Final Report

WEATHER STUDY FOR GREAT NORTHERN TRANSMISSION LINE

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Abstract

This report provides wind, ice, temperature and related climatic information to inform the design of transmission lines planned in southern Manitoba. The study area is a region defined as south and east of Portage La Prairie and Winnipeg to the U.S. and Ontario borders. Information developed in this project concerns the 50-year return period values of ice accretion and wind speed and corresponding combinations, updating information in, and, for the most part consistent with the measures outlined in CAN/CSA-C22.3 No. 60826-10 (Design criteria of overhead transmission lines). Related information on wind and temperature combinations is provided. Information on the probability of extreme weather including tornadoes affecting twin parallel lines in the same events at various separation distances, line lengths and directional orientations is also provided. For operational planning, a rate of ice accretion on conductors is recommended. Finally, information regarding the joint frequency of temperature, wind speed and solar irradiance is developed and provided to assist line rating calculations.

Acknowledgements

Thanks are extended to Environment Canada staff Trisha Ralph-Coffee and Julian Morales in Toronto ON for providing the archived weather observations and related information used in this project. David Halliwell at Environment Canada provided consecutive one-minute speeds from the research observing site at Bratts Lake, SK.

The author appreciates advice and copies of relevant reports and articles from Kathy Jones at the Cold Regions Research and Engineering Laboratory in Hanover NH.

Executive Summary

Information regarding design weather conditions is provided to support planning and design decisions regarding a major transmission line facility in southern Manitoba.

Reference 50-year return period ice thickness values were updated, consistent with information in CAN/CSA-C22.3 No. 60826-10 (Design criteria of overhead transmission lines – reference CSA (2010)). The Chaîné ice accretion model was used with the most recent surface weather observations from Environment Canada to compile freezing precipitation icing event data that was fitted to the Gumbel extreme value distribution to calculate 50-year return period values. The results are in tabular and map format for the study area. As points of comparison, the CRREL (simple) and Goodwin ice accretion models were also used to generate ice accretion event information. Consistent with similar studies over the past decade or so, the Chaîné model provides higher icing amounts than the other two ice accretion models. The 50-year ice thickness values from the Chaîné model is about 16 mm for the study area, similar to information in CSA (2010).

Updated hourly and peak wind speed observations were used to develop recommendations of reference 50-year return period wind speeds representative of a 10 minute averaging period, 10 m above ground over flat, open terrain. These values were updated from the recently developed values in CSA (2010) and, range from about 100 km/h in the western part of the study area to about 85 km/h over the eastern parts near the Ontario border.

Combinations of ice and wind were calculated for observing locations in the study area as per the methods in CSA (2010). The combinations included the 50-year reference ice thickness with the average maximum wind speed during icing, and the average annual maximum ice thickness with the 50-year wind speed during icing. The 50-year transverse load was calculated from the icing events and a selection of ice thickness values with corresponding wind speeds were provided for comparison.

A series of combined wind speed and temperature conditions were generated as per CSA (2010). The average daily minimum temperature was provided for use with the 50-year reference wind speed. In addition the 50-year wind speed was also calculated to correspond to conditions when the temperature is at or below the designated “minimum temperature” in CSA (2010) (denoted as the 1% January temperature i.e. temperature for which 1% of the hours in January are colder).

The rate of ice accretion for significant icing events is investigated and a conservative rate of 2 mm/h is recommended for operational planning.

To assist in the planning of the separation of major twin parallel transmission lines, the frequency with which tornadoes in southern Manitoba cross both lines of selected line orientation, length and separation distance was estimated from previously published information of tornado occurrence. Comments are also provided on the joint occurrence of extreme icing and wind events, based on previously published work and the “spatial factor” in CSA (2010).

Finally, information on the joint frequency of occurrence of wind speed, temperature, and solar irradiance is provided for selected stations in the study area to assist with line rating capacity calculations.

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1.0 Introduction

This report concerns generating and updating existing climatic design information for the design of electrical transmission lines for southern Manitoba. The study area extends from Portage La Prairie south to the U.S. border and east to the Ontario border, including Winnipeg. CSA standard C22.3 No. 60826-10 - Design criteria of overhead transmission lines (CSA, 2010) provides information previously developed concerning this subject matter. The current project both updates and further develops information consistent with the procedures and general principles contained in CSA (2010). Information updated includes reference (50-year return period) ice thickness and wind speed. Related information, consistent with CSA (2010), includes combinations of both ice and wind, and of temperature and wind. Additional information is developed that is relevant to severe weather (tornadoes, icing events, extreme wind events) impacting twin parallel transmission lines at the same time. Finally joint frequency information concerning hourly wind speed, temperature and solar irradiance is provided to assist in line rating calculations for the study area.

The extreme value analysis method used to calculate the reference ice thickness, wind speed and temperature values in this report is the Gumbel distribution fitted to annual maximum series. It is described in Section 2 and Appendix A along with a discussion of, and comparison to other methods.

CSA (2010) provides maps national maps and a table for selected locations of the reference 50-year ice and wind values. These values were adapted to CSA (2010) primarily from work by Environment Canada funded by CEATI (CEATI, 2009). The same general calculation procedures and data sets obtained from Environment Canada were used to update the reference ice and wind values for the study area.

The reference ice thickness provided is a point value due to freezing precipitation (rain and drizzle). Other forms of icing (frozen wet snow and rime or in-cloud icing), in some circumstances, result in higher icing loads and in some areas are the predominant forms of icing. For most of southern Canada from the Prairies to Atlantic Canada (except at higher elevations on the east coast), freezing rain is the weather event that results in the highest ice loads and hence is the basis for reference ice thickness in CSA (2010). Since ice accretion amounts due to freezing rain are not routinely observed in Canada, the approach generally taken is to model ice accretion from the standard hourly meteorological observations at airports. The Chaîné ice accretion model was used to develop the reference ice thickness amounts in CSA (2010) and to update this information for this project. Section 3 provides a general description of the Chaîné ice accretion model, other ice accretion models used elsewhere for this purpose, the data available from Environment Canada and the results including comparison both with CSA (2010) and other work for this area known to the author. A map of the study area with recommended reference ice thickness is provided. The equations and further details of the ice accretion models are in Appendix A.

The reference wind speed in CSA (2010) and for this project is represented by the 50-year return period value of the 10-minute average wind speed observed at 10 m above ground. The primary long-term hourly wind observations from Environment Canada generally represent a 2-minute (for some stations and periods 1- or 10-minute) mean speed once per hour. Adjustments are made to the standard wind speed observations to estimate the extreme 10-minute mean wind speed over flat open terrain. Section 4 presents details of procedures, locations whose data was used, comparison with previous results, and a map with recommended reference wind speed for the study area.

The reference ice thickness and wind speed are each developed without consideration of the other but the combined loads of ice and wind are also required and need to be identified. CSA (2010) provides two cases to be checked in the absence of direct analysis of the combined effect of wind and ice. The first combination is the 50-year return period ice thickness with the average annual maximum wind speed during the iced condition. This is referred to as low probability ice thickness with high probability wind speed. The second condition (high probability ice thickness with low probability wind speed) is represented by the average annual maximum ice thickness with the 50-year wind speed during the iced condition. For this project icing events are started with the first occurrence of freezing precipitation and ended after the last hour of freezing precipitation was followed by a period of 168 hours or by an hour with the temperature rising above 1C, whichever occurs first. In addition to the two combinations described above, the 50-year nominal transverse load on the conductor is calculated from the wind pressure on the iced conductor from all icing events. Combinations of ice and wind leading to the (nominal) 50-year transverse load are compared with the two combinations described above and presented in Section 5 for the study area.

Section 6 concerns the combinations of wind and temperature. CSA (2010) provides for two conditions of temperature and wind. The first temperature condition required is the average daily minimum temperature to be used with the reference wind speed. The second condition is the 50-year return period minimum temperature combined with a reduced wind speed. The reduced wind speed is defined as the 50-year wind speed calculated from those hours coincident with the "minimum temperature" provided for in CSA (2010). The "minimum temperature" is represented by the 1% January temperature (the temperature for which 1% of the hours in January are lower). The various 50-year values for the study area are calculated and presented in this section.

Section 7 covers certain aspects of severe weather impacting twin parallel lines at the same time. The first aspect deals an estimate of the frequency of tornado paths crossing both lines. This information is developed from various references on frequency of occurrence of tornadoes in the U.S. and Canada and the characteristics of tornado path lengths. The information from these sources is adapted to southern Manitoba to develop the data presented in this section. Other severe weather such as non-tornadic winds and ice loading affecting both lines are also discussed with results from other reports. Comments are also provided concerning the spatial factor used in CSA (2010) to extend the single point, reference ice thickness values to a larger spatial area such as a service area, or along a linear development such as a transmission line. Finally, information on the rate of icing is presented in this section to aid in operational contingency planning to deal with significant icing events that can affect both of the twin parallel lines.

Joint frequency information of wind, temperature and solar irradiance is provided in Section 8 to assist with line rating calculations. Environment Canada has developed and made available hourly files (CWEEDS – Canadian Weather Energy and Engineering Data Sets) that combine standard meteorological observations with solar irradiance observations (for the locations and periods it is available) mainly as required input for simulation of building and renewable energy systems. Most observing programs do not include solar irradiance, so a significant aspect of CWEEDS files is that hourly solar irradiance values are modelled where observations are not available (almost all locations). Solar irradiance was modelled from standard hourly meteorological observations (mainly cloud layers and sky conditions) and the earth-sun geometry. Recently, however Environment Canada and Natural Resources Canada acquired gridded solar irradiance estimates from the State University of New York (SUNY) derived from GOES geostationary satellite imagery. This SUNY hourly solar gridded data is now available for all of Canada south of 58N at 0.1 degree latitude and longitude (about 10 km) grid spacing. Terms of the arrangement includes a restriction that data for the most recent 2 years are not further distributed. As a result Environment Canada now uses the SUNY data for the period 1998-2011 to incorporate into new or updated CWEEDS files south of 58N for the period 1998-2011. Since CWEEDS files represent a time series of hourly values of wind speed, temperature and solar irradiance, it is a straight forward matter to compile joint frequency of occurrence data of the three elements. The procedures and software currently used by Environment Canada are used to compile CWEEDS files incorporating SUNY solar irradiance data for representative locations in the study area. The CWEEDS files are then used to compile joint frequency data. Further details and results are presented in Section 8.

2.0 Extreme Value Analysis

The frequency of extremes of weather related variables, such as a 50-year return period of wind speed and ice thickness is generally calculated using extreme value analysis. Return period in this context is defined as the reciprocal of the annual exceedence probability. So the 50-year return period corresponds to an event that has a 0.02 (= 1/50) probability of occurring or being exceeded in any given year. The 50-year return period also corresponds to the average number of years over the long term between years in which the 50-year event occurs or is exceeded, and as such is often also referred to as a recurrence interval.

CSA (2010) indicates that the Gumbel extreme value distribution is suitable for determining the return levels of weather related loads. It further provides a method by which the annual maximum values of wind or ice may be fitted by the Gumbel distribution (CSA (2010) section C). Note that the CSA (2010) procedure requires use of parameters that reflect the number of years of annual maximum values used in the calculation. The CSA method is known to exhibit a high bias. For this project, the method of moments is used to fit the Gumbel distribution to the annual maxima of ice thickness and wind, and to the annual minimum series of temperature.

The equation used to fit the Gumbel distribution to the annual maximum or minimum series and calculate return levels is:

$$X(T) = X_m - j\,\frac{\sqrt{6}}{\pi}\left(0.5772 + \ln\ln\left(\frac{T}{T-1}\right)\right)X_{sd} \qquad (1)$$

where $X(T)$ is the T-year return period estimate of the weather element being considered (ice, wind, temperature), X_m and X_{sd} are the mean and standard deviation of the annual maximum (or minimum) series of X, j = +1 if the annual series is maximum and j = -1 if the annual series is comprised of minimum values, and T is the return period (years).

Equation (1) is the same as the CSA (2010) return level equation (C.24 in the standard) when the number of years in the annual maximum series is considered to be infinite.

Environment Canada has used the Gumbel distribution fitted with the method of moments since the early 1980's in calculating return levels of ice, wind and snow loads for codes and standards and extreme rainfall for the design of hydrologic structures. In particular, it was used to develop the maps of reference ice thickness and wind speeds in CSA (2010).

The uncertainty of the return level calculations generally decreases with a longer period of record. For this reason only stations with at least 10 years of observations are used in compiling an annual maximum series for extreme value analysis.

Further discussion and details are provided in Appendix A.

3.0 Ice Accretion and Reference Ice Thickness

Since ice accretion on structures in general, and on conductors specifically, are not included in any weather or climate observational networks, a common approach to estimate ice accretion amounts is through the use of models using standard hourly meteorological observations. For this project, the Chaîné ice accretion model is used to model the ice accretion on conductors from freezing precipitation. Two other models, the CRREL simple model and Goodwin model are also used to provide comparative results. The ice accretion models are further described in Appendix B including assumptions and equations. Ice accretion resulting from rime (in-cloud) icing and frozen wet snow are not dealt with in this project.

The approach and steps using the ice accretion models are:

- Acquire weather data - Hourly 24/7 standard human meteorological observations for stations with at least 10 years of record at locations relevant to the study area are obtained from Environment Canada ("standard" in this context refers to the weather observations made mainly at airports both in support of aviation operations and weather forecasting)

- Assign hourly precipitation amounts - The standard meteorological observations include weather and atmospheric elements each hour including temperature, humidity, wind speed and direction, visibility, sky conditions, present weather (occurrence of each type and an indication of intensity of precipitation) and total precipitation (water equivalent of all precipitation types) that occurs in a 24-hour period. The type and an indication of intensity (light, moderate, heavy) of precipitation, but not the respective amounts, are recorded each hour. In this step, the daily total precipitation amount is prorated to each hour, for each precipitation type that occurs each hour, weighted by a nominal rate characteristic of each type and intensity observed. In this way the hourly rate of freezing precipitation is estimated for each hour it occurs.

- Identify icing events – The file of hourly weather conditions with assigned hourly precipitation types is processed for each location. An icing event is identified and starts with the first hour with freezing precipitation. It continues until the temperature rises to above 1C or until 168 hours without freezing precipitation occurs, whichever is first. The hourly data for the event is output to a file of icing events. During this step the wind speed is adjusted to the standard 10 m height above ground if the height was different from 10 m. An estimate of the maximum 10-minute average wind speed for each hour also made at this step.

- Estimate the ice accretion – The file of icing events is processed and the ice accretion models applied. For each event the ice accretion on the conductor is calculated every hour during the event. The ice accretion amounts and other observed (temperature, wind speed etc.) and calculated (transverse load) elements are output to a file with a summary record for each event (maximum ice thickness on the conductor, maximum transverse load, maximum wind speed, maximum and minimum temperature).

- Compile the annual maximum series – The file of event summaries is processed and the maximum or minimum of each element of interest (ice thickness, wind speed, temperature, transverse load) for each winter (not calendar) year is output to a file.

- Extreme value analysis – The 50-year return period of the various elements of interest are calculated from each element's annual maximum series using equation (1).

The ice accretion models and related software routines were rewritten for this project using the same equations and procedures as used by EC to develop the reference ice and wind values in CSA (2010). Intermediate results were checked with the EC results and were generally comparable. In the data processing and ice accretion model runs made for this project there were some minor differences. First, more recent data was used where available. Second, although the EC processing system ended icing events after 7 days (168 hours) if no further icing occurred, in subsequent checking for this project it was noticed that some of the previous EC runs did not end after 168 hours. It is not known if the 168-hour limit was not implemented generally in all cases or only in some cases. For this project, the icing events were ended after 168 hours. (Initial runs for this project ended the icing events after 72 hours but the final results reported in this report are based on 168 hours.) There are a few cases where the previous EC results indicate higher icing amounts since otherwise separate icing events were merged into single event with the separate icing amounts combined. The means and standard deviation of the annual maximum values are sometimes different and the extreme value analysis results in different 50-year values (more details are provided in Section 3.2 below).

3.1 Data and Locations

Stations used with the Chaîné ice accretion model in the Canadian context are those with 24/7 standard hourly meteorological observations and daily precipitation amounts (water equivalent of all precipitation types that occurred) made by human observers (not autostations). The stations used for this project for ice accretion modelling are listed in Table 1. They are located in southern Manitoba and adjacent areas of Saskatchewan and Ontario and are the same locations used by EC to prepare the data in CSA (2010). More recent data was used for this project, where available from EC. Results from the EC analysis and the analysis from this project are also presented in Table 1.

Table 1. Observing Stations and Ice Accretion Modelling Results									
Name	EC climate ID	Latitude	Longitude	Elevation (m)	Analysis Period used for CSA (2010)	50-year ice thickness (mm) used for CSA (2010)	Analysis period used for this project	Number of years	50-year ice thickness (mm)
Winnipeg Richardson Int'l A	5023222	49.92	-97.23	238.7	1954-2006	15.8	1954-2007	54	16.1
Portage Southport A	5012320	49.9	-98.27	269.7	1954-1991	11.8	1954-1992	39	11.8
Brandon A	5010480	49.91	-99.95	409.4	1960-2006	11.1	1958-2013	56	10.7
Rivers A	5012440	50.01	-100.32	473.4	1954-1969	10.2	1954-1969	16	8.3
Gimli Gimli A	5031038 5031040	50.63 50.63	-97.02 -97.05	222.8 222.0	1954-1990	16.0	1954-1990	37	14.9
Dauphin A	5040680	51.1	-100.05	304.5	1954-1994	12.7	1953-1994	42	11.6
Broadview Broadview A	4010879 4010880	50.37 50.25	-102.57 -102.53	599.8 619.7	1966-1994 1954-1964	8.5 8.3	1954-1993	40	9.1
Estevan A	4012400	49.21	-102.97	580.3	1954-2006	7.5	1954-2013	60	6.9
Yorkton A	4019080	51.27	-102.47	498.3	1954-2004	9.8	1954-2005	52	9.8
Atikokan	6020379	48.75	-91.62	395.3	1968-1986	10.5	1967-1988	22	10.5
Kenora A	6034075	49.79	-94.37	409.7	1954-2007	12.9	1954-2007	54	13.0
Sioux Lookout A	6037775	50.11	-91.90	383.1	1954-2007	13.2	1954-2013	60	13.1

The locations most representative of the study area are Winnipeg Richardson Int'l A and Portage Southport A. Figure 1 shows the stations used for ice accretion modelling and the reference (50-year return period) ice thickness values updated at the stations.

The map of reference ice thickness developed for this project is provided in Figure 2. The values are mainly based on the two locations in the study area (Winnipeg and Portage) and are consistent with the generally increasing values from west to east. The results at Winnipeg and Gimli both suggest that the reference icing values are higher in southeastern Manitoba than even northwestern Ontario.

Note that several of the locations used for ice accretion in this project are still active airports with 24/7 weather observing. However a change in the observing program results in not having the suite of observations required as input to the ice accretion models.

