Prediction of icing events using NARR data

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***Abstract*—In Québec, Canada, the wind energy industry is growing rapidly, and with it the need for more information on atmospheric icing climatology and icing effects on wind turbines. Therefore, a method to estimate the annual mean number of icing events at any site in Québec was developed using numerical NARR data with 32 km resolution. With this data, different parameter combinations were tested and compared to four years of atmospheric icing measurements at six different airports in the province. The parameter combination involving temperature, a freezing rain forecast, and a relative humidity equal to or greater than 97 % gave the best results for the combination of performance criteria chosen. The method correctly predicts 56 % of the total actual icing events, it represents equally well each of the six sites, and the monthly distribution of predicted icing hours is similar to that observed.**

I. Introduction

AROUND the world, a growing number of wind turbines are installed in cold climates [1]. In the Canadian province of Québec, where cold climate conditions prevail for most of the territory, the wind energy industry is growing rapidly. In 2003, the Québec government issued a 1000 MW request for proposals, followed by a second one of 2000 MW in 2005 [2]. Icing climatology and icing effects on turbine operation are therefore of interest for Québec wind energy development. At the moment, most climatological icing studies done for Canada focus on precipitation icing only, and are done with unevenly spaced data [3-5]. This poses two problems for the wind energy industry. First of all, not only precipitation icing, but also in-cloud icing, can diminish wind energy production [6]. Secondly, there are interpolation and/or extrapolation challenges when dealing with sites far from weather stations. Consequently, this paper proposes a new method for estimating the number of icing events using the seamless data of the North American Regional Reanalysis (NARR). This method can estimate the mean annual number of icing events or icing hours for any site in the province of Québec from the 27 years of NARR data available.

II. Previous Studies

There are a number of ways to predict icing events from routine meteorological observations and numerical data. In general, the objective is to identify the presence of supercooled clouds (clouds composed of below freezing liquid droplets). As cloud formation is due to the condensation of water vapor at saturation [7], it is common to predict icing events by detecting the occurrences of high relative humidity with subfreezing air temperatures. This is supported, for example, by measurements of Farzaneh and Savadjiev [8] at Mont-Bélair, where, for the measurement period, both in-cloud icing and precipitation icing occurred at relative humidity values near 100 % and at negative air temperatures. This method has been studied to predict icing events with data from a wind turbine park in Finland [9]. In addition, it has been applied to the output of meteorological models to forecast aircraft icing by Schultz and Politovich [10] in 1992. More recently, LeBot and Lassegues [11] applied it to two different meteorological model outputs in order to identify areas most prone to aircraft icing.

When more detailed meteorological information is available, other options include the use of cloud base height and temperature. This method has been studied or used by Makkonen and Ahti [12], Sundin and Makkonen [13], Tallhaug [14], and for the European icing atlas [15]. Visibility can also provide information on the presence or absence of clouds or fog and was used, with cloud base height, for the European icing atlas [15].

Finally, information on liquid water content can also be considered. Liquid water content expresses the mass of liquid water in a given volume of air and is often referred to when speaking of atmospheric icing. It can be useful for predicting icing events or estimating icing intensity, and is an input parameter for some ice accretion models [16, 17].

III. Data

To develop an icing event identification method, and to use this method to estimate the annual mean number of icing events, meteorological data with certain characteristics were sought. It was important to have a spatial resolution fine enough to avoid uncertain interpolations. It was also considered useful to have access to a large number of meteorological parameters. Finally, since the frequency of icing can vary significantly from year to year [18], it was crucial to obtain data spanning a long time period, 30 years if possible, as recommended by the World Meteorological Organization (WMO) for climatological analysis [19].

The datasets retained are the NARR data for development of the method and the METAR (METeorological Airport Report) data for its validation. The following is a description of these datasets.

