these stations cannot be used in modeling ice loads from freezing rain unless human observers are there to augment the automatically recorded measurements. The Automated Surface Observing System (ASOS) is being phased in for many U.S. stations. Some are currently augmented by manual observations. As upgrades for ASOS equipment are planned for the future, the impact ASOS will have long-term on the data needed to model ice loads is unknown. At this point, the overall effect has been negative from a climatological standpoint. For more information, see the NWS World Wide Web site -- http://www.nws.noaa.gov/modernize/asostech.htm.

The precipitation amount is measured to hundredths or tenths of an inch, varying over time and from station to station. The precipitation gauges that are used include 8-inch standard gauges (8-inch opening at top) which are checked manually, automated tipping bucket gauges, and automated weighing bucket gauges. Some stations have more than one gauge type. All of these gauges are still in use, with the tipping bucket being the primary gauge at ASOS sites. Since most tipping bucket gauges are unheated, they cannot measure freezing or frozen precipitation reliably. In many cases, the local observer will augment the observations to reflect a more accurate amount reported by another gauge, such as the 8-inch gauge. Fortunately, since the automated tipping bucket has only come into widespread use during the past few years, most of the historical data do not include these measurements. We have found other gauge types to generally be accurate regardless of the type of precipitation, except in the case of snow. During snowfall, gauges typically undercatch precipitation, with the measurement error increasing as wind speed increases.

As a general rule of thumb, the 8-inch manual gauge has been the gauge used to record daily (24-hour) and 6-hour precipitation amounts. Any ice in the gauge is melted at least once per day to ensure an accurate daily precipitation record. The 8-inch gauge is still used by most cooperative stations (see below) and by some airport sites (e.g., NWS). Hourly precipitation has been measured by automated weighing bucket gauges for cooperative sites which record hourly precipitation, and for airport sites prior to ASOS. In areas subject to freezing and frozen precipitation, the gauges are sometimes heated. For users of the data, cooperative sites can be assumed to have accurate precipitation data for the entire period of record for daily and hourly data. Airport sites generally have accurate daily and 6-hourly reports throughout their period of record and accurate hourly data prior to ASOS (1994-1996 time frame) for most locations.

Wind speeds are measured by cup-type anemometers to the nearest knot (0.5 m/s). These anemometers are accurate to within a few meters per second even at high wind speeds. The threshold wind for recording a speed (other than calm) is about 1-2 m/s. The wind speed recorded every hour is normally a 1 to 2-minute average, and not an average for the preceding hour. Wind gust speeds are also reported by many stations if winds are gusty. Since anemometers are usually unheated, they often become inoperable during freezing rain. If temperatures are near freezing, the wind measurement will show a gradual decrease as the cups become hindered by increasing ice, until total “freeze-up” occurs. At temperatures well below freezing, the instrument will stop working very quickly. In some cases, the observers will remove the ice from time to time, but will estimate the wind speed if it’s not working properly. Therefore, one can assume that wind speeds, although less accurate during freezing rain, are still accurate to within a few m/s.

Dry-bulb and dew-point temperatures are measured to the nearest 1ºF (5/9ºC). Dry-bulb temperature equipment has changed over the years, and also varies from station to station, from old-fashioned mercury thermometers to automated digital thermistors. Accuracy, however, has changed very little, and is considered to be within 0.5ºC. Temperature equipment is usually located in ventilated enclosures to shield the instruments from the direct rays of the sun, avoid cooling from the evaporation of precipitation, and to maintain wind ventilation. Freezing precipitation has little effect on the accuracy of these instruments, with accuracy within 0.5ºC during freezing rain.

5. Using Historical Weather Data

To use weather data to determine ice loads that have occurred in past ice storms, a number of decisions must be made about the data that are separate from the model used, but affect the model results. These include:

– prorating 6-hourly (or 24-hourly) precipitation amounts to each hour
– correcting the measured wind speed from the height of the anemometer to the height of the wire
– deciding how much of the precipitation accretes as ice when there are other types of precipitation mixed with freezing rain
– interpolating the weather data when hourly data are not available or when hours are missing
– deciding when a freezing rain storm ends.