Winnipeg Richardson Int'l A stopped reporting daily total precipitation in 2008 so the hourly freezing precipitation amounts are not available even though the hourly present weather (occurrence and an indication of intensity) is still reported (it is needed for aviation operations).

Portage Southport A became an autostation in the early 1990's so that although there are still 24/7 observations that could be used for ice accretion modelling, their use in Canada has not been investigated for this purpose. Further work including testing would be needed to adapt the autostation data for this purpose. Note that in the U.S. all of the hourly weather observations reported at airports are from autostations. K. Jones at CRREL who uses this data for ice accretion modelling has indicated (pers. comm.) that the current autostation observations are difficult to deal with owing to apparent different reporting procedures amongst stations, and the need to reconcile precipitation totals from different periods (hourly vs. daily, for instance).

At the airports, the observations used for aviation purposes (and ice accretion modelling) are now under the control of NavCanada. Recently NavCanada introduced a new reporting system at stations with human observers with some different instruments, although nominally the same elements are reported although with some different procedures. The observations are still received by EC, archived and made available on request. When a station switches to this new system, EC retires the old station ID and creates a new one representing a station at the same location. The data is handled differently by EC (EC does not quality check these new observations for instance). But the data is still available for ice accretion modelling. Of the locations listed in Table 1, in the last year or so, Brandon, Winnipeg, Kenora and Sioux Lookout now have different stations. The data at these new stations were not used for this project, but with some further investigation may prove useful for ice accretion modelling to update the icing results at these locations in the future.

3.2 Ice Accretion Results and Comparison with Previous Studies

There are two recent published results with which to compare the results of this project. CSA (2010) based on CEATI (2009) indicates reference ice thickness values in the range of 15 to 16 mm for southeastern Manitoba. This is comparable to the updated results in Figure 2 that range from 13.5 to 16 mm. The slight differences are partly a result the addition of recent years at some locations. The assumed ice resident time for icing events of 7 days (168 hours) adopted for this project is nominally the same as used by EC previously. As mentioned above in Section 3.0, a check of some of the EC results indicated that some icing events were longer than 7 days resulting in some events that combined events that would otherwise be treated as separate, smaller events. For locations where there were no more recent data than what was available for EC's previous work, such as Gimli and Rivers, the differences in Table 1 are due to a few longer EC events. The map in CSA (2010) also reflects a somewhat more conservative approach to the analysis.

CEATI (2006) provides a study of icing results by K. F. Jones at CRREL. The results are based on primarily the CRREL simple model results with the Manitoba stations merged into "superstations" with some U.S. observing stations to the south. The value of 50-year ice thickness is 12.5 mm (0.5 inches) for southern Manitoba. This difference is most likely due to the different performance of the CRREL simple model compared with the Chaîné ice accretion model (the CRREL simple model provides smaller ice accretion amounts that the Chaîné model with the same input). Further discussion of the ice accretion models and their differences are provided in Appendix B.

The results of this project are consistent with the general spatial pattern of increasing ice accretion amounts from west to east. Southern Manitoba is in a transition zone between areas of lower icing amounts to the west and significantly higher amounts to the east. Although Manitoba is subject to incursions of moist air masses from the southern U.S., relatively flat terrain that gently slopes to the north does not promote the trapping of cold air at the surface in advance of a warm front that contributes to the significant and relatively frequent icing conditions due to freezing rain along the north shores of the Great Lakes, the Ottawa River and St. Lawrence Valleys, and Atlantic Provinces.

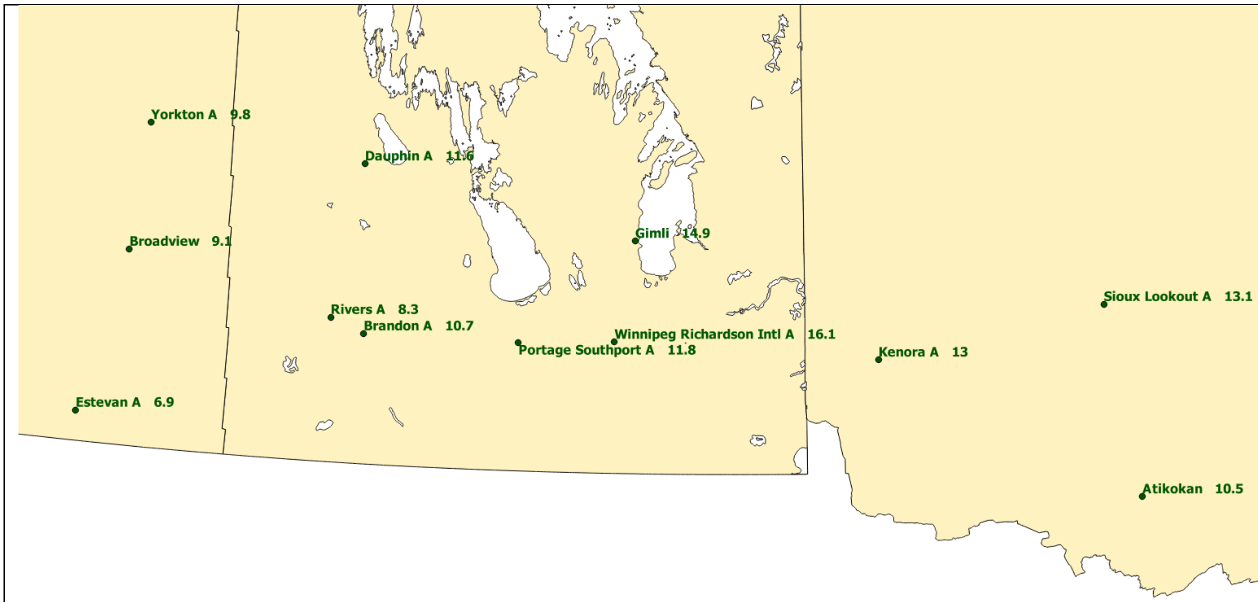

Figure 1. Stations used for ice accretion modelling and updated 50-year radial ice thickness (mm).

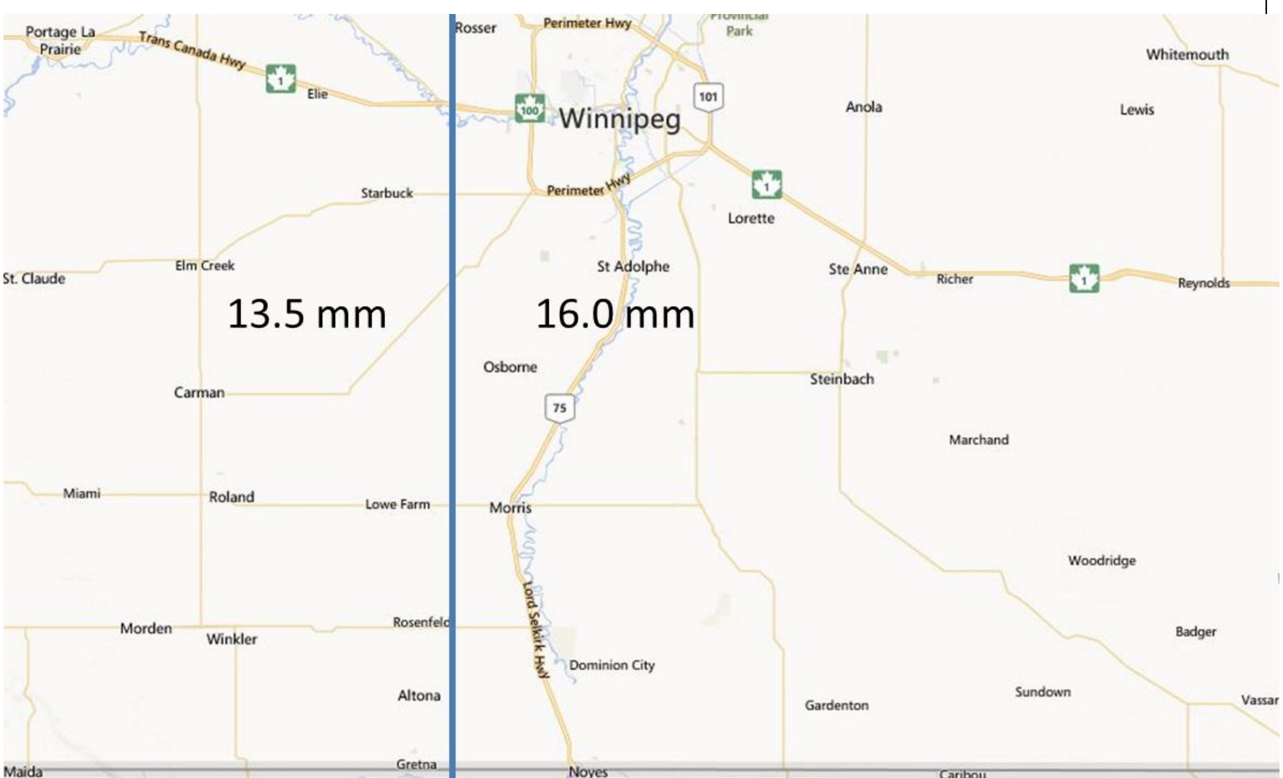

Figure 2. Recommended reference ice thickness (mm) for the study area

4.0 Reference Wind Speed

4.1 Background, Methods and Wind Data

The reference wind speed is represented by the 50-year return period value of the 10-minute wind speed at 10 m above ground over flat, open terrain.

There are significantly more observing stations with anemometers from which the reference wind speed can be calculated, than are available for ice accretion modelling. In addition to the 24/7 human observations at airports used for ice accretion modelling, there are both aviation and surface weather autostations, and supplementary climate stations whose wind observations were abstracted from daily charts from a recorder.

As with the variety of observing stations, there is variety in the characteristics of the archived wind observations that are available for analysis.

The categories and characteristics of wind observations used for this study are listed in Table 2.

Table 2. Categories and Characteristics of Wind Observations

Category	Description
Aviation Winds	Observed at airports either by human observers or aviation autostations, the wind speed is observed once per hour, at the top of the hour. The averaging period is one minute up to 1985 and two minutes thereafter.
Surface Weather Winds	Observed at EC autostations at airports or elsewhere, the wind speed is reported hourly as a ten-minute wind speed at the top of the hour (i.e. from minute 50 to 60). For some of these stations for some of the period, the wind speed reported was the two-minute average speed.
Wind Run	Observed at supplementary climate stations, this hourly wind observation represents the hourly average speed and prevailing direction for the entire hour, abstracted from a daily chart from a recorder. These observations have been discontinued and the most recent are from the 1990's.
Peak Wind of the Day	The peak instantaneous (5-second average) speed at both surface weather and aviation autostations determined from the continuous record for the daily 24-hour period, reported once per day.

CSA (2010) provisions for wind load calculations, similar to most wind engineering applications, assume some specific wind characteristics. The reference wind speed provided corresponds to a 50-year return period of the 10-minute average wind speed, 10 m above ground, and flat open terrain (CSA roughness category B). CSA (2010) provides measures to adapt the reference speed to other roughness regimes. The characteristics of the terrain (roughness) categories are provided for convenience in Table 3, abstracted from CSA (2010) Tables A.7 and A.8. The various elements are referenced in discussion below. Note that the roughness length (m) is a value widely used in wind engineering applications to characterize the surface roughness of an area or site.

Table 3. Roughness/terrain characteristics relevant to wind loads (from CSA (2010) tables A.7 and A.8)				
Element	Terrain (roughness) category			
	A	B	C	D
z_0 - roughness length (m)	0.01	0.05	0.30	1.00
K_R	1.08	1.00	0.85	0.67
Description	Large stretch of water up-wind, flat coastal area, flat dessert	Open country with very few obstacles, for instance moorlands or cultivated field with a few trees or buildings	Terrain with numerous small obstacles of low height (hedges, trees and buildings)	Suburban areas or terrain with many tall trees

The required wind speed observation to determine the reference wind speed is the maximum 10-minute average speed. The available hourly speeds are the either one-, two- or ten-minute speeds observed once per hour. In addition the roughness characteristic of each observing site may not be flat, open terrain (roughness category B) as required to represent the reference wind speed. CSA (2010) provides adjustment factors to deal with this. Figure A-7 in CSA (2010) indicates the ratio between wind speeds of various durations for four roughness categories. For instance, for roughness category B, the ratio between the maximum 10-minute average speed and its corresponding 1-hour average speed is 1/0.9 = 1.11. The approach taken in CEATI (2009) was to estimate the hourly average speed with the running average of two consecutive hourly observations of the short-duration (1-, 2- or 10-minute) speeds, then compile the annual maximum series of the hourly average speeds, calculate the 50-year return period value of the hourly average speeds, and adjust the 50-year value by the 1.11 factor at locations with roughness category B to represent the 50-year 10-minute average speed. Some observing sites were situated in rougher terrain (category C) and the appropriate factor, 1.18 from CSA (2010) Figure A-7, was used to adjust the 50-year hourly average speed to the reference speed in those cases. The primary means by which the terrain (or roughness) category was determined was by the description of the site abstracted from the EC paper files of station inspection and maintenance records. This description was interpreted subjectively as either representing category B or C (a few were A or D) and the factor of 1.11 was used to adjust the 50-year 1-h speed to a 50-year 10-min speed for category B, and 1.18 for category C. This was a very approximate approach since only two adjustment factors were used – 1.11 or 1.18.

For the CEATI (2009) project the one-hour to 10-minute average speed ratio was calculated for a research data set of consecutive one-minute average wind speeds for 2003 from Bratts Lake SK (roughness category B) and found to be consistent with the 1.11 value noted above. Although it is intuitive that the running average of consecutive short-duration wind speeds at the top of each hour will represent the hourly average speed in an unbiased fashion, calculations were also performed to confirm this procedure too. Details are found in CEATI (2009). For this project the ratios were calculated and confirmed for an additional period from 1999 to 2005 at Bratts Lake.

CSA (2010) Table A-8 provides an additional factor - to adjust the reference speeds from one roughness category to another. Reproduced in Table 3 above, CSA (2010) Table A.8 provides values of factor K_R for this purpose. For instance, the value of K_R is 0.85 to adjust the reference speed from category B to C (or its reciprocal 1.18, to adjust from category C to B). For CEATI (2009) this additional factor was not applied. Should both factors be applied, the logical sequence is to adjust the maximum wind speed for the roughness first to represent roughness category B, then adjust the averaging period from 1 h to 10 minutes for category B using the value 1.11.

For this project an approach was adopted similar to that used by EC to update the design wind pressures in the 2010 National Building Code of Canada.

For the NBCC 2010 update, the hourly average wind speeds were adjusted to correspond to flat, open terrain (about the same as CSA terrain category B) by estimating the effect of roughness by subjectively assessing the terrain around the anemometer site with Google Earth imagery. This was done by first estimating the average distance from any surrounding wooded or built up areas upstream in the direction of the prevailing wind direction (generally westerly and southwesterly). Then a roughness adjustment factor was estimated from Figure 3. As indicated by Table 3, the change of surface roughness from 0.5 m to 0.05 m represents a change from a roughness regime between terrain category C and D, and category B. This procedure provides an approximation of the effect on the wind speed of surface roughness around an anemometer. The values expressed on the graph in Figure 3 are from equations in Taylor and Lee (1984) to estimate the change in wind speed downwind from a step change in surface roughness. The ratio of wind speed for various distances downwind compared to the wind speed 10 km downwind are presented. The 10 km distance was used for this purpose since the ratio of 0.75 (for small distances compared to 10 km downwind) has the same interpretation of going from between terrain category C and D to category B (comparing with values of K_R in Table 3).

This is an approximate method to assess the roughness at anemometer sites and the adjustment factor needed to account for it. It provides for more granularity in assessing the roughness effect than just using the values in Table 3 (as was done for the development of CSA (2010)). It was also used at EC for subsequent work for updating the design wind pressures in the 2010 NBCC.

In the EC work to update the 2010 NBCC design wind pressures, additional detailed information was provided by a NBCC task group member from the environmental engineering firm RWDI in Guelph ON. In the course of its wind engineering work over the years RWDI had assessed the roughness characteristics of anemometer sites at a number of major Canadian airports. RWDI provided the adjustment factors by implementing commercial wind engineering software (from ESDU - http://www.esdu.com/cgi-bin/ps.pl?sess=unlicensed_1090604172037xhn&t=ser&p=ser_wind) based in large part on Deaves (1981). RWDI provided an adjustment factor for each of 16 directional sectors incorporating the roughness changes for many km upstream in each direction. RWDI denoted open terrain as having a z_0 value of 0.03 m (compared to 0.05 m for CSA category B). EC then adjusted every hourly wind speed by the direction-specific factor provided by RWDI and compared the resulting 50-year wind speeds with both the unadjusted wind speeds, and for a few cases, the 50-year wind speeds adjusted by the simpler EC method described above.

The EC simpler method compared reasonably well with the detailed RWDI results. The RWDI factors for sixteen locations were used for the NBCC project, and the EC method for other locations. Winnipeg Richardson Int'l A (5023222) was the only location in Manitoba for which RWDI provided factors. The overall adjustment was 1.10 using the RWDI directional factors, compared to the unadjusted results. The value used in this project for station 5023222 is 1.08 which reflects a z_0 value of 0.05 m corresponding to CSA category B, compared to the z_0 value of 0.03 m assumed for open terrain by RWDI.