A. NARR Dataset

As specified by the name, North American Regional Reanalysis (NARR) data are *reanalysis* data, and come from numerical weather forecast models. The forecast models assimilate all available weather observations (from weather stations, airport stations, radars, radiosondes, pilot reports, etc.) to compute *analysis* data, which are three-dimensional representations of the atmosphere as accurate as possible at the given time [11]. Based on this representation of the atmosphere, the model can go on to forecasting. Because the numerical weather forecast models evolve in time and because new data sources are integrated, the analysis data also evolve in time [11]. It is therefore useful to reanalyze many years of weather observations with a fixed model in order to obtain a homogeneous database representing the states of the atmosphere over a long period [11]. This is called *reanalysis* data.

The National Center for Environmental Prediction (NCEP) in the US has developed the NARR System, based on the 2003 version of the operational Eta Model to generate the NARR data from 1979 until mid 2007 [20]. The database is updated on a regular basis [20]. The model has a temporal resolution of three hours and a spatial resolution of 32 km horizontally and of 45 pressure levels vertically [20].

This dataset was chosen for its relatively good spatial resolution, because it spans nearly 30 years, and because it offers a wide range of parameters usable for predicting icing events: temperature, relative humidity, visibility, cloud base height, cloud water, and a three hour freezing rain forecast. Cloud water, the mass of water per kilogram of air, has been converted to liquid water content by multiplying by air density. The data manipulations and treatments in this paper use this calculated liquid water content value.

B. METAR Dataset

A dataset with direct icing measurements was needed to validate the method developed with the NARR data. The METAR data indicate events of precipitation icing, which include freezing rain or freezing drizzle, and events of in-cloud icing, which correspond to freezing fog events. Four years of data (2000-2003) from six airports in the province of Québec were selected: two in-land sites (Chibougamau and Bagotville), two coastal sites (Gaspé and Mont-Joli) and two sites near urban centers (Québec and Mirabel). The data were treated to extract all information pertaining to icing. The validation of the method is based on 480 precipitation icing events and 131 in-cloud icing events for the selected time period. Tab. I gives the total number of precipitation icing events and in-cloud icing events for each station. In-cloud icing events represent between ten and 43 % of the total icing events.

It is important to point out that although it is icing at the wind turbine hub height that is of most interest to the wind energy industry, the method presented here can only be validated at the airport data level, which is within the first few meters above ground.

TABLE I: PRECIPITATION ICING AND IN-CLOUD ICING EVENTS PER STATION

Station name	Precipitation icing events	In-cloud icing events
Gaspé	39	30
Mont-Joli	50	15
Québec	88	20
Chibougamau	110	12
Mirabel	117	18
Bagotville	76	36

C. Preliminary Data Treatment

Some preliminary data treatment was necessary before developing the icing event detection method. The data treatments primarily focus on the temporal and spatial resolution of the different datasets.

Due to the different temporal resolution of the datasets, the coincident time periods (every three hours) were retained for data comparison. Icing events from the METAR dataset having occurred in the two hours preceding the coincident time step were retained as icing at the coincident time step. An indication of icing at any three hour time step was considered to represent an icing event lasting three hours.

Geographically, the NARR grid points and METAR station coordinates do not coincide. Thus, the NARR information was interpolated using a weighted average of the four closest NARR grid points. The weight applied to each grid point value was a function of its distance from the station point.

As for the data height, the NARR pressure, temperature, humidity and visibility are available at fixed heights above ground, and comparisons with the METAR data were done at either the two meter level or at the surface. However, cloud water is only available at the pressure levels, which vary in height. For this reason, the cloud water values (and the air density values for conversion to liquid water content) were always taken from the closest pressure level above ground.

Before proceeding to icing event detection, scatter plots between certain variables of the two datasets were prepared to show how the experimental METAR data compares to the numerical NARR data. Fig.1, on the next page, presents the relationship between experimental and numerical data for temperature at Mirabel airport and the dew point correlation for the Bagotville airport. The numerical and experimental data correlate well in these graphs and the results are similar for all stations. The correlation coefficients vary from 0.94 to 0.98.

Finally, for the time period considered, some data files were incomplete. There were some short periods of missing data in both datasets. For the NARR dataset, this amounted to 0.56 % of missing data, compared to 1.38 % for the METAR dataset.