5.1 Prorating 6-hourly precipitation

Weighting factors are used to prorate 6-hourly precipitation amounts to each hour. The weight assigned to each hour in the weather record is determined by the present weather codes for the hour. If there is no precipitation, the weight is zero. The fraction of the 6-hour accumulation of precipitation attributed to each hour is the weighting factor for the hour divided by the sum of weighting factors for all six hours. This fraction is then multiplied by the 6-hour precipitation amount to obtain the estimated hourly precipitation rate. A similar procedure can be applied to 24-hourly precipitation amounts. These weighting factors are not used at the stations where the precipitation amount is reported hourly.

5.2 Correcting measured wind speed for anemometer height

The height above ground of the anemometer at any weather station has typically varied over time, and anemometer heights also vary between stations. It is important to know the anemometer height since wind speed increases with height above ground through the earth's boundary layer. The rate of increase of wind speed with height depends on the roughness of the terrain and the exposure of the site. In a recent CRREL study, the wind speed was assumed to be proportional to the 1/7 power of the height, following ASCE Standard 7-93 (1993) for fastest-mile wind speeds, which is appropriate at these airport weather stations. Thus,

$$V_0 = (h_o/h_A)^{1/7} V_A,$$

where V_0 and V_A are the wind speeds at the desired height h_0 and the height of the anemometer h_A, respectively.

5.3 Mixed precipitation

It is difficult to decide what portion of the precipitation is freezing rain or freezing drizzle when the present weather indicators for one hour also list other types of precipitation for the same hour. Freezing rain may occur at the same time as, or alternately with ice pellets, cold rain (not freezing), and snow. We have chosen to be conservative and have allowed the ice accretion models to accrete mixed rain and snow, and rain falling at an air temperature of freezing or below, as well as freezing rain or drizzle. For hours in which present weather indicators show freezing rain or drizzle falling with other types of precipitation, we have assumed that all the precipitation may accrete on the structure. In Jones (1998), qualitative information is used to fine tune the algorithm that chooses the types of precipitation that may accrete on structures.

5.4 Interpolating

Users of the data will need to interpolate weather data when data are missing for certain hours. For example, at many NWS stations, from around 1965 to as recently as 1981, the weather records were digitized by NCDC only every three hours even though observations were recorded (on paper records) every hour. During those years, precipitation amounts were still archived every hour, but all other weather elements were digitized at 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 Greenwich Mean Time (GMT) only. We deal with these gaps in the data by assuming that the weather was the same as the archived hour in the hour immediately before and immediately after. For example, the wind speed at 0200 and 0400 is assumed equal to the wind speed at 0300. We investigated the sensitivity of the modeled ice loads to this interpolation scheme by comparing the ice load 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 the total thickness. In storms in which the conditions are changing rapidly, we would expect larger errors in the calculated ice thicknesses from the interpolated data. The original handwritten hourly data are available at NCDC, so one could use these complete weather records if it were considered worthwhile to manually key-enter the missing records.

5.5 End of storm

An important aspect determining the maximum ice load and the maximum wind-on-ice load in a past freezing rain storm is deciding when the storm ends. In modeling ice loads using weather data in Canada, AES defined the end of a freezing rain storm as the first hour after freezing rain ends in which the air temperature rises above freezing, or 24 hours after freezing rain ends, whichever occurs first. In a recent project to determine extreme ice loads in the United States, we ended storms after freezing rain ended when the air temperature increased to at least 33ºF. This choice is more conservative than the Canadian model and sometimes results in ice accreting on top of previously accreted ice that is many days or weeks old. Ideally, one would model the melting and sublimation of accreted ice; however, that is more difficult than modeling accreting ice because melting by direct solar radiation and ice shedding before complete melting must be taken into account. CRREL is currently investigating the relationship between the residence time of glaze ice and the weather by measuring the decrease in the ice load on a Pole-ice meter located at our weather station.