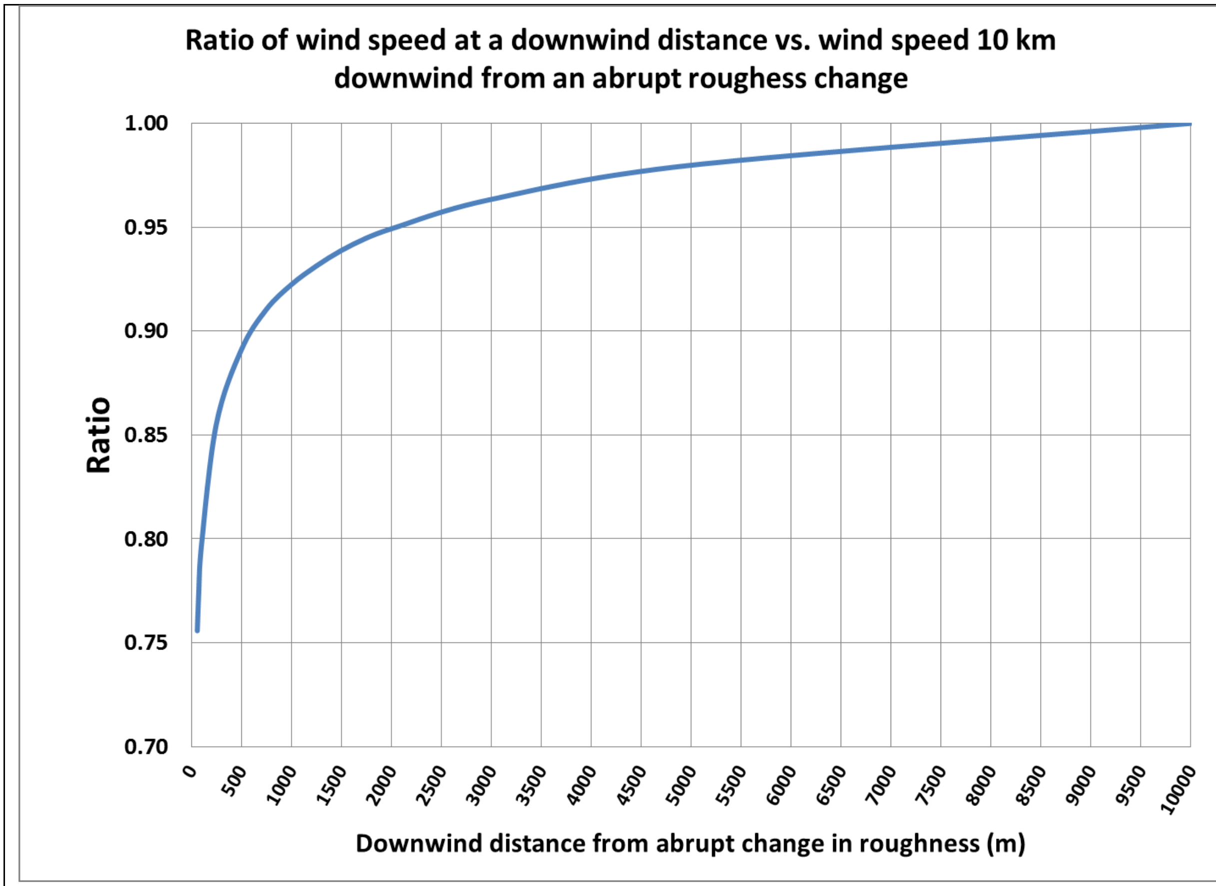

Figure 3. Ratio of wind speed at 10 m above ground over a wooded or built up area (roughness length z_0 = 0.5 m) to wind speed over open terrain (z_0 = 0.05 m) vs. the downwind distance (m) from the step change in roughness. Based on equations to evaluate the change in wind speed downstream from a step change in surface roughness (Taylor and Lee, 1984)

Note that the EC simple method to determine a roughness adjustment factor is approximate. The location of the anemometer is not always obvious, and a single downwind distance was subjectively selected based on the visual inspection of the Google Earth image of the site based on the EC coordinates for the weather station, and an assumed generally westerly direction for extreme winds. The visual inspection of each site used in southern Manitoba resulted in an adjustment factor greater than 1.0 for almost every location. As evident for Portage Southport A in Figure 3, there are at least some buildings or trees, even wooded areas, in the vicinity of almost all anemometer sites.

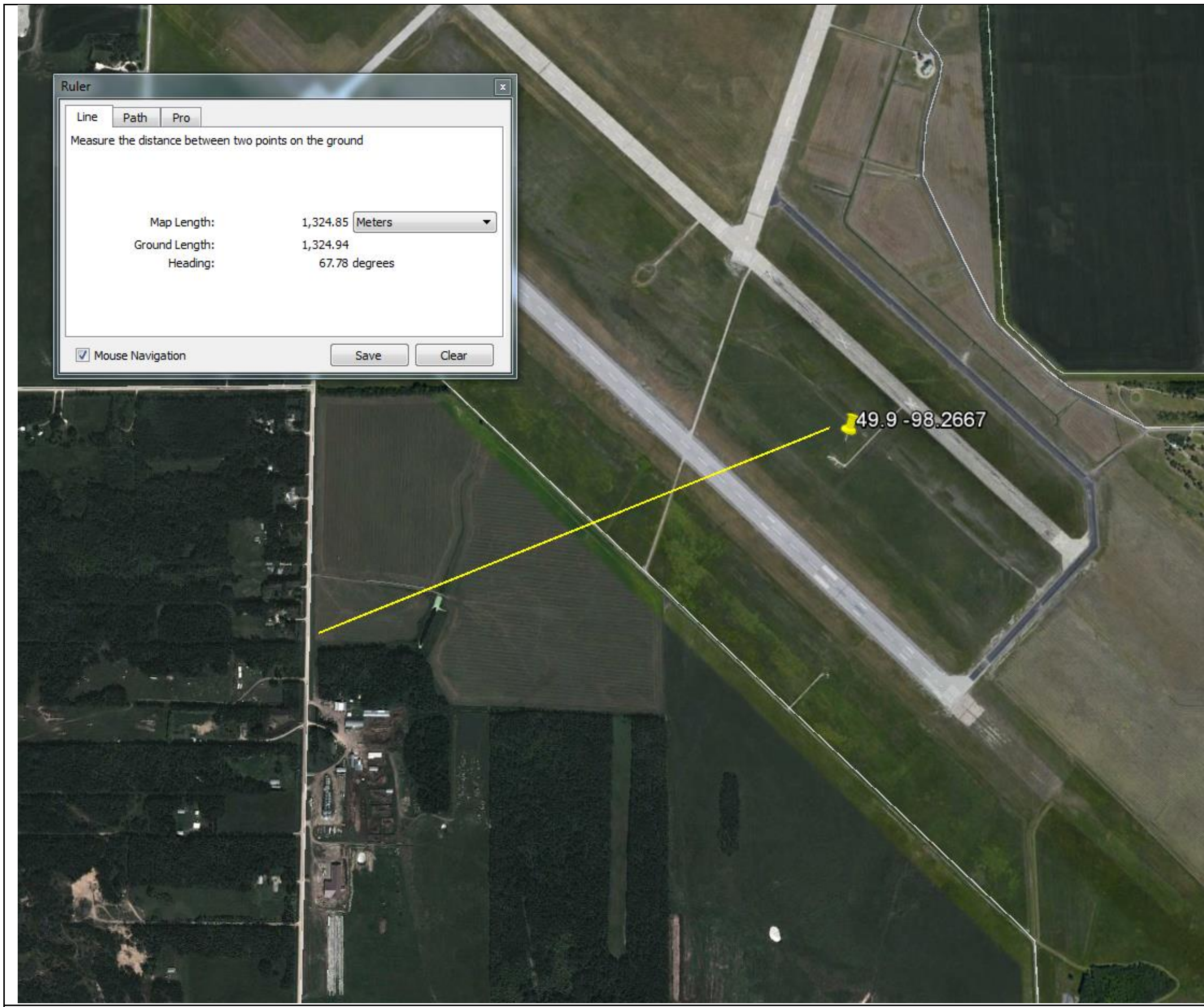

Figure 3. Example of a Google Earth image of an airport anemometer site. This location is Portage Southport A. The yellow line indicates an assessment of about 1.3 km for the distance from the step change in roughness from roughness length 0.5 m to 0.05m at the anemometer site. The adjustment factor from Figure 2 corresponding to this distance is about 0.925. Its reciprocal, 1.08, was used to adjust the 50-year hourly average wind speed at this location to represent category B.

The steps taken for the analysis of the hourly aviation and surface weather wind speeds for calculating the reference wind speeds in this project were:

- The hourly average wind speeds at each southern Manitoba station were estimated by the running mean of consecutive hourly short-term wind speeds, adjusted to 10 m above ground. In addition, years for which the anemometer was on top of a building were not used.
- The annual maximum series for each station was compiled and a check of suspicious values conducted and data considered not valid were removed from the data set.
- The 50-year return period value was calculated by fitting the Gumbel distribution by the method of moments to the annual maximum series for each station with at least 10 complete years of data.

- The roughness for each station was assessed using the methods described above and a roughness adjustment factor assigned.
- The 50-year value of the 10-minute average speed was calculated by multiplying the 50-year hourly average speed by the roughness factor and by the value of 1.11 to convert the hourly average speed to a 10-minute maximum speed. The value of 1.11 was used at all locations since the 50-year speed had already been adjusted to terrain category B by the adjustment factor.
- The resulting reference wind speeds at each station were plotted on a map and a contour map prepared based on a subjective analysis.

The hourly winds from airports and EC surface weather stations, along with the resulting reference wind speeds calculated are listed in Table 4. The results for the wind run stations are in Table 5.

Table 4. Stations in southern Manitoba with aviation and surface weather wind observations and the results. The factor to adjust the hourly average wind speed to a 10-minute maximum value is not listed since the same value of 1.11 was used for each location.

Climate ID	Name	Elev (m)	Lat	Long	No. of years	Most recent year	50-Year hourly average speed (km/h)	Roughness factor	50-year 10-minute average speed (km/h)
5010480	BRANDON A	409	49.91	-99.95	51	2012	82.7	1.02	93.7
5010547	CARBERRY CS	384	49.91	-99.36	19	2013	69.0	1.05	80.5
5012320 5012324	PORTAGE SOUTHPORT A PORTAGE SOUTHPORT	270 273	49.90 49.90	-98.27 -98.28	28 17	1991 2013	80.7	1.08	96.8
5012440	RIVERS A	473	50.02	-100.32	17	1969	89.4	1.00	99.3
5012654	SHOAL LAKE CS	561	50.45	-100.60	18	2013	75.6	1.10	92.3
5013117	WASAGAMING	627	50.66	-99.94	16	2013	33.5	1.18	43.8
501A7AR	MELITA	446	49.28	-100.99	19	2013	70.4	1.18	91.9
5020882	EMERSON AUT	242	49.00	-97.24	11	2008	81.7	1.10	99.7
5021220	GRETNA (AUT)	253	49.03	-97.56	17	2013	82.2	1.03	94.0
5021849	MORDEN CDA CS	298	49.19	-98.08	13	2013	50.9	1.20	67.8
5022125	PILOT MOUND (AUT)	470	49.19	-98.90	16	2010	82.7	1.06	97.3
5022759	SPRAGUE	329	49.02	-95.60	19	2013	58.5	1.15	74.7
5023222	WINNIPEG RICHARDSON INT'L A	239	49.92	-97.23	48	2012	80.9	1.08	97.0
502I001	CARMAN U OF M CS	268	49.50	-98.03	18	2013	60.5	1.12	75.2
5031038	GIMLI	223	50.63	-97.02	19	1990	59.8	1.20	79.7
5031041	GIMLI HARBOUR CS	217	50.63	-96.98	11	2012	68.0	1.20	90.5
50310D0	GIMLI INDUSTRIAL PARK	230	50.63	-97.05	15	2009	72.3	1.10	88.3
5032951	VICTORIA BEACH (AUT)	220	50.70	-96.57	18	2013	83.7	1.05	97.5
503B1ER	PINAWA	268	50.18	-96.06	18	2013	48.3	1.25	66.9
5040680	DAUPHIN A	305	51.10	-100.05	57	2009	82.7	1.05	96.4
5043158	MCCREARY	351	50.71	-99.53	16	2013	68.5	1.15	87.4
504K0NM	OAKPOINT MARINE	250	50.50	-98.04	15	2010	78.8	1.02	89.2

The wind run observing program was stopped at all stations by the late 1990's so there were no further observations available for this project. The EC data for Manitoba used by EC in CEATI (2009) was used in this project. The analysis was similar to that for the aviation and surface weather hourly winds described above except that there was no running averaging of consecutive wind speeds, since the hourly wind speed observation is the average speed (wind run) for the hour. The stations and results are provided in Table 5.

Table 5. Stations in southern Manitoba with wind run observations (hourly average speed) and the results. The factor to adjust the hourly average wind speed to a 10-minute maximum value is not listed since the same value of 1.11 was used for each location. This is the same data as used in CEATI (2009) since there has been no more recent wind run observations since then.

Climate ID	Name	Elev (m)	Lat	Long	No. of years	Most recent year	50-Year hourly average speed (km/h)	Roughness factor	50-year 10-minute average speed (km/h)
5013117	WASAGAMING	627	50.65	-99.93	14	1987	48.9	1.25	67.8
5021054	GLENLEA	234	49.65	-97.12	29	1999	85.4	1.05	99.5
5021848	MORDEN CDA	298	49.18	-98.08	16	1997	63.6	1.18	83.4
5022125	PILOT MOUND (AUT)	470	49.20	-98.90	19	1982	77.4	1.10	94.5
5030282	BISSETT	259	51.03	-95.70	14	1982	50.0	1.25	69.3
5040764	DELTA MARSH CS	248	50.18	-98.38	18	1987	82.7	1.05	96.4
5043158	WILSON CREEK WEIR CS	351	50.72	-99.53	24	1996	73.5	1.15	93.8

In addition to hourly wind speeds most stations with wind observations also report some form of gust or peak wind observations. The most useful form for this project is the daily peak wind speed recorded and archived for every day in the EC climatological database. For either aviation or surface weather autostations the daily peak wind is the highest of consecutive 5-second average wind speeds continuously recorded. Since most of these observations in southern Manitoba began in the 1990's the longest period of record is only 19 years. The autostation peak wind stations and results are provided in Table 6.

These peak wind observations are considered supplementary in compiling the reference wind speeds. No adjustment is made for roughness since many of the peak wind observations are the result of convective weather events (severe thunderstorms) which less sensitive to the surface roughness. CSA (2010) Figure A.7, as discussed above allows the adjustment for the standard roughness categories of various durations to a 10-minute average wind speed. For a 5-second wind speed the adjustment to a 10-minute speed is about 1.35 for category B. So for a 135 km/h 5-second gust would be expected on average to be associated with a 100 km/h 10-minute average wind speed. Where the 50-year peak wind values are higher than nearby or the same location's 50-year 10-minute wind speed by a ratio greater than 1.35, this might indicate that there is a significant contribution of severe convective weather to the extreme wind in that area, that might not be fully captured in the hourly observations since thunderstorms can often occur between regular hourly observations. The daily peak wind information is used subjectively along with the 50-year 10-minute wind speed in composing the reference wind speed map for the project area.

Table 6. Autostations in southern Manitoba with daily peak wind speed observations. These speeds are the highest 5-second average speed sometimes referred to as gusts. No adjustment for duration or roughness is made.

Climate ID	Name	Elev (m)	Lat	Long	No. of years	Most recent year	Highest peak wind speed (km/h)	50-year peak wind speed (km/h)
5010547	CARBERRY CS	384	49.90581	-99.3574	19	2013	146	129
5012654	SHOAL LAKE CS	561	50.45489	-100.604	18	2013	104	110
5013117	WASAGAMING	627	50.655	-99.9419	18	2013	104	101
501A7AR	MELITA	446	49.28128	-100.986	19	2013	98	97
5020882	EMERSON AUT	242	49	-97.2375	11	2008	133	143
5021220	GRETNA (AUT)	253	49.03083	-97.56	18	2013	165	165
5021849	MORDEN CDA CS	298	49.18764	-98.0839	13	2013	95	99
5022125	PILOT MOUND (AUT)	470	49.19103	-98.9049	14	2010	102	107
5022759	SPRAGUE	329	49.02361	-95.5983	18	2013	115	114
5023262	WINNIPEG THE FORKS	230	49.88834	-97.1294	14	2013	126	129
502I001	CARMAN U OF M CS	268	49.49811	-98.0298	18	2013	137	139
5031041	GIMLI HARBOUR CS	217	50.63111	-96.9822	11	2012	145	145
50310D0	GIMLI INDUSTRIAL PARK	230	50.63333	-97.05	15	2009	109	122
5032951	VICTORIA BEACH (AUT)	220	50.7	-96.5667	17	2013	113	117
503B1ER	PINAWA	268	50.17723	-96.0647	19	2013	85	90
5040680	DAUPHIN A	305	51.1	-100.05	15	2009	104	110
5043158	MCCREARY	351	50.71194	-99.53	16	2013	204	204
504K0NM	OAKPOINT MARINE	250	50.49946	-98.0367	16	2010	115	119

A second set of daily peak wind speeds from airport locations with human observers and during the years when U2A anemometers with a chart recorder were used. With this equipment the observer determined the peak wind directly from the pen trace on the daily chart. The peak speed so reported is generally considered to be a gust of 3-5 seconds duration. A critical aspect of this observation is that, similar to the autostation peak wind data, the daily highest value is determined from a continuous record. At the manned airport stations, the U2A anemometers and chart recorders were replaced with 78D anemometers with digital readouts in the mid to late 1990's. The readout displays the current 2-minute speed and maximum speed over the most recent 10 minutes for reporting on the hour. There is no continuous recording of the wind speeds. The observer then reports the daily peak speed as the highest hourly speed or gust that was observed when making regular hourly observations, or when conditions warranted, making special observations between hours. There is no assurance that higher gusts did not occur between observations that were not observed and reported. For this reason the daily peak wind speeds from manned airport observing stations is only used during the period when the U2A chart recorder system was in use. The manned airport daily peak observations were not used in the EC CEATI (2009) project after 1996, about when the U2A systems were replaced. This data used by EC for CEATI (2009) for southern Manitoba stations is provided in Table 7 along with results.

Table 7. Airport stations in southern Manitoba with daily peak wind speed observations from a chart recorder. These speeds are the highest 3- to 5-second average speed sometimes referred to as gusts. No adjustment for duration or roughness is made. This is the same data as used in CEATI (2009) since there has been no more recent daily peak wind speed observations made since then. Chart recorders were taken out of service generally in the 1990's.						
Climate ID	Name	Lat	Long	No. of Years	Highest peak wind speed (km/h)	50-year peak wind speed (km/h)
5010480	BRANDON A	49.91	-99.95	35	139	145
5012320	PORTAGE SOUTHPORT A	49.90	-98.27	30	140	140
5023222	WINNIPEG RICHARDSON INT'L A	49.92	-97.23	30	129	136
5031038	GIMLI	50.63	-97.02	20	106	105
5040680	DAUPHIN A	51.10	-100.10	25	122	124

Figures 4 and 5 provide maps showing the locations of the hourly and peak wind observing stations. Figure 6 shows the 50-year return period 10-minute wind speed values calculated at the hourly wind observing stations. Figure 7 shows the 50-year return period peak wind speeds (generally 5-second gust).

Although the observations from EC generally undergo quality checks, occasionally some of the data is in error. The surface weather autostations in particular, experienced some spurious values. When some of the annual maximum values appeared suspicious they were checked and removed if found to be in error. Some were obvious such as a string of consecutive identical high wind speed values e.g. 111 or 159 km/h, often followed by several hours of missing data, indicating a sensor or data logger processing issue at the station. Some high values that initially were considered suspicious, were kept after investigation. For instance, there are two notably high annual maximum peak wind speeds evident in Table 6. A peak wind speed of 165 km/h at Gretna on September 22, 2008 was not reflected in the hourly wind speeds that day at that station, but inspection of the historical radar images on the EC web site (http://climate.weather.gc.ca/radar/index_e.html) indicates the passage of an organized line of convective showers that may well have accounted for this high wind speed between the hourly observations. Also there was a high peak wind speed of 106 km/h at nearby Emerson the same day, so the 165 km/h value was retained. A 204 km/h peak wind at McCreary June 27, 2008 was retained because the data flag was "E" or "estimated", indicating that the value was checked by EC staff. Another aspect of McCreary's record is suspicious in that all the annual maximum peak wind speeds higher than 100 km/h occurred in the first half of the period suggesting some change in the observing program, siting or instrumentation that would need to be further investigated if this station were important for analysis of the study area. McCreary's record and results were retained but were not weighted heavily for the analysis of the reference wind speed for the study area. It also provides a good example of how variable and apparently random very high peak wind speeds are, and the importance of checking autostation observations.