IV. DEVELOPMENT OF THE ICING EVENT DETECTION METHOD

Given the various parameters of the NARR dataset, it was decided to start by testing the performance of simple two-parameter methods (for example temperature and relative humidity) and to evolve towards three-parameter methods. Since the objective of this study is to develop a global approach to icing event detection, the first analysis is done using the four years of available data and the results are averaged for all six stations. The second analysis will look at how well the best global method models each station individually. Finally, a third analysis will look at how the monthly variations in the number of icing hours are reproduced.

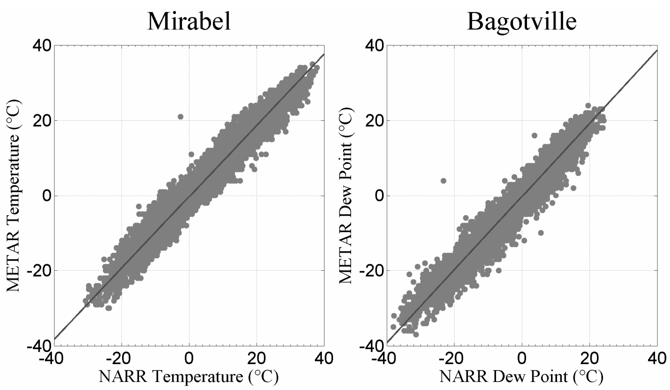

Fig. 1 Temperature scatter plot for Mirabel airport and dew point scatter plot for Bagotville airport.

A. Performance Indicators

To measure the performance of the methods tested, two key criteria were chosen. Since the research is meant to provide the wind energy industry with a clearer idea of the impacts of icing on wind energy production, the first key criterion is expressed in terms of annual wind energy production and is here referred to as the error in annual energy production (ERR_{aep}). Equation (1) expresses, as a percent, the difference in available wind energy production between predicted and actual icing events, divided by the total annual energy production.

$$ERR_{aep} = 100 \cdot \frac{\sum_{i}^{N_i} \rho_i u_i^3 - \sum_{j}^{N_j} \rho_j u_j^3}{\sum_{k}^{N_k} \rho_k u_k^3} \tag{1}$$

In (1), N_i are the number of predicted NARR icing events, N_j the number of actual icing events, N_k the total annual number of observations from the NARR dataset (icing and non-icing), u the wind speed, and ρ the air density. When the wind energy production during the actual icing events equals the wind energy production during the predicted icing events, the ERR_{aep} is zero and the icing estimation method is considered adequate.

It is important to mention that, in the ERR_{aep} equation, no loss factor from icing is considered because loss estimations are beyond the scope of the present paper. In the same way, persistence (the length of time for which icing remains on the wind turbine once the atmospheric icing conditions are over) is ignored. The ERR_{aep} is therefore meant only as a guidance tool in the choice of the most appropriate icing event detection method for the wind turbine industry. It does not provide direct information on potential energy losses due to icing.

The second criterion was chosen to measure the performance of the method in terms of predicting an event at the right time. One of the methods of verifying a dichotomous forecast is the critical success index (CSI), used, for example, in aircraft icing forecasts [21]. This index, shown in (2), takes into account the number of correct predictions (hits, *H*), the number of events that are not predicted (misses, *M*), and the number of falsely predicted events (false alarms, *F*). The perfect CSI score is one, which happens when both *M* and *F* are zero. When either *M* or *F* increases, the index approaches zero.

$$CSI = \frac{H}{H + M + F} \tag{2}$$

It was considered that the nature of the present study did not require a strict time correlation; as a result, a hit was defined as a real event for which an estimated event was detected in either the 12 hours preceding or the 12 hours following the real event. Similarly, a false alarm was defined as a predicted event for which no real event could be found in the preceding or following 12 hours.

The CSI and the ERR_{aep} were the two main parameters chosen to evaluate the methods, but for a better comprehension of the results, other indices and values were also calculated and are discussed. These include probability of detection (POD) which is the number of hits on the number of actual icing events, and the false alarm rate (FAR), expressing the number of false predictions on the total number of predictions. These indices vary from zero to one, and an ideal prediction will give a POD of one and FAR of zero. Finally, the difference in the number of predicted and actual icing hours (D_h) was also calculated. The miss ratio, which is the number of missed events on the total number of actual icing events, is not presented here, but is the complement of the POD (miss ratio = 1 – POD).