6. Additional Data

The U.S. also has a network of over 8000 "cooperative" weather stations manned mostly by volunteer observers. They send monthly forms to NCDC, which then key enters the data into digital files. This is considered to be one of our most valuable observer networks and climatic datasets. Most of these stations observe the daily maximum and minimum temperature and the daily precipitation, and about 2000 of the stations also record hourly precipitation. These data do not include the hourly wind speed, precipitation type (e.g., freezing rain), or hourly temperature desired for modeling purposes. However, they do provide additional data for studying particular events.

Quite often, a severe ice storm may occur over a rather narrow band and not affect any hourly weather stations. In these cases, the cooperative network daily data can provide valuable information about the storm. And, even in storms which affect hourly stations, the daily data can be useful in delineating the extent of the storm. If a station's maximum temperature for the day is freezing or below, then all of that day's precipitation can be assumed to be frozen or freezing, and thus may have been freezing rain. Other data and information will often indicate if the precipitation was in the form of freezing rain. NWS summaries about the storm will indicate if most of the precipitation fell as freezing rain and may describe what damage occurred. The cooperative paper records include remarks where the observer can report on the day's event. These remarks are not digitized but are available from the paper records. For example, a February 1994 ice storm severely affected a large area in the southeastern U.S. with rainfall (freezing) amounts exceeding 100 millimeters in some locations. The cooperative daily data proved quite valuable in mapping the total precipitation over the storm footprint (Lott and Sittel 1996).

There is also qualitative information in *Storm Data*, a National Oceanographic and Atmospheric Administration publication (NOAA 1959-present) that summarizes destructive weather-related occurrences including freezing rain storms, hurricanes, lightning strikes, tornadoes and blizzards. Each monthly publication is ordered alphabetically by state. *Storm Data's* predecessors, *Monthly Weather Review* (1921-1949), *The Report of the Chief of the Weather Bureau* (1929-1935), *U.S. Meteorological Yearbook* (1936-1949), and *Climatological Data, National Summary* (1950-1959) also include storm information. The information in *Storm Data* is compiled regionally using information from police reports, newspaper articles, and weather spotters. Qualitative information on the type of storm (ice storm, tornado, etc.), locations (states, forecast zones, counties, cities, or highways) where the storm was particularly destructive, severity (number of deaths, dollar amount of damage, number of days without power, highways closed), are often included in the storm description, along with the date and time of occurrence.

7. Examples

We have chosen three examples to illustrate the variations in the historical weather records. The weather stations are in Indianapolis, at Grissom AFB and in Lafayette, all of which are in Indiana, south of the Great Lakes in the central region of the United States. At all three stations, weather data is recorded 24 hours a day.

The weather station at the Indianapolis International Airport, formerly known as Weir Cook Municipal Airport, is run by the National Weather Service. The weather station in downtown Indianapolis was established in 1871, and moved to the airport in 1931. In 1938 a weighing bucket rain gauge was installed to supplement the 8" and tipping bucket rain gauges already at the station. Precipitation was measured hourly. The cup anemometer was originally installed at 52 ft above ground on the hangar building when the weather station moved to the airport. Its height varied up to 64 ft until it was moved in 11/59 to a field site and installed at 20 ft above ground, where it has remained. The computer-archived weather records at Indianapolis begin in January of 1948 and the hourly precipitation record begins 4 months later. From 1965 through 1971 the weather records were archived only every three hours. The data are archived at NCDC after automatic and manual quality control.

At Grissom AFB, formerly Bunker Hill AFB, the weather station has been run by the Air Force since 1955. The anemometer was originally installed atop the control tower at 54 ft above ground, and was moved to the field at the intersection of the two runways in 1959 and installed at 13 ft above ground. Since 1963, two anemometers have been used, one for each runway; both are at 13 ft. The precipitation amount is measured every six hours. The type of rain gauge is not specified in the station history records. The complete computer-archived weather records begin in 1973. In February of 1994 the station became part-time, operating 17 hours per day. Weather data from Grissom is archived at AFCCC after automatic and manual quality control.