Figure 4. Locations with hourly wind speed observations used in the reference wind calculations. Locations with blue names have short-term hourly wind speed observations at the top of each hour. The locations with green names have wind run (average wind speed for the hour).

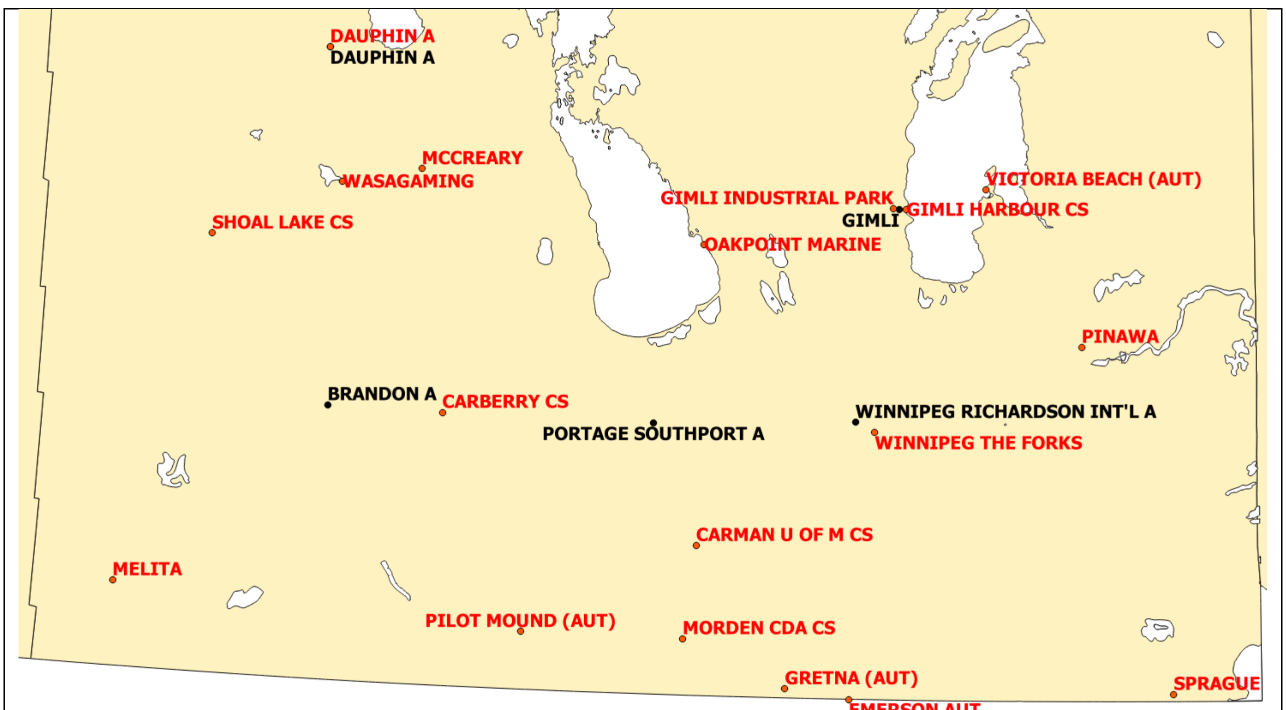

Figure 5. Locations with daily peak wind speed observations used as supplementary information in the reference wind speed calculations. Stations with red names are autostations. Stations with black names have the daily peak wind taken from the U2A chart recorder by the observer.

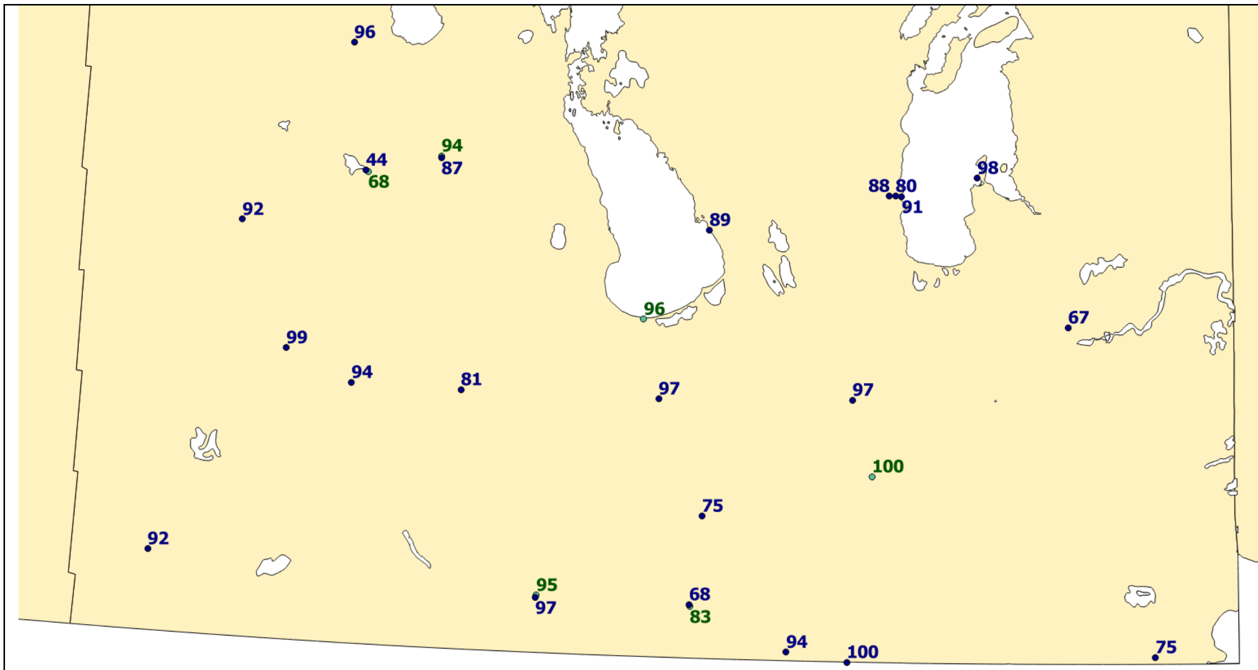

Figure 6. Calculated values of 50-year return period 10-minute average wind speed values. The wind records from two Portage Southport stations are combined.

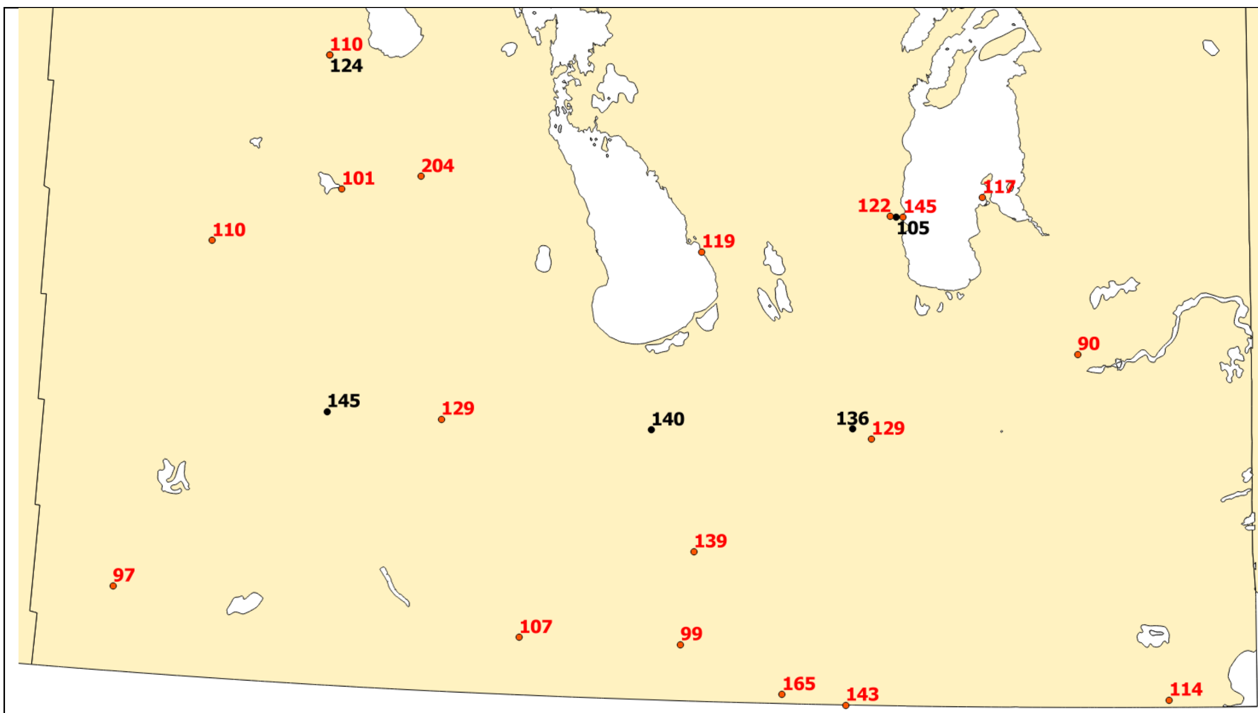

Figure 7. Calculated values of the 50-year return period peak wind (gust) used as supplementary information in determining the reference wind speed.

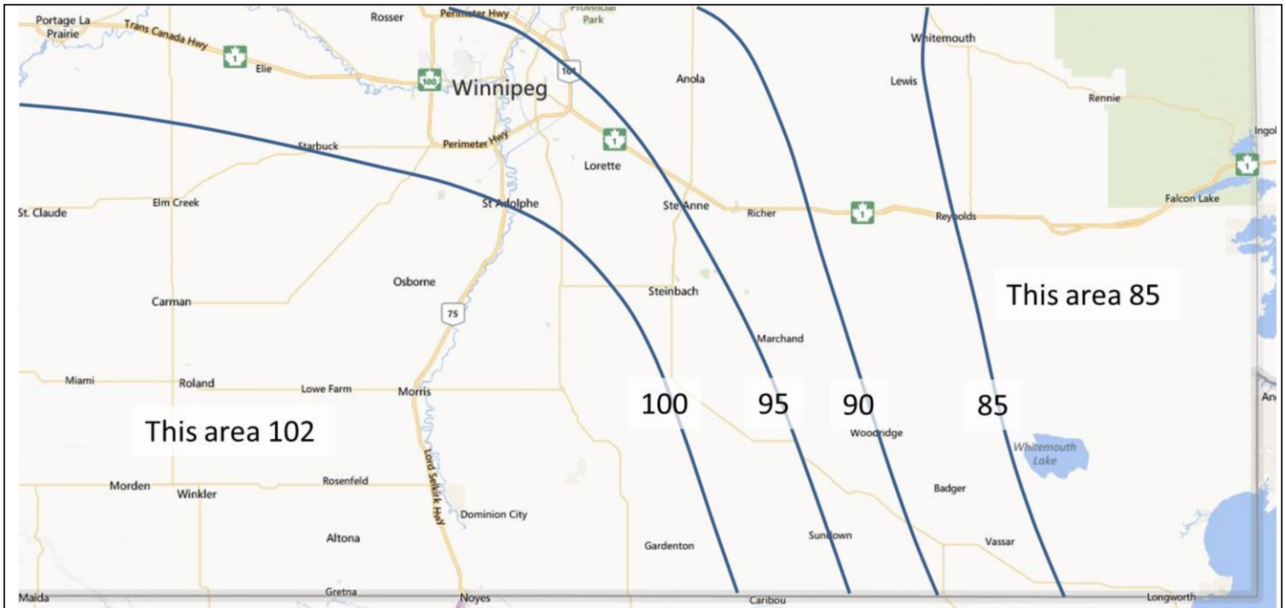

Figure 8. Reference wind speed for the study area. Labelled contours are km/h. The area west and south of the 100 contour is 102 km/h. The area east of the 85 contour is 85 km/h.

4.2 Wind Results and Discussion

The resulting reference wind speeds recommended for the study area are provided in Figure 8. The general pattern is similar to CSA (2010) (Figure CA.6) with a few important differences. The values for the study area in this project are slightly higher with the 100 km/h contour positioned slightly further east. In addition, an 80 km/h contour was not used for this project. The main reason for the slightly higher values is that an additional step was added to the procedure to account for roughness so that the calculated values at each station represented terrain category B. For Winnipeg Richardson Int'l A, for instance, in CEATI (2009), on the basis of the EC site description, the location was assumed to be category B and just the 1.11 factor was used to adjust the 50-year hourly average speed to the 10-minute average speed corresponding to the reference wind speed. In this study, a more detailed look at the roughness of the anemometer site was undertaken and at this station an additional factor of 1.08 was applied to adjust the wind results to represent terrain category B. For CEATI (2009) the reference speed for Winnipeg was 91 km/h. For this study it is 97km/h. Some of the difference is accounted for by the additional six years of record.

For southeastern Manitoba, the lowest contour used for this project is 85 km/h compared to 80 km/h in CSA (2010). This change was made in part due to the more detailed accounting for surface roughness. Another reason is that peak wind speeds (gusts) generally appear higher than the calculated 10-minute average speeds than the 1.35 factor from CSA (2010) Figure A-7 would suggest. As discussed above, this may be due to the higher peak wind speeds occurring as a result of convective events (e.g. severe thunderstorms) that are less influenced by surface roughness than the winds from larger, organized frontal weather systems. The recommended minimum reference wind speed for heavily wooded areas is

85 km/h. A similar change was made to the 2010 NBCC where the minimum value was raised to 80 km/h for the hourly (not 10-minute) average speed.

5.0 Ice and Wind Combinations

The following ice and wind combinations are specified by CSA (2010) (page 73).

> *"Low ice probability (return period T) associated with the average of yearly maximum winds during icing presence, and low probability wind during icing (return period T) associated with the average of the maximum yearly icing."*

These are the specifics of the data needed for the two wind and ice combinations:

- Combination 1 – 50-year ice thickness with the average of annual maximum wind speeds during icing.
- Combination 2 – annual average maximum ice thickness with the 50-year return period wind during icing.

Two locations, Winnipeg Richardson Int'l A and Portage Southport A are the only stations with icing results in the study area. As part of the ice accretion modelling, one of files with intermediate results for each station included a list of each icing event relevant information such as the date, maximum ice thickness, maximum 10-minute maximum wind speed (2-hour running average of the wind speed on the hour multiplied by 1.11), and maximum transverse load.

The transverse load was calculated from the following equations. First the wind pressure, q (Pa), was calculated as per example CA.1 in CSA (2010) annex CA:

$$q = 0.049\ v^2 \tag{2}$$

where v is the 10-minute average maximum wind speed (km/h) for each hour.

The transverse load, TL (N/m), was calculated by applying the wind pressure to the iced conductor assuming a drag coefficient of 1.0 by:

$$TL = 2\ q\ (1.1/1.04)\left(r_{eq} + r\right)/1000 \tag{3}$$

where r_{eq} is the radial ice thickness (m) and r is the conductor radius (m) (12.5 mm in this case). The TL calculation in this context is to provide a general indicator to further investigate the wind speed and ice thickness values that lead to the 50-year combined effect and is not meant to represent a rigorous estimate of actual loads on the line. The 1.1/1.04 factor accounts for the increased air density when dealing with wind and ice combinations (from CSA (2010) Table CB.1).

From the event summary files, the average annual maximum ice thickness and 10-minute wind speeds during icing were calculated directly.

The 50-year wind speed during icing and 50-year TL values were calculated by compiling the annual maximum series of each and fitting the Gumbel distribution by the method of moments.

The results for the two locations are provided in Table 8.

Table 8. Combined wind and ice conditions. The first two rows represent combination 1 and following two rows represent combination 2 from the discussion in the text above. The 50-year transverse load and wind speeds corresponding to various ice thickness values to give the same 50-year transverse load are provided for comparison.

Parameter	Winnipeg Richardson Int'l A	Portage Southport A
50-year ice thickness (mm) (combination 1)	16.1	11.8
Average annual maximum wind speed during icing (km/h) (combination 1)	57.0	54.3
Average annual maximum ice thickness (mm) (combination 2)	4.1	3.5
50-year wind speed during icing (km/h) (combination 2)	84.5	79.3
50-year transverse load (N/m)	14.5	10.4
Wind speed (km/h) corresponding to TL with ice thickness = 0 mm	105.8	89.5
Wind speed (km/h) corresponding to TL with ice thickness = 5 mm	89.4	75.7
Wind speed (km/h) corresponding to TL with ice thickness =10 mm	78.8	66.8
Wind speed (km/h) corresponding to TL with ice thickness = 15 mm	71.3	60.4
Wind speed (km/h) corresponding to TL with ice thickness = 20 mm	65.6	55.6

A consideration in the calculations done for Table 8 for combination 2 was whether to restrict the icing events to those having an ice thickness value equal to or higher than a selected threshold. Restricting the icing event thickness to even a few mm results in several years without any icing events. This complicates both the calculation and interpretation of the 50-year wind speed during icing. With all icing events included there were at least one event each year (the average number of icing events is about 5). To investigate this aspect further and gain insight into the sensitivity of the results to restricting the calculation of wind speed (and associated transverse load) to icing events above selected thresholds, a number of thresholds were selected for Winnipeg Richardson Int'l A. These results are in Table 9.

In Table 9, the icing event threshold is in the first column and the next two columns show the number of years with at least one event matching the threshold (non-zero years) and the number of years for which no icing events occurred matching the threshold (zero years). Even for the smallest threshold (1 mm), there are 16 years in the overall 55-year period for which all the icing events were smaller than 1 mm. The 50-year wind speed is calculated with the annual maximum wind speeds during icing from the 39 years with icing events above the 1 mm threshold for this row in the table. The years with no events are accounted for by adjusting the return period of 50 years by the following: $RP_{50}^* = 50\ N_n/(\ N_n + N_z)$ where RP_{50}^* is the effective return period, N_n is the number of years with events (non-zero years) and

N_z is the number of years without events (zero years). The zero years cannot be ignored since they are complete and do not simply reflect missing data. This approach has the effect of assuming that there are two icing populations that contribute each year. The first comprises icing events matching the threshold and its corresponding wind speeds, and the second is a zero probability of having a qualifying icing event. The wind speed probability of occurrence is adjusted by incorporating the zero distribution in this way. Note that if all the years have qualifying events (i.e. N_z = 0) then RP_{50}* = 50 and no adjustment is made.