B. Two-Parameter Methods

The first methods for predicting icing events from the NARR dataset included two parameters of which one was always the temperature. The temperature limits were set at zero and -20°C as in [10] because supercooled liquid water has rarely been observed at temperatures below -20°C. The other parameters are relative humidity, cloud height, visibility, liquid water content and the freezing rain forecast. A range of parameter values were tested for each combination. For example, the temperature and relative humidity method was tested for a relative humidity greater than or equal to 90 %, greater than or equal to 91 %, and so on by steps of one percent up to 100 %. Tab. II presents the information for all parameter variations.

For each method, the parameter values at which maximum

CSI and minimum ERR_{aep} were reached were isolated. The results for maximum CSI are shown in Tab. III and the results for minimum ERR_{aep} are shown in Tab. IV.

TABLE II: PARAMETER LIMIT VARIATIONS

Paramter	Varies from:	Until:	In steps of:
Relative humidity	90 %	100 %	1 %
Cloud height	0 m	500 m	50 m
Visibility	0 m	2400 m	200 m
Liquid water content	0 g/m^3	0.12 g/m^3	0.01 g/m^3

TABLE III: TWO-PARAMETER METHOD RESULTS FOR MAXIMUM CSI (RH = RELATIVE HUMIDITY, CH = CLOUD HEIGHT, VIS = VISIBILITY, LWC = LIQUID WATER CONTENT, AND FRZ = FREEZING RAIN FORECAST)

Method	CSI	ERR_{aep} (%)	D_h (h)	POD	FAR	Parameter value for maximum CSI
T, RH	0.21	0.02	482	0.58	0.69	RH ≥ 95 %
T, CH	0.07	5.80	2760	0.70	0.86	CH ≤ 100 m
T, VIS	0.10	4.81	1840	0.63	0.85	VIS ≤ 1600 m
T, LWC	0.23	-0.12	36	0.40	0.67	LWC ≥ 0.07 g/m^3
T, FRZ	0.34	-0.16	-59	0.45	0.37	-

TABLE IV: TWO-PARAMETER METHOD RESULTS FOR MINIMUM ERR_{aep} (RH = RELATIVE HUMIDITY, CH = CLOUD HEIGHT, VIS = VISIBILITY, LWC = LIQUID WATER CONTENT, AND FRZ = FREEZING RAIN FORECAST)

Method	CSI	ERR_{aep} (%)	D_h (h)	POD	FAR	Parameter value for minimum ERR_{aep}
T, RH	0.21	0.02	482	0.58	0.69	RH ≥ 95 %
T, CH	0.02	-0.37	25	0.08	0.87	CH ≤ 0 m
T, VIS	0.06	0.79	615	0.20	0.89	VIS ≤ 200 m
T, LWC	0.23	0.02	89	0.42	0.68	LWC ≥ 0.06 g/m^3
T, FRZ	0.34	-0.16	-59	0.45	0.37	-

Of the two-parameter methods examined, the freezing rain forecast is the one which performs best in terms of maximum CSI. Even though both precipitation icing and in-cloud icing are relevant for the wind energy industry, the freezing rain forecast provides the best overall result. With a CSI value of 0.34, it allows 45 % of the icing events to be detected. 37 % of the predicted events are false alarms, and there is a difference in predicted and actual icing hours of 59 h.

In terms of minimum ERR_{aep}, the best result, at 0.02 %, is from the temperature and relative humidity combination with a relative humidity of 95 % or more. The CSI value is 0.21, and 58 % of the real events are detected. The FAR is 0.69 and there is a 482 h difference between estimated and actual icing hours.

Looking at the POD column of Tab. III, it can be seen that the temperature and cloud height combination for a cloud height of 100 m or less detects 70 % percent of all actual icing events. However, because there are a great number of false alarms, resulting in a significant difference between the number of predicted and actual icing events, the method yields a poor CSI and ERR_{aep} value. The method using visibility also has lower CSI values and higher ERR_{aep} values than the other methods tested.