The Lafayette weather station, run by the FAA, was installed at the Purdue University Airport in 1938. The anemometer was originally installed at 52 ft above ground on a hangar building, and was moved to a field site and installed at 20 ft above ground in 1961. Precipitation was measured in an 8" rain gauge every six hours. The computer-archived weather records do not begin until 1973 and are about 97% complete with hourly data missing sporadically throughout the period of record. The weather data goes through only an automatic quality control before being archived by AFCCC.

We look for obvious errors while processing the weather data from these stations to extract freezing rain storms. Because of the lower level of quality control of FAA data, the few errors we find are usually at FAA stations. Based on experience we know to look for 1) unusually high wind speeds, often occurring simultaneously with missing temperature and dew point data, and 2) precipitation amounts of 1024 mm. We found one freezing rain storm at Lafayette with an anomalously high wind speed (22.1 m/s on 11/12/88 at 1300 GMT) as compared to the previous and following hours. We also found a number of occurrences of 6-hour precipitation totals archived as 1024 mm in November and December of 1978. This error occurs only in these months and only at FAA stations. These data can be corrected using the original paper records.

The ice accretion model is run on the extracted freezing rain storms. Ice loads from these three stations, presented as a uniform radial ice thicknesses calculated by the revised simple model (Jones 1998), are shown in Figure 2. Only episodes with a freezing rain storm at one or more of these three stations are shown, with the graphs divided into decades. Note the shorter periods of record at Grissom AFB and Lafayette, and the years with three-hourly records at Indianapolis. Also note the maximum value of just over 2 cm (radial thickness) estimated for Grissom AFB.

8. Conclusions

The usage of conventional meteorological data in modeling ice loads from freezing rain involves a learning process in properly using the data. CRREL, NCDC, and AFCCC have gained valuable experience in working with the data to map ice loads in the eastern half of the United States. Others interested in pursuing similar efforts should find beneficial information in this paper, and can contact CRREL or NCDC for further details.

9. References

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Figure 1: U.S. Full-Time Weather Stations

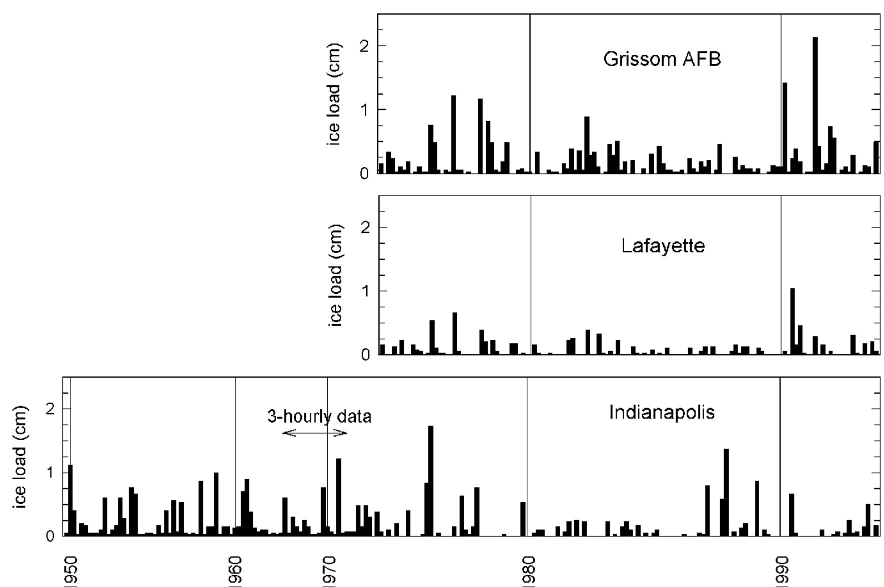

**Figure 2: Ice Loads Calculated Using Historical Weather Data--
Three Stations in Indiana, from the Simple Model**