Table 9. Effect of Icing Event Threshold on the Calculation of 50-year Wind Speed During Icing for Winnipeg Richardson Int'l A

Icing Event Threshold (mm)	Number of Non-zero Years (N_n)	Number of Zero Years (N_z)	50-year Effective Return Period Adjusted for the Number of Zero Years (RP_{50}*)	50-year 10-minute wind speed (km/h)	Average Annual Maximum Radial Ice Thickness (mm)	50-year Transverse Load (N/m)	Transverse Load (N/m, calculated from the 50-year wind and average ice)	Average Annual Number of icing Events
0	55	0	50.0	84.5	4.1	14.5	12.3	5.0
1	39	16	35.5	82.5	5.6	15.1	12.8	2.0
2	32	23	29.1	81.6	6.4	15.4	13.1	1.5
3	25	30	22.7	82.1	7.5	15.8	14.0	1.3
4	22	33	20.0	81.8	8.1	16.0	14.3	1.09
5	15	40	13.6	75.8	9.8	15.7	13.3	1.07
6	11	44	10.0	74.5	11.4	15.9	13.8	1.0

As indicated in Table 9, as the icing event threshold increases, the number of zero years increases, the 50-year wind speed during icing decreases (owing to fewer events from which to select the annual maximum), the average annual maximum ice thickness increases, and the annual number of icing events (in years with qualifying events) decreases. The results for the threshold of 0 mm (i.e. all icing events are used) is the same as presented for Winnipeg in Table 8. The other cases in Table 9 present possible alternate versions of combination 2. As the icing threshold increases, the transverse load calculated from the 50-year wind and average ice remains roughly constant suggesting that the selection of the icing threshold is not critical. In fact the transverse load increases which is not a real physical effect but an artifact of how the return level calculation is performed. It appears that the mean and the standard deviation of the annual maximum wind speed increases with increasing icing threshold (indicating that stronger winds are associated with more significant icing events). This effect on balance contributes more to increasing the return level value than does applying the effective return period, RP_{50}*, to account for the years without qualifying icing events.

CSA (2010) in table CB.1 provides default values for distribution lines. The value in this CSA table is 60% of the reference wind speed (low probability) and 40% of the reference wind speed (high probability). For transmission systems CSA (2010) Section 6.4.4.1 (page 75) suggests a range of 60 to 85% of the reference speed for the low probability wind speed, and a range of 40 to 50% of the reference speed for the high probability wind speed.

Both Winnipeg and Portage have reference wind speeds of about 97 km/h. As indicated by the results in Table 8, for Winnipeg the low probability wind speed is 88% (85/97) of the reference speed, and the high probability wind speed is 59% (57/97). For Portage the corresponding numbers are 82% (79.3/97) and 56% (54.3/97). The same percentages can be obtained from Table 9 for Winnipeg from Table 9 for the various icing thresholds, but the wind speed corresponding to each threshold will be a smaller percentage of the reference speed (97 km/h) as the icing threshold increases.

Another general observation from both Table 8 and 9 is that the transverse load calculated from the 50-year wind speed and average ice thickness is consistently lower than the 50-year transverse load calculated directly by the return level equation from the annual maxima of transverse loads. This suggests that combination 2 may be an underestimate of the true combined effects of wind and ice (although the transverse load calculations performed are nominal and are only provided for comparison purposes).

The most appropriate values of wind and ice to use for combination 2 are not obvious from Tables 8 and 9. Table 9 does provide some alternate choices of higher average ice with lower 50-year wind than Table 8 (which does not reflect applying any icing event thresholds). It is interesting that the various 50-year wind and average ice values corresponding to the different icing thresholds result in similar transverse loads. Engineering considerations will assist in selecting the most appropriate set of values for combination 2.

6.0 Temperature and Wind Combinations

CSA (2010) (Section 6.2.4, pages 45-46) provides two requirements for checking wind and temperature combinations.

The first condition is the high (reference) wind speed in combination with the average daily minimum temperature.

The second condition is a reduced wind speed with a temperature associated with the reduced wind speed. The reduced wind speed required is specified as the reference wind speed multiplied by a coefficient chosen according to local meteorological conditions. In the absence of specific knowledge of this coefficient a value of 0.6 is suggested. The temperature to be associated with the reduced wind speed is the 50-year minimum temperature.

CSA (2010) Section 6.2.4 in the Canadian Deviations (page CSA 12) notes that short spans shall be verified for the combination of absolute minimum temperature. For this purpose, the exact definition of minimum temperature is not defined, nor how it should be used in determining the reduced wind speed. The same section states that the suggested reduced wind speed is 60% of the reference wind speed (or 80% when extreme high winds and cold temperatures are concurrent). However, the minimum temperature is defined as that provided in table CA.1. The minimum temperature in table CA.1 is the 1% January temperature (abstracted from the 2005 NBCC). It represents the temperature in January that occurs or is colder for 1% of the hours on average over the long term (i.e. 7.44 hours every January). This is approximately equal to the 0.4% annual cold temperature occurring on average about 35 h each year ASHRAE (1997).

To meet the requirements for these conditions, the following approach was taken.

First, the daily average minimum temperature is available by calculation from the hourly time series files obtained from EC for this project. EC also provides climatological statistics in the form of Canadian Climate Normals online at http://climate.weather.gc.ca/climate_normals/index_e.html. The monthly and annual daily minimum temperatures are available for many locations at this online link. One distinction is that the daily minimum temperature calculated from the hourly temperature observations will be on average about 0.5C less extreme than the daily minimum temperatures observed by a minimum temperature thermometer (the source of EC's minimum temperature records). This occurs because the minimum thermometer maintains a continuous reading of temperature and since the minimum temperature will almost always occur between hours, the true minimum temperature will always be slightly colder than the daily minimum of the temperatures observed once per hour at the top of the hour. As an example, the average daily minimum temperature for Winnipeg Richardson Int'l A, calculated from the hourly time series for the past 30 years is -2.2C, whereas the daily average minimum temperature from EC's online Climate Normals for the 1981-2010 period is -2.7C. Monthly and annual average daily minimum temperatures in Table 10 were abstracted for from the EC web site. All the locations in Table 10 represent an analysis from daily minimum temperatures from a minimum thermometer read manually every day, not the daily minimum of temperature observations each hour.

Table 10. Monthly and annual average daily minimum temperatures (C) for selected locations in southern Manitoba from EC Canadian Climate Normals 1981-2010.

Climate ID	Name and period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
5020040	Altona 1981-2007	-19.9	-16.8	-9.4	-0.9	5.9	12.0	14.3	12.9	7.2	0.2	-8.1	-16.1	-1.6
5020551	Carman 1990-2007	-20.5	-16.9	-9.9	-1.5	5.0	11.4	13.4	11.9	6.9	-0.1	-8.7	-16.0	-2.1
5021054	Glenlea 1981-2002	-22.6	-19.0	-11.1	-1.9	5.3	10.8	13.2	12.1	6.1	-0.8	-9.7	-19.1	-3.1
5021848	Morden CDA 1981-1998	-19.1	-15.1	-8.3	-0.9	6.0	11.8	14.3	13.2	7.7	1.0	-8.3	-16.2	-1.2
5022129	Pilot Mound 2 1987-2005	-20.2	-16.6	-10.1	-1.6	5.4	11.1	13.4	12.3	7.0	-0.3	-8.6	-16.1	-2.0
5022760	Sprague 1981-1998	-22.1	-18.2	-10.8	-2.9	4.1	9.8	12.2	10.9	5.6	-0.6	-9.8	-18.5	-3.4
5022780	Steinbach 1981-2005	-22.0	-18.1	-10.7	-2.6	4.2	9.8	12.5	11.4	6.0	-0.5	-9.3	-18.3	-3.1
5023222	Winnipeg Richardson Int'l A 1981-2007	-21.4	-18.3	-10.7	-2.0	4.5	10.7	13.5	12.1	6.4	-0.5	-9.2	-17.8	-2.7
5032162	Pinawa WNRE 1981-2007	-22.1	-19.0	-11.6	-2.5	4.6	10.3	13.2	12.0	6.7	0.4	-8.3	-17.6	-2.8

Next, the reduced wind speed was calculated by compiling the annual maximum series of wind speeds occurring during hours for which the temperature was than -33C or colder. The temperature threshold of -33C was selected since the CSA (2010) minimum temperatures for southern Manitoba listed in CSA (2010) Table CA.1 are generally between -33 and -35C. The 50-year wind speed corresponding to these conditions are provided in Table 11.

Table 11. Reduced wind speed associated with minimum temperatures for selected stations in southern Manitoba. 50-year wind speed is calculated for hours with temperature -33C or colder.							
Climate ID	Name	Elev(m)	Lat	Long	No. of Years	Most recent year	50-year 10-min wind speed (km/h) when temperature is -33C or colder
5010480	BRANDON A	409	49.91	-99.95	51	2012	48
5010547	CARBERRY CS	384	49.91	-99.36	19	2013	43
5012320	PORTAGE SOUTHPORT A	270	49.90	-98.27	28	1991	48
5012324	PORTAGE SOUTHPORT	273	49.90	-98.28	19	2013	38
5012440	RIVERS A	473	50.02	-100.32	17	1969	56
5012654	SHOAL LAKE CS	561	50.45	-100.60	19	2013	47
5013117	WASAGAMING	627	50.66	-99.94	19	2013	17
501A7AR	MELITA	446	49.28	-100.99	19	2013	36
5020882	EMERSON AUT	242	49.00	-97.24	11	2008	52
5021220	GRETNA (AUT)	253	49.03	-97.56	19	2013	52
5021849	MORDEN CDA CS	298	49.19	-98.08	13	2013	39
5022125	PILOT MOUND (AUT)	470	49.19	-98.90	17	2013	43
5022759	SPRAGUE	329	49.02	-95.60	19	2013	36
5023222	WINNIPEG RICHARDSON INT'L A	239	49.92	-97.23	48	2012	49
5023262	WINNIPEG THE FORKS	230	49.89	-97.13	14	2013	26
502I001	CARMAN U OF M CS	268	49.50	-98.03	18	2013	39
5032951	VICTORIA BEACH (AUT)	220	50.70	-96.57	16	2013	43
503B1ER	PINAWA	268	50.18	-96.06	18	2013	27
5040680	DAUPHIN A	305	51.10	-100.05	57	2009	59
5043158	MCCREARY	351	50.71	-99.53	16	2013	27
504K0NM	OAKPOINT MARINE	250	50.50	-98.04	16	2010	35

Finally, the temperature associated with the reduced wind speed is the 50-year return period minimum temperature, calculated by fitting the Gumbel distribution to the annual minimum series with the method of moments (Equation (1) accounts for whether the annual series is maximum or minimum). Results for selected southern Manitoba stations are provided in Table 12.

Table 12. Extreme minimum temperatures associated with reduced wind speeds, for selected locations in southern Manitoba.

Climate ID	Name	Elev(m)	Lat	Long	Minimum temperature (C) in period analyzed	No. of Years	50-year Minimum Temperature (C)
5010480	BRANDON A	409	49.91	-99.95	-45	51	-41
5010547	CARBERRY CS	384	49.91	-99.36	-43	19	-41
5012320	PORTAGE SOUTHPORT A	270	49.90	-98.27	-42	28	-39
5012324	PORTAGE SOUTHPORT	273	49.90	-98.28	-40	19	-37
5012440	RIVERS A	473	50.02	-100.32	-42	17	-41
5012654	SHOAL LAKE CS	561	50.45	-100.60	-44	19	-42
5013117	WASAGAMING	627	50.66	-99.94	-48	19	-45
501A7AR	MELITA	446	49.28	-100.99	-42	19	-40
5020882	EMERSON AUT	242	49.00	-97.24	-40	11	-40
5021220	GRETNA (AUT)	253	49.03	-97.56	-41	19	-39
5021849	MORDEN CDA CS	298	49.19	-98.08	-37	13	-36
5022125	PILOT MOUND (AUT)	470	49.19	-98.90	-39	17	-38
5022759	SPRAGUE	329	49.02	-95.60	-45	19	-44
5023222	WINNIPEG RICHARDSON INT'L A	239	49.92	-97.23	-45	48	-40
5023262	WINNIPEG THE FORKS	230	49.89	-97.13	-35	14	-35
502I001	CARMAN U OF M CS	268	49.50	-98.03	-41	18	-40
50309J6	FISHER BRANCH (AUT)	253	51.08	-97.55	-44	18	-42
5032951	VICTORIA BEACH (AUT)	220	50.70	-96.57	-39	16	-38
503B1ER	PINAWA	268	50.18	-96.06	-44	18	-43
5040680	DAUPHIN A	305	51.10	-100.05	-44	59	-41
504K0NM	OAKPOINT MARINE	250	50.50	-98.04	-41	16	-40

6.1 Results of Wind and Temperature Combinations

The daily minimum temperatures for selected stations are listed in Table 10. Annual average daily minimum temperatures range from -1.6C to -3.4C.

Table 11 provides reduced wind speeds for use with associated minimum temperatures. The wind speeds represent 50-year return period 10-minute average speeds selected only from hours at -33C or colder. This is considered to meet the requirement for determining the reduced wind speed consistent with the local climatic conditions. Calculated in this way the reduced wind speed is in the range of 40% to 50% of the reference wind speed. For instance, the Winnipeg and Portage reduced wind speeds are 48 and 49 km/h compared with the reference speed of 97 km/h. Gretna and Emerson are 52 km/h compared with 102 km/h reference speed. Other stations show generally lower fractions of the reference speed.

Calculated values of the 50-year minimum temperatures to represent the minimum temperature associated with the reduced wind speed are provided in Table 12. Most of these temperatures are in the range of -40C to -42C, especially for the stations with longer records. As expected, the minimum temperatures observed in the analysis period show more variation, ranging from -35C to -48C.

In summary, the first combination comprises the reference wind speed and the daily minimum temperature, either by month, or annually, in Table 9. For the second combination, 50% of the reference wind speed and an associated 50-year minimum temperature of -42C are recommended.

7.0 Extreme Weather Impacts on Twin Parallel Lines

7.1 Rate of Ice Accretion Due to Freezing Rain

Information on the rate of growth of ice accretion on conductors may have value for operational planning. To investigate this issue, the icing events with radial thickness greater than 5 mm for two locations, Winnipeg Richardson Int'l A and Portage Southport A, are presented in Table 13. For each event, the start date, the final radial ice thickness on the conductor, the number of hours of freezing precipitation, the duration between the first and last hour with freezing precipitation and the maximum and average hourly rate of ice accretion on the conductor are provided. The data is from the ice accretion modelling and analysis undertaken for this project and described in Section 3.0. Recall that only the daily total precipitation amounts are directly measured - all of the hourly amounts are estimated as part of the modelling scheme, not observed.

Table 13. Ice accretion rate on the conductor for icing events with final radial accretion > 5 mm at Winnipeg Richardson Int'l A and Portage Southport A.

Start Date	Number of hours with freezing precipitation	Elapsed time between first and last icing hour (h)	Event ice thickness (mm)	Maximum hourly icing rate (mm/h)	Average icing rate (mm/h)
Portage Southport A					
11/26/54	3	3	5.5	2.9	1.8
10/07/59	13	49	12.5	1.9	0.3
3/28/60	4	4	6.5	2.0	1.6
4/02/63	13	14	11.4	1.3	0.9
11/29/66	7	8	5.1	1.1	0.7
11/30/70	12	12	5.5	0.8	0.5
3/31/71	6	6	7.8	1.7	1.3
12/08/73	6	6	7.2	1.3	1.2
3/19/79	10	30	7.3	1.1	0.7
3/06/83	8	27	5.2	0.9	0.7

4/27/84	7	7	10.4	1.8	1.5
4/30/91	3	8	6.0	2.3	2.0
Winnipeg Richardson Int'l A					
11/05/55	6	6	6.5	1.1	1.1
2/26/58	5	42	5.4	1.5	0.1
11/16/58	17	25	5.0	0.5	0.2
10/08/59	16	23	10.7	1.5	0.5
4/02/63	15	21	9.2	1.9	0.4
11/29/66	4	4	8.1	2.3	2.0
11/13/73	7	7	5.5	1.1	0.8
12/08/73	7	7	5.2	1.1	0.7
3/19/79	19	20	5.8	1.0	0.3
11/08/80	2	2	6.1	3.2	3.0
3/06/83	13	25	12.2	2.4	0.5
4/27/84	4	4	9.2	4.0	2.3
3/07/89	4	5	7.7	2.3	1.5
10/28/91	10	10	20.5	3.9	2.0
4/05/97	7	10	22.5	3.9	2.2
1/02/07	1	1	5.3	5.3	5.3

There is considerable variation in the maximum rates and average rates in the events summarized in Table 13. However, the largest events, both at Winnipeg (20.5 and 22.5 mm), experienced average icing rates over teach event's 10-h duration of about 2 mm/h. This is likely a conservatively high estimate of an ice accretion rate scenario for an icing event with the prospect of damaging ice loads on a transmission line system. Significant icing events from freezing rain generally occur along a warm front with light rain caused by the ascent of a warm air mass along the frontal surface over the cold air at the surface. Typically, significant freezing rain events last several hours or even days. For instance, in the 1998 Ice Storm in eastern North America, the large ice accretion amounts of 40 to 50 mm or more occurred with intermittent light rain over 4 days or so. Larger short-duration amounts happen occasionally but are not generally sustained over long periods.

7.2 Impact of the Spatial Extent of Extreme Icing Events on Two Separate Transmission Lines

Icing events from freezing rain usually occur along a warm frontal surface in advance of a low pressure weather system. The area at any one time experiencing icing conditions is usually elliptical in shape and can extend several 10's of km along the frontal system (mostly west to east) and up to a few 10's of km across the frontal system (mostly north to south). At the same time the system is usually moving in an easterly or northeasterly direction. As a result, the total area experiencing ice accretion can extend over 100 km west to east and 40 km north to south. In this affected area the maximum ice accretion will be generally in an area near the middle or along the main west to east line.

Weather stations where the ice accretion amounts can be modelled, as was done for this project, are fairly widespread, and the highest ice accretion amount for an event will not generally occur at a weather station. Nonetheless, with many years of record, the results from weather stations are reliable indicators of the frequency of the amounts that will be experienced at a single point. Over the years, on average, the areas with the highest accretion amounts of each icing event will hit the weather station, or not, with the same frequency as other locations in the general vicinity of the weather station. So for individual structures such as towers or for a single point on a transmission line, the single station icing results are reasonable estimates of the probability of icing amounts.

However, the ice accretion annual exceedence probability that at any point along a transmission line will be higher than at any single point since the transmission line offers greater exposure to icing events than any given single point.

CSA (2010) provides a factor to deal with this effect. A combined factor of 1.5 comprises a height and a spatial factor. The height factor is 1.15 to account for the effect of the increase of height above ground from the standard anemometer height of 10 m to the assumed transmission line average conductor height of 30 m. The spatial factor of 1.30 accounts for the extending the single station reference ice thickness from a single point to a service area or along the length of a transmission line. The combined factor of 1.5 is a product of the height and spatial factor (1.15 x 1.30 = 1.5).

Jones (2004) investigated this effect with ice accretion modelling results from several weather stations in the U.S. and Canada and found the following factor, f_{si}, to account for the increase of the icing probability from a single point to any point along a line of length d (km):

$$f_{si} = 1.0 + 0.00117\, d \qquad \text{for } 0 < d < 600 \text{ km} \tag{4}$$

For a transmission line of length 150 km, f_{si} is 1.18. The CSA (2010) spatial factor 1.30 corresponds to a line of length about 250 km.

The spatial factor for ice does not directly address the issue of a single icing event impacting two nearby twin transmission lines. But the underlying characteristics of icing events from freezing (relatively uniform conditions over a large area) strongly suggest that if one line experiences a significant event, say close to the designed strength limits, then a point on a nearby line will likely experience similar conditions.

7.3 Impact of the Spatial Extent of Extreme Wind Events on Two Separate Transmission Lines

Extreme wind events generally occur as a result of either one of two weather systems. The first is large, organized mid-latitude low pressure weather systems (referred to as synoptic-scale systems) with associated frontal zones often extending hundreds of km and whose passage over a point can last several hours (similar to freezing rain events). The second weather system creating extreme winds are convective weather events such as severe thunderstorms and tornadoes. These are generally much smaller in size limited to a few km or in the case of some organized systems, 10’s of km. Convective systems are generally referred to as meso-scale systems.

Synoptic-scale winds result from the horizontal pressure gradients and extreme winds result from intense systems with high pressure gradients. The high winds occur generally in a uniform way across the weather system as it moves across a region and the peaks or highest gusts are sprinkled more or less randomly over the region affected by the system. As a result the highest winds are not generally as spatially organized as the maximum ice accretion areas with a freezing rain event.

Convective events are much more localized although the largest systems such as tornadoes or thunderstorm clusters often have path lengths several km long (see Section 7.4). The highest wind speeds observed at weather stations are generally mostly from synoptic-scale weather systems since convective systems are highly localized.

Jones (2004) investigated a spatial factor with respect to extreme winds. The analysis was probably dominated by synoptic-scale extreme winds at the weather stations used for the study. The resulting spatial factor for wind, f_{sw}, indicates a weaker effect of the length of the line on the increase relative to the extreme wind probability at a single point:

$$f_{sw} = 1.0 + 0.00027\, d \qquad \text{for } 0 < d < 600 \text{ km} \tag{5}$$

For instance, this spatial factor for wind results in a value of 1.04 for a line length of 150 km, compared with 1.18 for ice in Section 7.3 above. CSA (2010) does not require a spatial factor for wind as it does for extreme ice. The primary concern regarding extreme wind damaging both parallel lines during the same event arises from convective weather, addressed in the following section.

7.4 Impact of Tornadoes and Other Convective Events on Twin Parallel Transmission Lines

Tornadoes and other extreme convective weather events such as severe thunderstorms represent a significant risk to life and structures. The effects are localized compared to extreme wind speeds experienced by much more widespread synoptic-scale weather systems. Their extreme winds are rarely if ever observed by weather observing networks since they occur generally over small areas with little likelihood of impinging on a weather observing station. Although tornado tracks can be several km, even 10’s of km long, their width is less than a km or so, except for the largest, rarely occurring ones. In spite of tornadoes’ low probability of occurrence on any given point i.e. hitting a single structure, because of their often long track lengths there is a much higher probability of tornado path crossing a transmission line, or two parallel nearby transmission lines (some have described transmission lines as nets designed to snare tornadoes). For this project, the probability of tornadoes crossing a transmission line or twin lines was investigated and estimated.

Tornadoes are discrete events whose impacts are rarely measured directly by weather observing stations. Their occurrence is usually confirmed by direct sighting by members of the public, with subsequent inspection of the damage patterns. Sometimes supplementary evidence is available from weather satellite or radar images.

For some years tornado records have been compiled by EC for Canada and NOAA in the U.S. The first Canadian tornado database was developed by M. Newark at EC and described in Newark (1991) along with some general characteristics of tornadoes (the average translational speed of tornadoes is 55 km/h for instance). Work in this area was continued by others and a recent paper (Cheng et al. 2013) updated the description of the Canadian tornado database and tornado statistics for Canada.

The nature of the tornado databases includes specific information about each event including date, intensity, touchdown point, and path length and width. Not every entry in the Canadian tornado database contains information on all fields. Personal communication with David Sills at EC indicates that the Ontario entries in the Canadian database are currently the only ones with path length data, for instance.

Tornado intensity is described by the F (Fujita) scale and range from the weakest, F0, to the largest and most powerful, F5.

Brooks (2004) describes an approach in characterizing the length and width of tornado path lengths and width by fitting a 2-parameter Weibull distribution to the statistics of the path dimensions for each F scale. The Weibull distribution is often used to represent environmental data, and was used in this project for an analysis of tornado path lengths in southern Manitoba. The cumulative distribution function (CDF) gives the probability that the tornado path length L (km) is less than x, Pr (L<x) is:

$$\Pr(L < x) = 1 - \exp(-(x/\beta)^{\alpha}) \quad (6)$$

where α is the Weibull shape parameter (unitless) and β the scale parameter (km).

The mean of the Weibull function (i.e. mean path length), L_m (km), is given by:

$$L_m = \alpha\,\Gamma(1 + 1/\beta) \quad (7)$$

where Γ denotes the gamma function.

Table 14. Weibull shape (α) and scale (β) parameters for tornado path length, and relative frequency, by F scale.

	Brooks (2004) for the U.S.				Banik et al. (2007) for southern Ontario			
F scale	α	β	mean	Relative frequency	α	β*	mean	Relative frequency
0	0.65	0.9	1.2	40.22%	0.64	1.1	1.5	43.43%
1	0.62	3.1	4.5	35.35%	0.66	2.0	2.7	31.13%
2	0.64	7.5	10.4	18.35%	0.66	3.4	4.6	16.62%
3	0.83	20.4	22.5	4.81%	0.83	12.7	14.1	5.74%
4	1.01	43.9	43.7	1.15%	0.99	37.9	38.1	2.46%
5	1.2	57.7	54.3	0.12%	1.88	200.0	177.5	0.61%

*note that Banik et al. (2007) uses the reciprocal of scale length in calculations and that there appears to be a typographic error in the paper for the F5 scale factor. It is presented as 0.0005 km^{-1}, which is not reasonable nor in agreement with related data in the paper. The value is probably 0.005 km^{-1} (i.e. β = 200 km, not 2000 km). The Brooks (2004) parameters were used to represent F5 tornadoes, rather than assuming a corrected value from Banik et al. (2007).

Further to Brooks (2004) work for U.S. tornadoes, Banik et al. (2007) developed tornado hazard information on southern Ontario tornadoes using U.S. data from adjacent states in addition to Canadian tornado data. The Weibull parameters used for the tornado length distributions and relative frequency for each F scale are shown from both reports in Table 14.

The tornado path length exceedence probability values were calculated directly for each F scale using Equation (6) for a variety of tornado lengths from 1 to 150 km. Then the values for each F scale were weighted by the relative frequency and summed for each length, resulting the overall tornado CDF presented in Figure 9. The values from Banik (2007) were used for the results in Figure 9, with the assumption that the values developed for southern Ontario are likely more representative of southern Manitoba than those developed from the population of all U.S. tornadoes. As indicated, the Canadian database does not have sufficiently complete data to develop the same information based only on Manitoba tornadoes.

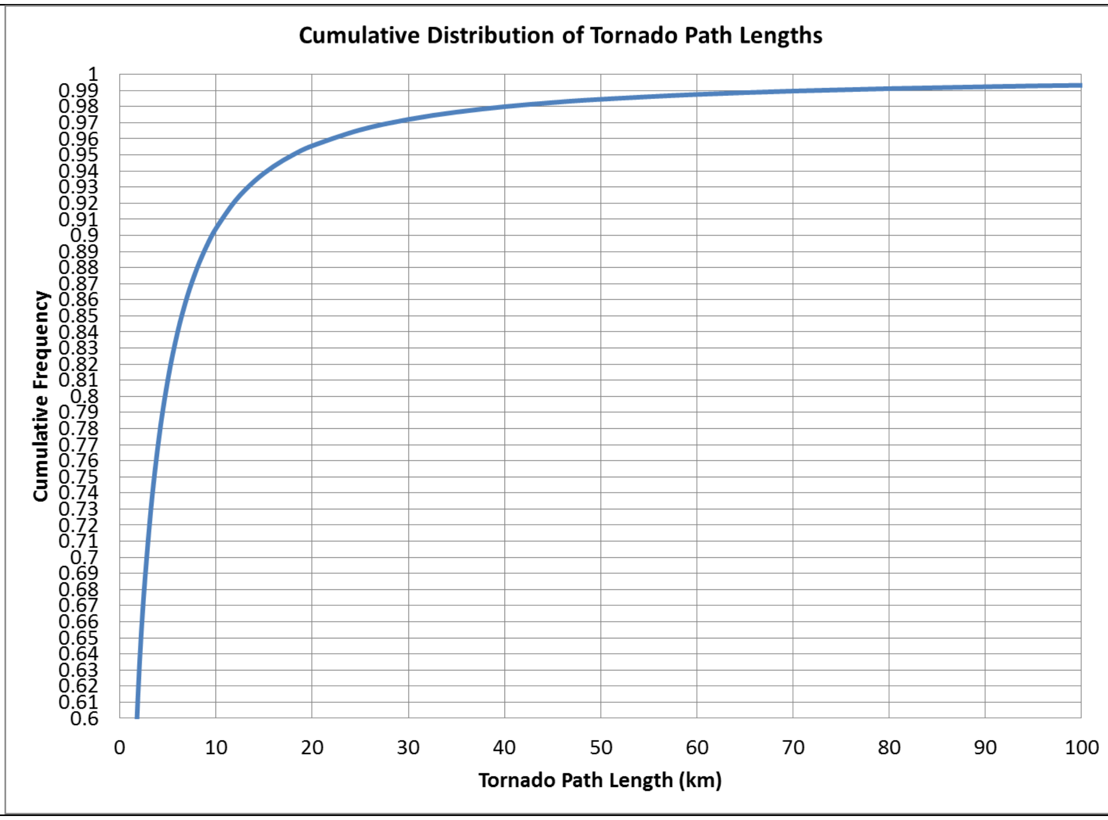

Figure 9. Cumulative distribution of tornado path lengths for southern Manitoba based on the tornado characteristics estimated by Banik et al. reflecting the contributions from each F scale.

Although of interest, the information in Figure 9 does not provide direct information on the probability that a tornado will cross a transmission line, or more to the point, cross one, then a second nearby parallel transmission line. To develop this more relevant information, a Monte Carlo approach was adopted based on the annual frequency of occurrence of tornadoes in southern Manitoba reported by

Cheng et al. (2013) of 2.0 tornadoes per 10,000 km^2. (Note that the map in Cheng et al. (2013) indicates that the annual frequency of tornadoes ranges from about 1.0 to 2.5 in southern Manitoba.)

The steps taken were:

- A physical domain was set up from -250 to +250 km in both the *x* and *y* (i.e. E-W and N-S) directions.
- Based on the annual occurrence of tornadoes of 2 tornadoes per 10,000 km^2 in southern Manitoba, 1,000,000 locations (centroids) for tornado paths were generated randomly over the 500x500 km (250,000 km^2) area representing the tornadoes that could occur in a 20,000-year period. 2 tornadoes per year per 100,000 km^2 leads to 2 x 250,000/10000= 50 tornadoes per year on average over the entire physical domain.
- For each tornado generated, an F scale, path length, and direction were drawn from the corresponding statistical properties of tornadoes assumed for southern Manitoba using Monte Carlo methods, and applied to the tornado path centroid generated in the step above.
- The position, orientation and path length of each of 1,000,000 tornadoes generated were then compared against (overlaid on) a set of twin parallel lines, 150 km long, with separation distances varying from 1 to 10 km, and for three directional orientations for the twin parallel lines of 90 (N-S), 135 degrees (NW-SE) and 180 degrees (W-E), as per the standard trigonometry circle with 0 degrees from the origin pointing east as positive, backing counter-clockwise with increasing values of the angle. The number of hits on each of the twin lines, and the transits (intersections) with both lines were recorded and further summarized.

The relative directional frequency used was taken from Banik et al. (2007) and is provided in Table 15.

Table 15. Relative direction frequencies of tornadoes from Banik et al. (2007)

Direction	Relative Frequency
N	0.042
NE	0.378
E	0.448
SE	0.108
S	0.008
SW	0.003
W	0.002
NW	0.011

The list of 1,000,000 tornadoes generated by this method was analyzed for the overall probability of path length and to almost exact agreement, reproduced the information in Figure 9.

Figure 10 provides an example plot of the track of every 500th tornado of the 1,000,000 generated.

Each tornado was checked for crossing either or both twin lines for the cases of line separation of 1 to 10 km and three line orientations: north to south (N-S), northwest to southeast (NW-SE) and west to east (W-E).

The frequency of occurrence expressed as a return period (the reciprocal of the annual probability of occurrence) are shown in Table 16 for separation distances from 0 to 10 km and line lengths from 25 to 150 km.

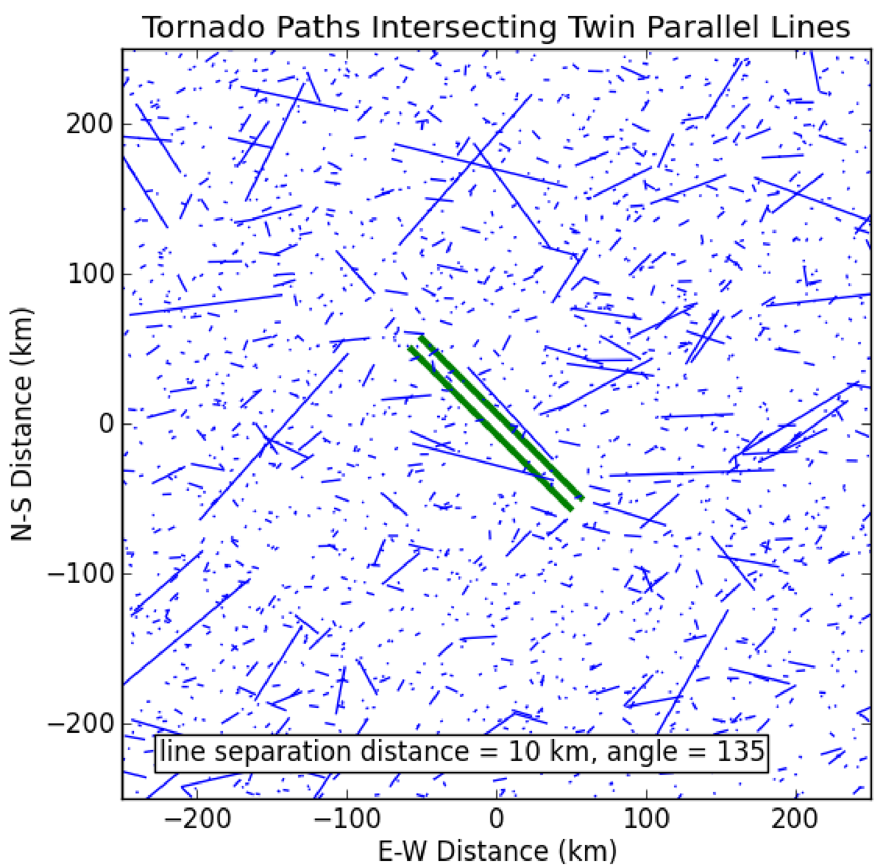

Figure 10. Tornado tracks of every 500th tornado of 1,000,000 simulated to represent 20,000 years at an annual tornado occurrence rate of 2 tornadoes per 10,000 km^2. Twin parallel lines are shown in green, 150 km long, separated by 10 km.

Another Monte Carlo run was made, further to those made for the twin lines, counting the tornadoes crossing 32 separate 1x1 km areas. The average number of hits on each 1x1 km area was 25.5 tornadoes (over the simulated 20,000 year period) implying that the return period of tornado occurrence for a single 1x1 km area is 784 years.

The results in Table 16 indicate that there is about a 10% probability of either N-S or NW-SW 150 km long twin line being hit by a tornado each year. The annual probability of both lines being crossed each year by the same tornado decreases from about 8% (1/12.5) at 1 km separation to about 3% at 10 km separation. The W-E line experiences fewer intersections since it is closer to parallel to the prevailing tornado track direction. The probability of a tornado hitting a single W-E line each year is about 6% (1/16) and decreases from 4.5% (1/22) at 1 km separation to about 1.75% (1/57) for 10 km separation.

Table 16. Return period (years) of simulated tornado path intersections with twin parallel transmission lines. Separation distance of 0 km corresponds to the occurrence of tornadoes crossing either of the twin lines (i.e. a single line).						
	Line Length (km)					
Separation (km)	25	50	75	100	125	150
N-S line						
0	63	31	20	15	12	10
1	78	39	24	18	14	12
1.5	87	42	26	20	16	13
2	95	46	28	22	17	14
3	106	52	32	24	19	16
4	122	59	36	27	22	18
5	134	64	39	29	23	20
6	152	70	43	32	26	21
7	163	74	45	34	27	23
8	177	79	49	37	29	24
9	190	85	53	39	32	26
10	202	88	55	41	33	28
NW-SE line						
0	68	32	21	16	13	11
1	87	39	26	20	16	13
1.5	93	43	29	22	17	14
2	101	45	31	23	18	15
3	112	51	34	26	21	17
4	133	57	38	29	23	19
5	153	65	43	32	26	21
6	177	72	48	36	28	23
7	192	77	51	39	31	25
8	220	85	56	42	33	26
9	250	93	60	46	36	29
10	282	104	64	49	38	30
W-E line						
0	93	47	32	24	19	16
1	127	65	43	32	25	22
1.5	145	73	48	36	29	24
2	167	82	53	39	31	26
3	204	97	61	44	35	30
4	247	113	71	50	40	34
5	294	133	84	56	45	37
6	345	148	94	63	50	41
7	385	167	103	70	56	46
8	455	189	112	76	59	49
9	556	217	124	85	65	53
10	588	230	133	90	68	57

The effect of the line length is roughly proportional for small separation distances. For instance, for a W-E line at 1 km separation, the return period for a 150 km line is 22 years and 43 years for a 75 km length

– about half the annual probability of occurrence for a line half as long. For greater separation distances, the effect of changing the line length creates a larger-than-proportional change in the annual probability.

Another relevant result is that the percentage of F2-F5 tornadoes that the N-S and NW-SE lines increases from about 73% at 1 km separation to 93% at 10 km separation. The overall percentage of F2-F5 tornadoes is about 25% (from Table 13) and their greater percentage of twin line hits results from the longer path lengths of these more intense and potentially damaging F2-F5 tornadoes.

The results in Table 16 are based on estimates of tornado characteristics reported in the literature. The assumed annual tornado frequency of occurrence for southern Manitoba is 2.0 tornadoes per 10,000 km^2. This is based on Cheng et al. (2013) which used an updated Canadian tornado database compared to a previous version used by Banik et al. (2007). The frequency of occurrence of tornadoes for southern Ontario increased from about 1 tornado per 10,000 km^2 in Banik et al. (2007) to 2.5 per 10,000 km^2 in Cheng et al. (2013). The increase according to David Sills at EC is due mostly to more vigilant of reporting of tornadoes in recent years due to increased public awareness and more convenient means of reporting (e.g. cell phones). Some of the increase is also due to corrections for population density and lightning occurrence (but this was not an important factor in southern Ontario). The number of tornadoes in southern Manitoba assumed for this report is similar to the number reported by NOAA for Minnesota, an adjacent state to the south (area = 225,181 km^2 and 45 tornadoes per year results in 2 tornadoes per 10,000 km^2) (http://www.ncdc.noaa.gov/climate-information/extreme-events/us-tornado-climatology).

The frequency of tornado information presented here should be compared with any related Manitoba Hydro information such as damage or outage reports to assess how it might be best used.

Finally, a significant wind event known as a derecho, a line of severe thunderstorms with severe downburst or straight line wind speeds often up to 160+ km/h. Durachos can persist continuously or nearly continuously for 400 km or farther with irregularly spaced episodes of higher wind speeds along the path. NOAA information (http://www.spc.noaa.gov/misc/AbtDerechos/derechofacts.htm#definition) indicates a frequency of about one derecho every 4 years in northern Minnesota. Similar, if slightly less frequent occurrences should be expected in southern Manitoba. The path lengths for derechos are significantly longer than most tornadoes but since high wind events arise from individual convective elements within the overall derecho structure, and dissipate and re-occur further along the line of the derecho, the path length of individual elements are not well known and thus estimates expressed in a similar fashion to those for tornadoes, above, are not currently available.

8.0 Frequency of Wind, Temperature and Solar Irradiance

Joint frequency information of wind, temperature and solar irradiance are useful to assist with line rating calculations. The approach to developing this information starts with compiling up-to-date files comprising weather elements including hourly values of dry-bulb temperature, wind speed and solar irradiance for locations representative of the study area. Environment Canada's CWEEDS (Canadian Weather Energy and Engineering Data Sets) files are suitable for this purpose.

CWEEDS files combine standard meteorological observations with solar irradiance observations (for the locations and periods it is available) mainly as required input for simulation of building and renewable energy systems. Most observing programs do not include solar irradiance, so a significant aspect of CWEEDS files is that hourly solar irradiance values are modelled where observations are not available (almost all locations). Solar irradiance is modelled from standard hourly meteorological observations (mainly cloud layers and sky conditions) and the earth-sun geometry. Existing CWEEDS files are publicly available from:
ftp://ftp.tor.ec.gc.ca/Pub/Engineering_Climate_Dataset/Canadian_Weather_Energy_Engineering_Dataset_CWEEDS_2005/ZIPPED%20FILES/ENGLISH/ , compiled from data up to 2005. Almost all of the solar irradiance data in these files is modelled as described above. Recently, in part with a view to updating CWEEDS files, Environment Canada and Natural Resources Canada acquired gridded solar irradiance estimates from the State University of New York (SUNY) derived from GOES geostationary satellite imagery. This SUNY hourly solar gridded data is now available for all of Canada south of 58N at 0.1 degree latitude and longitude (about 10 km) grid spacing. Terms of the arrangement NRCAN and EC have with SUNY includes a restriction that data for the most recent 2 years are not further distributed nor made publicly available. As a result Environment Canada now uses the SUNY data for the period 1998-2011 to incorporate into new or updated CWEEDS files south of 58N for the period 1998-2011. Since CWEEDS files represent a time series of hourly values of wind speed, temperature and solar irradiance, it is a straight forward matter to compile joint frequency of occurrence data for the three elements. The CWEEDS files generated for this project and a description of their content and format is provided on a DVD accompanying this report.

The procedures and software currently used by Environment Canada were used to compile CWEEDS files incorporating SUNY solar irradiance data for representative locations in the study area. The CWEEDS files were then used to compile joint frequency data.

Table 17. Locations for which CWEEDS files were compiled and joint frequency of occurrence information developed. The solar irradiance data from the SUNY grid points were incorporated into the CWEEDS files along with the hourly meteorological observations at the climate stations.

Location (Climate ID)	Latitude	Longitude	Elevation (m)	Period	Number of hours of non-missing data (percent complete)	SUNY grid point latitude	SUNY grid point longitude
WINNIPEG RICHARDSON INT'L A (5023222)	49.92	-97.23	239	1998-2011	122583 (99.89%)	49.95	-97.25
PORTAGE SOUTHPORT (5012324)	49.90	-98.20	273	1998-2011	121471 (98.99%)	49.95	-98.25
GRETNA (AUT) (5021220)	49.03	-97.56	253	1998-2011	119581 (97.45%)	49.05	-97.55
MORDEN CDA CS (5021849)	49.19	-98.08	298	2001-2011	95634 (99.20%)	49.15	-98.05
PILOT MOUND (AUT) (5022125)	49.19	-98.90	470	1998-2011	120625 (98.30%)	49.15	-98.95
SPRAGUE (5022759)	49.02	-95.60	329	1998-2011	120973 (98.58%)	49.05	-95.65
CARMAN U OF M CS (502I001)	49.50	-98.03	268	1998-2011	121639 (99.13%)	49.55	-98.05

The locations and periods for the CWEEDS files used in this project are provided in Table 17. The files combine the hourly observations at the Environment Canada stations with the hourly SUNY solar irradiance data from the nearest SUNY grid point (within 0.1 degrees latitude and longitude, or about 10 km). The number of non-missing data reflect the number of hours in the period for which the dry-bulb temperature, wind speed and solar irradiance values were all present in the file for the same hour and used in the joint frequency analysis. The solar irradiance element used in the analysis is the total solar radiation (diffuse plus direct beam components) incident on a horizontal surface.

The joint frequency analysis involved selecting bins of each value of temperature, wind speed and solar irradiance and compiling the counts of hours of occurrence for each combination of bins.

The bin intervals selected for the analysis were for each element are based in part on the overall range of values for the seven locations:

The solar irradiance bin centre points (bin width 100 w/m^2) are 0, 50, 150, 250, … , 850, 950.

The temperature bin centres (bin width 2C) are -49, -47, -45, -43, … , 39, 41, 43.

The wind speed bin centres (bin width 2 m/s) are 0, 1, 3, 5, … , 39, 41, 43.

The first bin for solar irradiance and wind speed are both values of zero, (i.e. with zero bin width, representing overnight hours for solar irradiance, and calm for wind speed).

Formatting the output of the analysis to allow easy visualizing of the 3-dimensional array is a challenge. For this study, the results are provided in a wind and temperature 2-dimensional table for each solar irradiance bin and a separate table of temperature and wind speed aggregated across all values of solar irradiance. Two measures of frequency are used – the total counts over the period and average number of hours per year – for each temperature-wind-solar bin. The results are provided in a spreadsheet file for each station, and accompany this report.

An example of relative frequency results is provided in Table 18. Due to space limitations, only a portion of the full table is presented.

An example of the frequency expressed as counts is provided in Table 19, which presents the counts of hourly occurrences of temperature and wind speed for the solar irradiance bin of >900 w/m^2 and <=1000 w/m^2, the highest solar irradiance bin. Due to space limitations, the temperature range is limited to greater than 0C and the wind speed to lower than 14 m/s, which happens in this case to include all of the hours with solar irradiance in this bin. The total of hours in Table 19 is 197, which represents all of the occurrences in 14 years at this location of solar irradiance values in this highest solar bin.

The frequency counts for each temperature, wind and solar bin is intended for transmission line rating calculations and the bin sizes were selected based on the assumption that a fair amount of granularity in values of these elements is required. There is other summarized information that can be developed and provided, if required, such as cumulative counts of relative frequency, mean values of one element coincident with the others, other bin sizes, and monthly, seasonal or time-of-day subtotals.

Table 18. Example of Frequency Table for Winnipeg Richardson Int'l A, aggregated over all solar irradiance values. The values are limited to the first few temperature and wind speed bins. Relative frequency is expressed as (h/yr). The shaded row displays the frequency of wind speed alone for the corresponding wind speed bin, summed across all of the temperature bins. The shaded column shows the subtotals for each temperature bin, across all wind speed bins.

			Wind lower bin value (m/s)	-1	0	2	4	6	8
			Wind upper bin value (m/s)	0	2	4	6	8	10
			Wind mid points (m/s)	0	1	3	5	7	9
T mid points (C)	T lower bin value (C)	T upper bin value (C)	T/W subtotals	203.7	1226.1	2208.5	2469.8	1491.8	754.1
-49	-50	-48	0	0	0	0	0	0	0
-47	-48	-46	0	0	0	0	0	0	0
-45	-46	-44	0	0	0	0	0	0	0
-43	-44	-42	0	0	0	0	0	0	0
-41	-42	-40	0.57	0	0.1	0.4	0	0	0
-39	-40	-38	1.93	0	0.5	0.9	0.6	0	0
-37	-38	-36	3.22	0.4	0.8	1.4	0.7	0	0
-35	-36	-34	6.79	0.4	1.8	2.9	1.2	0.5	0
-33	-34	-32	17.37	1.0	4.7	6.9	4.1	0.6	0
-31	-32	-30	34.02	1.4	7.5	13.2	10.6	1.2	0.1
-29	-30	-28	57.81	2.4	12.0	22.6	15.7	4.3	0.4
-27	-28	-26	76.61	2.5	15.8	27.7	22.1	5.3	2.0
-25	-26	-24	106.91	2.5	17.7	36.0	33.4	10.8	4.1
-23	-24	-22	131.78	4.4	22.1	36.0	42.9	16.1	7.5
-21	-22	-20	154.07	5.4	26.7	39.7	48.4	20.0	9.6

Table 19. Frequency data (counts) for the solar bin with midpoint 950 (w/m^2). Subtotals in the shaded row and column correspond to wind speed and temperature subtotals.

			Wind lower bin value (m/s)	-1	0	2	4	6	8	10	12
			Wind upper bin value (m/s)	0	2	4	6	8	10	12	14
			Wind mid points (m/s)	0	1	3	5	7	9	11	13
T mid points (C)	T lower bin value (C)	T upper bin value (C)	T/W subtotals	4	14	38	57	48	28	4	4
1	0	2	0	0	0	0	0	0	0	0	0
3	2	4	1	0	0	0	1	0	0	0	0
5	4	6	0	0	0	0	0	0	0	0	0

7	6	8	0	0	0	0	0	0	0	0	0
9	8	10	3	0	0	0	1	0	1	1	0
11	10	12	7	0	1	2	1	0	3	0	0
13	12	14	12	0	2	2	2	2	2	0	2
15	14	16	16	0	2	3	4	3	3	1	0
17	16	18	13	0	2	4	2	3	2	0	0
19	18	20	23	1	1	7	4	9	1	0	0
21	20	22	35	1	3	3	9	11	8	0	0
23	22	24	23	0	2	6	9	4	2	0	0
25	24	26	25	1	1	7	8	5	3	0	0
27	26	28	22	1	0	3	8	7	2	1	0
29	28	30	17	0	0	1	8	4	1	1	2
31	30	32	0	0	0	0	0	0	0	0	0
33	32	34	0	0	0	0	0	0	0	0	0
35	34	36	0	0	0	0	0	0	0	0	0
37	36	38	0	0	0	0	0	0	0	0	0
39	38	40	0	0	0	0	0	0	0	0	0
41	40	42	0	0	0	0	0	0	0	0	0
43	42	44	0	0	0	0	0	0	0	0	0

9.0 Summary

Climatic information relevant to transmission line design is provided for the study area in southern Manitoba covering the region south of Portage La Prairie, south to the U.S. Border and east to the Ontario border, including Winnipeg.

Recommended 50-year return period reference ice thickness values on a 25 mm conductor were developed by first applying the Chaîné ice accretion model to historical long-term 24/7 standard weather observations (made by human observers) at airport locations in southern Manitoba and adjacent southern Saskatchewan and Ontario. Icing events were defined to persist for each occurrence of freezing precipitation (rain or drizzle) until the air temperature rose to above 1C or until the end of continuous 168 hours with temperature below 1C. The annual maximum series of ice thickness values from each event was assembled at each weather station. The 50-year return period value ice thickness was calculated by fitting the Gumbel extreme value distribution to the annual maximum series by the method of moments (not the fitting method in CSA (2010) that takes explicit account of the number of years in the annual maximum series). The recommended values for the study area presented in Figure 2 range from 13.5 mm in western portions to 15.0 mm. These values are largely influenced by the results from Portage Southport A and Winnipeg Richardson Int'l A, the only two airport weather stations located within or on the boundary of the study area. These results are similar, if a little lower, that the values in CSA (2009, Figure CA.11). The reference ice thickness values represent ice accretion from freezing rain, and do not account for other forms of icing (frozen wet snow or in-cloud rime icing).

Recommended 50-year return period reference wind speed values were developed based on analysis of the long-term wind records at about a dozen weather observing stations in and near the study area. In addition to the stations with 24/7 standard human observations used for ice accretion modelling, the stations whose data was used included several stations, including autostations, with a limited observing elements and thereby unsuitable for ice accretion modelling, but nonetheless with hourly wind speed observations. Adjustments were made both for the station's surface roughness and the duration of the observations so that the annual maximum series at each location represents 10-minute maximum wind speeds at 10 m above ground, over flat, open terrain (CSA terrain category B). The 50-year return period values were calculated at each location by fitting the Gumbel distribution to the annual maximum series by the method of moments. The recommended 50-year reference wind speeds are presented in Figure 8 and range from 102 km/h in western portions to 85 km/h close to the Ontario border. This is similar to the values in CSA (2010, Figure CA.6) except a little higher in eastern portions where a value of 85 km/h is now indicated rather than 80 km/h. This is largely a result of more explicit accounting for surface roughness at observing sites so the results represent flat, open terrain.

For determining the loads resulting from wind on iced conductors, two combinations of ice and wind are specified nominally representing the 50-year wind-on-ice load: combination 1: 50-year ice thickness with the average of annual maximum wind speeds during icing; and combination 2: annual average maximum ice thickness with the 50-year return period wind during icing. These values were calculated for the two airport locations in the study area, Portage Southport A and Winnipeg Richardson Int'l A, and the results presented in Table 8. The 50-year transverse load and various ice and wind combinations resulting in the same transverse load are also presented for comparison.

Two conditions concerning the combinations of wind and temperature were investigated and recommendations developed for the study area. The first combination comprises the reference wind speed and the daily minimum temperature, either by month, or annually, with the results presented in Table 9. For the second combination, 50% of the reference wind speed and an associated 50-year minimum temperature of -42C are recommended. CSA (2010) is somewhat ambiguous regarding the minimum temperature value to use (January annual average 1% or 50-year return period minimum temperature – a subject for resolution with the CSA RBD technical committee).

A number of aspects of the impact of severe weather on the spatial extent of a transmission line or twin lines were investigated.

To help with operational planning a rate of 2 mm/h representing ice accretion thickness on a conductor during significant events is recommended.

CSA (2010) provides for the use of a spatial factor of 1.3 by which to increase the reference ice thickness (which represents a single point) to account for the probability of greater amounts of ice thickness occurring at any point within a service area or along a transmission line due to increased exposure to icing events. It was noted that work done by Jones (2004) suggests that a value of spatial factor of 1.3 corresponds to a transmission line length of about 250 km.

CSA (2010) does not require the use of a spatial factor for wind, and this is reflected in the much weaker spatial effect for wind, compared to ice thickness, noted by Jones (2004).

The probability of tornadoes impacting two parallel transmission lines of various separation distances was investigated. A Monte Carlo approach was taken to simulate the occurrence of tornadoes of strength ranging from F0 (weakest) to F5 (most intense) based on the probability of occurrence of tornadoes in southern Manitoba, probability of direction of travel, and the track length characteristics and relative frequency of each F scale. The information regarding tornado characteristics is taken from the literature and assumed to apply to southern Manitoba for the purpose of this study. It was estimated that the probability of a single transmission line (150 km in length, oriented N to S, or NW to SE) being hit by a tornado was about 9% and the annual probability of both of twin lines being hit by a tornado decreased from about 8% for a 1 km separation to about 3% when the line separation increased to 10 km. Corresponding probabilities for a W to E line, 150 km in length, is about 4.5% for 1 km separation and 1.75% for 10 km separation. As the line length decreases, the annual probability of occurrence decreases roughly proportionally for small line separations, and decreases more than proportionally for longer separations. As the separation distance increases the proportion of tornadoes that cross both lines that are F2 or stronger increases, reflecting the longer path lengths of more powerful tornadoes.

Hourly joint frequency statistics of dry-bulb temperature, wind speed and solar irradiance on a horizontal surface are provided for seven locations in or near the study area. The data is provided in spreadsheet files accompanying this report.

Some of the information provided in this report and accompanying files can be readily modified to different specifications, if required. For instance, tornado statistics can be calculated for different twin line lengths, separation distance or directional orientation. Similarly, for the temperature, wind speed and solar irradiance joint frequency data, requirements for different bin sizes or a file format adapted for use in software that deals with line rating analysis can be accommodated.

A DVD with a variety of the output files and a description of their contents and format accompanies this report.

References

ASHRAE. 1997. Handbook of Fundamentals. Chapter 26 (Climatic Design Information). American Association of Heating Refrigerating and Air-Conditioning Engineers. Atlanta, GA.

Atlas, D., Srivastava, R.C., and Sekhon, R.S. (1973) Doppler Radar Characteristics of Precipitation at Vertical Incidence. Reviews of Geophysics and Space Science, 849, 1-34

Banik, S.S., Hong, H.P., Kopp, G.A., 2007. Tornado hazard assessment for Southern Ontario. Can. J. Civil Eng. **34**, 809–842.

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

Brooks, H.E. 2004. On the relationship of tornado path length and width to intensity. Wea. Forecasting, **19**, 310–318.

CEATI (CEA Technologies Inc.) (Authors K.F. Jones and R. Morris). 2002. Investigation of the Differences in the Application of the Canadian and U.S. Methodology for Estimates of Ice Loads for a 50-yr Return Period. CEATI Report No.T003700-3306

CEATI International Inc. (Author R. Morris). 2009. Updating the Ice and Wind Load Design Information Used for Reliability Based Design in CSA 22.3 No.1-01, Report No. TO53700-3325A. July 2009.

CEATI Technologies Inc. (Author K. Jones). 2006. Extreme ice thicknesses and concurrent wind speeds in Canada along the U.S. border. 2006.

Chaîné, P.M., and G. Castonguay (1974) New approach to radial ice thickness concept applied to bundle-like conductors. Industrial Meteorology-Study IV, Environment Canada, Toronto.

Cheng, V.Y.S., Arhohditsis, G.B., Sills, D.M.L., Auld, H., Shephard, M.W., Gough, W.A.,Klaassen, J. 2013. Probability of Tornado Occurrence across Canada. J. Climate. DOI: 10.1175/JCLI-D-13-00093.1.

Coles, S., 2001. An Introduction to Statistical Modeling of Extreme Values, Springer-Verlag, London, 208 pp.

CSA. 2010. CAN/CSA Standard C22.3 No. 60826. *Design criteria of overhead transmission lines*. Canadian Standards Association, Mississauga, Ontario.

Deaves, D.M. 1981. Computations of wind flow over changes in surface roughness, J. Wind Engr. Indust. Aerodyn., **Vol. 7**, pp. 65-94.

Goodwin, E.J., Mozer, J.D., DiGioia, A.M., and B.A. Power (1981) Predicting Ice and Snow Loads for Transmission Line Design, *Proceedings of the First International Workshop on Atmospheric Icing of Structures*, Hanover, NH

Hosking, J.R.M. and J.R. Wallis. 1997. Regional frequency analysis. An approach based on L-moments. Cambridge University Press, Cambridge, UK, 224 pp.

Jones, K.F. 1998. A simple model for freezing rain ice loads. Atmospheric Research, **46**, 87- 97

Jones, K.F. 2004. Spatial factors for extreme ice and extreme wind: task 2 calculation of spatial factors from ice and wind data. CEATI Report T033700-3316B. CEA Technologies Inc. (CEATI), Montreal QC.

Newark, M.J., 1991. A design basis tornado. Can. J. Civil Eng. **18**, 521-524.

Lowery, M.D. and J. E. Nash, 1970, A Comparison of Methods of Fitting the Double Exponential Distribution, Journal of Hydrology, pp 259-275, **Vol 10**, No. 3

Rogers, R. R, and M.K. Yau (1989) A Short Course in Cloud Physics, Third Edition, Butterworth-Heineman, Woburn, MA, 290 p.

Stallabrass, J.R., and P.F. Hearty (1967) The icing of cylinders in conditions of simulated sea spray. Mechanical Engineering Report MD-50, National Research Council of Canada, Ottawa.

Taylor, P. A. and R.J. Lee. 1984. Simple guidelines for estimating wind speed variations due to small scale topographic features. *Climatological Bulletin*. **18(2)** 3-32.

Appendix A. Extreme Value Analysis

This appendix provides further background information to the description of extreme value analysis in Section 2.

Extreme value theory is concerned with the probability distributions that are suitable for fitting and estimating the probability of extreme events. The theory gives rise to a number of important results described by many authors including Coles (2001).

The distribution of the extreme values (maxima or minima) selected from blocks of long sequences of IID (independent, identically distributed) observations will asymptotically approach one of the traditional extreme value distributions known as Type I, II, or III as the number of observations in each block grows large. Collectively, these are widely known as Gumbel, Fréchet and Weibull families, respectively. All have location and scale parameters, and additionally the Fréchet and Weibull (not the 2-parameter Weibull distribution used to represent tornado path lengths in Section 7) families have a shape parameter. These three families can be formulated as the Generalized Extreme Value Distribution (GEV).

This is a powerful result, and in a sense is the extreme value analogue of the Central Limit Theorem used every day in regular statistical sampling and reporting for routine issues such as polling results on public issues. Regardless of the parent distribution of observations from which the block extremes are selected, the extremes will be GEV-distributed (for independent, identically distributed observations, as the block size becomes large). Also, for many physical elements having certain parent distributions of their regular hourly observations (e.g. exponential), such as wind speed, icing amounts, and rainfall, the theory suggests that the Gumbel distribution is the theoretical best fit to the block extremes (the parent distributions are in the domain of attraction of the Gumbel distribution). Thus the Gumbel distribution, fitted to the annual maximum series (the block extremes) is commonly used to calculate the frequency of extreme events. It is the preferred method to calculate return level values for wind and ice extremes in CSA (2010) for example (although it recognizes that the POT approach described below is used under certain circumstances when there are no or few icing events in some years).

Another result of extreme value theory is that the distribution of extremes above a suitably high threshold value will be described by the Generalized Pareto Distribution (GPD), also a 3-parameter distribution with location, scale, and shape parameters. Thus, one often sees extreme value results compiled as the result of the GPD fit to peaks over a threshold (often called peak-over-threshold or POT).

An issue with the use of the Gumbel distribution relates to the number of events from which the maximum value is selected for the annual maximum series. As noted above, extreme value theory requires the number of independent observations in the block segment (i.e. year) to be large. For some elements such as ice accretion amounts this is a difficult condition to meet. For instance the average number of icing events per year at Winnipeg Richardson Int'l A is just over five events per winter season. Coles (2001) recommends in general the use of the GEV distribution with block maxima. The data will suggest the best fit if the conditions required by the theory do not apply. CSA (2010) specifies the use of the Gumbel distribution. Figure A-1 shows the fit of both the Gumbel and GEV distributions to the annual maximum series of ice accretion amounts at Winnipeg Richardson Int'l A. Figure A-2 has the fit of the both the Gumbel and GEV fit to the ice accretion amounts at Portage Southport A. At Winnipeg there is considerable difference between the 50-year ice thickness from the Gumbel and GEV distributions. There is far less difference for Portage Southport A.

The Gumbel distribution is fitted with the method of moments to the annual maximum series. The return level equation, following Lowery and Nash (I1070), for this method is given by:

$$X(T) = X_m - j\,\frac{\sqrt{6}}{\pi}\left(0.5772 + \ln\ln\left(\frac{T}{T-1}\right)\right)X_{sd} \quad \text{(A-1)}$$

Where $X(T)$ is the T-year return period estimate of X, in this case, ice thickness, T is the return period, and X_m and X_{sd} are the mean and standard deviation of the annual maximum series of ice thickness.

The GEV distribution in Figures A-1 and A-2 is fitted by the method of L-moments (linear combinations of probability weighted moments) as per Hosking and Wallis (1995). It is a 3-parameter distribution that reverts to the Gumbel distribution in the limit as the GEV shape parameter goes to zero. The equations are not provided here. They are available in Coles (2001) and other references. In Figures A-1 and A-2 the GEV fit, owing to its third shape parameter, in some cases appears to fit the annual maximum data more closely. This may be due to the relatively few events per year resulting in the Gumbel distribution resulting in a biased fit, or due to natural sampling uncertainty.

The 95% confidence interval for the Gumbel distribution, further to Lowery and Nash (1970), represents the sampling uncertainty related to the use of data samples which represent only a small portion of the entire "population of events". Consider for instance, a time series of 100 years of annual maximum ice thickness of wind speed. Each 20-year portion of the time series could be used separately to estimate a given return level. Comparing across 20-year periods there would be differences amongst calculated return levels, due to the stochastic nature of extreme events. This variation is expressed as a confidence interval, which represents the statistical uncertainty of a return level, assuming the correct distribution is used to represent the population. The 95% confidence level is constructed so that, in repeated sampling, it covers the true, population return level for 95% of the samples (e.g., for 19 samples in 20). Alternately for one sample in 20, the true return level is outside of the sample's confidence interval. It is important to emphasize that confidence limits only reflect the statistical uncertainty related to sampling bias corresponding to the distribution and fitting method. They do not account for other uncertainties related to observational or modelling errors and uncertainties, non-stationarity of the data (e.g., trends or cycles in the annual maxima), or the use of incorrect extreme value distributions.

Confidence limits are generally wider, indicating more uncertainty for shorter periods of record, more variability in the annual maximum series (i.e. higher values if X_{sd}) and higher return periods.

The GEV and Gumbel distribution usually result in similar 50-year values of the fitted elements, but it is clear from Figure A-1 that higher return values need to be considered carefully since the GEV fit can produce significantly different results as its fit diverges from the Gumbel fit for higher return periods.

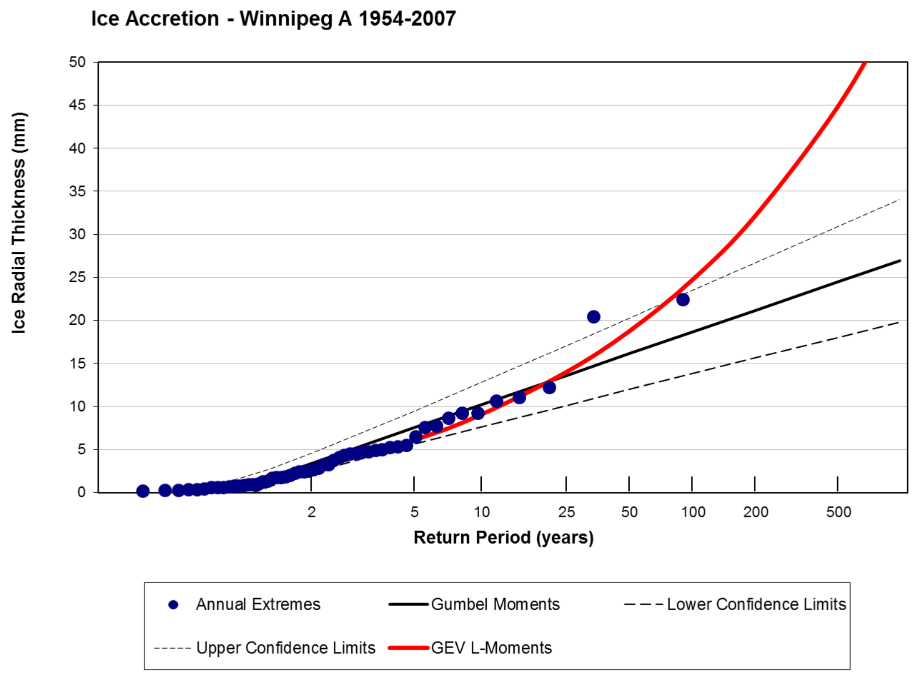

Figure A-1. Extreme value plots of the Gumbel and GEV extreme value distribution fitted to the annual maximum series of radial ice thickness values for Winnipeg Richardson Int'l A.

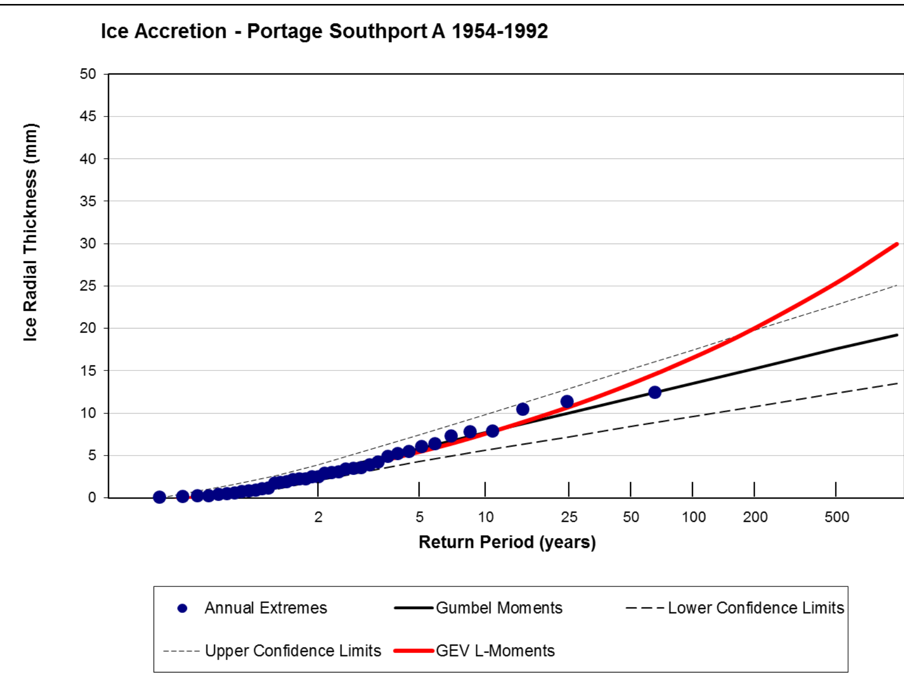

Figure A-2. Extreme value plots of the Gumbel and GEV extreme value distribution fitted to the annual maximum series of radial ice thickness values for Portage Southport A.

Appendix B. Ice Accretion Models

Three ice accretion models were implemented for this project.

The Chaîné model equation (Chaîné and Castonguay, 1974) is:

$$\Delta R = -r + \left[r^2 + \frac{K\,r}{2}\left(t_h^2 + t_v^2\right)^{1/2}\right]^{1/2} \tag{B-1}$$

where ΔR is the incremental change in ice thickness (mm), r (mm) is the radius of the cylinder at the start of the hour including ice already on the conductor, K is a correction factor (a function of T and V, wind speed), t_h is the hourly freezing precipitation (on a horizontal surface), and t_v is the hourly accretion on a vertical surface (mm) and is given in the original units by:

$$t_v = 0.078\,V\,P^{\,0.88} \tag{B-2}$$

where V is the wind speed (mph) and P is the freezing precipitation rate (in/h). P is the same value as t_h, the hourly freezing precipitation amount.

The correction factor from Chaîné and Castonguay (1974), based on wind tunnel icing results reported by Stallabrass and Hearty (1967), is adapted in a software routine from Figure B-1.

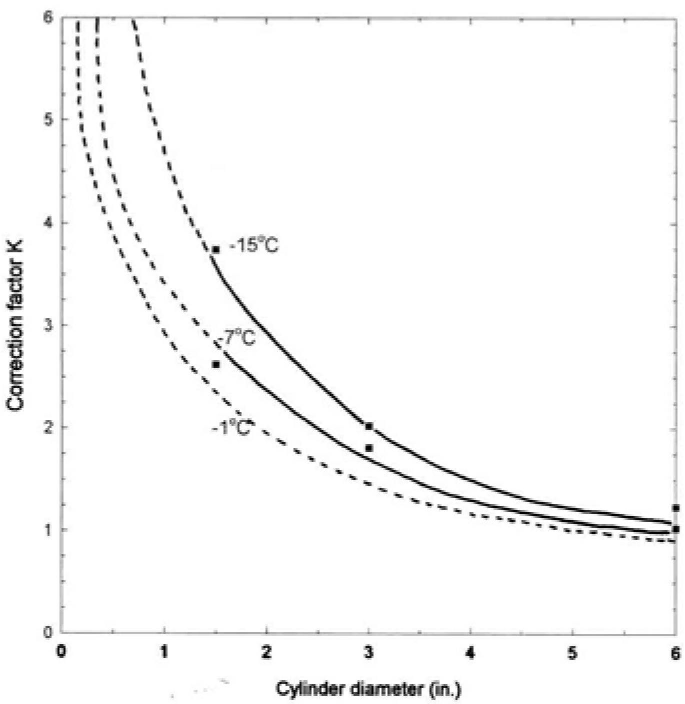

Figure B-1. Correction factor used with the Chaîné ice accretion model. The dashed lines indicate extrapolated values outside of the range of the original Stallabrass and Hearty (1967) icing wind tunnel results.

Two other ice accretion models were implemented. Both the Goodwin and CRREL models assume that the freezing precipitation occurring each hour is intercepted by and is distributed evenly around the conductor.

The Goodwin model (Goodwin et al., 1981) equation is:

$$\Delta R = \frac{P}{\rho\pi}\sqrt{1 + \left({}^{V_w}/_{V_t}\right)^2} \quad \text{B-3}$$

where ΔR is the incremental change in ice thickness (mm), P is the hourly freezing precipitation (mm), ρ is the specific gravity of ice (i.e. 0.9), V_w is the horizontal wind speed (m/s), and V_t is the terminal drop velocity (m/s).

The following expressions were used for V_t from Rogers and Yau (1989):

$$\begin{aligned} V_t &= 201\,(r_0/1000)^{-(1/2)} && \text{for } 0.6 < r_0 < 2.0\text{ mm} \\ V_t &= 8\ \ r_0 && \text{for } r_0 < 0.6\text{ mm} \end{aligned} \quad \text{B-4}$$

where r_0 (m) is the median rain drop size. The median drop diameter, d_0 (mm) is given by following Atlas et al. (1973) using the Marshall-Palmer drop size distribution:

$$d_0 = 3.67/(4.1P^{-0.21}) \quad \text{B-5}$$

where P (mm) is the hourly freezing precipitation amount.

The CRREL simple model (CEATI, 2001) equation is:

$$\Delta R = \frac{1}{\rho_i\,\pi}\sqrt{(P\rho_0)^2 + (3.6\,V\,W)^2} \quad \text{B-6}$$

where ρ_i is the density of ice, ρ_0 is the density of water, P is the freezing precipitation (mm), V is the wind speed in m/s, and W is the liquid water content of rain filled air given by the Best (1949) equation:

$$W = 0.067P^{0.846} \quad \text{B-7}$$

where P is hourly freezing rain amount in mm (equivalent to rate in mm/h).

Jones (1998) reports that the CRREL simple model (which is based on the Best drop size distribution) gives up to 9% more ice accretion than when using the Marshall-Palmer distribution, which provides a higher liquid water content than Best for a given precipitation rate (through a lower drop terminal fall speed). The Marshall-Palmer distribution better describes precipitation from stratiform cloud (not convective) which is generally more representative of freezing rain conditions. The implementation of the Goodwin and CRREL simple models for this project is consistent with difference noted by Jones (1998). The Goodwin model results in consistently higher ice accretion amounts than the CRREL simple model. Also, the Chaîné model results in higher ice accretion amounts than either the Goodwin or CRREL simple models. This is well known and reported in many of the references, especially Jones (1998) and CEATI (2002).

As a typical example, the average of the 10 highest icing event accretion amounts from Winnipeg Richardson Int'l A was 11.9 mm for the Chaîné model, 7.4 mm for the Goodwin model and 6.5 mm for the CRREL simple model.

All models require estimates of the hourly freezing precipitation which is provided by prorating the daily total precipitation amount for each precipitation type that occurs each hour, weighted by a nominal rate characteristic of each type and intensity observed.

The weights used for each precipitation type and intensity observed each hour is presented in Table B.1 below.

Table B.1. Weightings used to estimate hourly freezing precipitation rates

Precipitation Intensity	***R***	***RW***	***L***	***ZR***	***ZL***	***S***	***SG***	***IC***	***IP***	***IPW***	***SW***	***SP***	***A***
Light	1.8	1.8	0.1	1.8	0.1	0.6	0.6	0.0	1.8	1.8	0.6	0.6	1.8
Moderate	5.1	5.1	0.3	5.1*	0.3	1.3	1.3	0.0	5.1	5.1	1.3	1.3	5.1
Heavy	13.0	13.0	0.8	13.0	0.8	2.5	2.5	0.0	13.0	13.0	2.5	2.5	13.0

Rain – R
Rain shower – RW
Drizzle – L
Freezing rain – ZR
Freezing drizzle – ZL
Snow – S
Snow grains – SG
Ice crystals – IC
Ice pellets – IP
Ice pellet shower – IPW
Snow shower – SW
Snow pellet – SP
Hail – A

For example, if 25 mm of precipitation occurs in a 24-hour period, and there are two hours of light freezing rain, two hours of light freezing rain mixed with light ice pellets, and two hours of moderate snow, then the accumulated weightings for each type is 4 hours × 1.8 = 7.2 for light freezing rain, 2 hours × 1.8 = 3.6 for light ice pellets, and 2 hours × 1.3 = 2.6 for moderate snow. The total of all weightings is 13.4. The precipitation rate for each of the 4 hours with light freezing rain is then 25 mm × 1.8/13.4 = 3.4 mm/hr. Note that each weather type is weighted independently of any other weather type that occurs during the same hour.

**Note that the EC ice accretion modelling system used a value of 4.0 (not 5.1) to weight moderate freezing rain in developing the information for CEATI(2009) and CSA(2010). The reason for this value in the EC model is not known and is not supported by related information, including earlier documentation. The value of 5.1 as noted in Table B.1 was used with the ice accretion models for this project. This results in occasional (since occurrences of moderate freezing rain is relatively infrequent) slight differences in the EC and icing amounts used in this project.*