The sensitivity of the CSI and ERR_{aep} to the parameter variations differs from one parameter to another. The CSI is quite sensitive to the relative humidity limit over the entire span of values. However, when using cloud height, visibility or liquid water content parameters, the CSI varies significantly at the beginning (for the first couple steps) and eventually reaches a plateau.

As for the ERR_{aep}, it is very sensitive to the cloud height for which it varies continuously from -0.37 % at the zero meter limit to 31.27 % at the 500 m limit. The ERR_{aep} value of the temperature and liquid water content combination drops from 41.89 % to 2.57 % in the two first steps but afterwards varies much less. The variations in relative humidity and visibility cause less significant but more constant ERR_{aep} variations.

C. *Three-Parameter Methods*

To analyze the possibility of improving the results of two-parameter methods, three-parameter methods were tested. These all combined temperature and the freezing rain forecast since this two-parameter combination performed best in terms of CSI. The other parameters were added and varied as in Tab. II. An icing event was defined as an event satisfying either the temperature and freezing rain forecast *or* the temperature and third parameter combination. The results for a maximum CSI are shown in Tab. V. The results for the minimum ERR_{aep} are not shown since they are the same as in Tab. V for all methods except for the method using relative humidity.

TABLE V: THREE-PARAMETER METHOD RESULTS FOR MAXIMUM CSI (RH = RELATIVE HUMIDITY, CH = CLOUD HEIGHT, VIS = VISIBILITY, LWC = LIQUID WATER CONTENT, AND FRZ = FREEZING RAIN FORECAST)

Method	CSI	ERR_{aep} (%)	D_h (h)	POD	FAR	Parameter value for maximum CSI
T,FRZ,RH	0.35	-0.16	-56	0.46	0.37	RH ≥ 100 %
T FRZ,CH	0.30	0.30	262	0.50	0.45	CH ≤ 0 m
T,FRZ,VIS	0.34	-0.16	-59	0.45	0.37	VIS ≤ 0 m
T,FRZ,LWC	0.32	0.03	53	0.51	0.47	LWC ≥ 0.12 g/m^3

When combining three parameters, the maximum CSI values remain similar to the maximum CSI value for temperature and freezing rain forecast combination in Tab. III. In fact, the maximum CSI for all three-parameter combinations is attained when there is only a small contribution or even no contribution at all from the third parameter. Therefore, adding a third parameter to the original temperature and freezing rain forecast combination does not significantly improve the CSI results.

The minimum ERR_{aep} value is obtained with the temperature, freezing rain forecast and relative humidity combination for a relative humidity greater than or equal to 97 %. The ERR_{aep} is -0.02 %, the CSI is 0.33, there is a 138 h difference between predicted and actual icing hours, the POD is 0.56, and the FAR 0.49. This minimum ERR_{aep} value is equal to the minimum value of the temperature and relative humidity two-parameter method of Tab. IV.

If combining three parameters improves neither the CSI nor the ERR_{aep} values from earlier methods, it nonetheless provides a single method that can bring both a low ERR_{aep} value and a high CSI value at the same time. The temperature, freezing rain forecast and relative humidity method for a relative humidity greater than or equal to 97 % is therefore retained as the one that best satisfies the established criteria. The temperature, freezing rain forecast and liquid water content method in Tab. V yields similar but slightly inferior results. To determine whether these differences are significant or not would require further analysis.

When looking at the different icing types separately, of all the methods considered, the temperature and freezing rain forecast method and the temperature and liquid water content method give the best CSI results for predicting precipitation icing events. The CSI is 0.37 and the minimum ERR_{aep} value is -0.06 % for both methods. The best method for the detection of in-cloud icing events is the temperature and relative humidity method. It yields a CSI of 0.09 and an ERR_{aep} of 0.07 % at a relative humidity greater than or equal to 97 %. A significant difference exists between the attainable CSI for precipitation icing event detection and for in-cloud icing event detection.

Lastly, the sensitivity of CSI and the ERR_{aep} to the parameter variations for the three-parameter methods is similar to that of the two-parameter methods.

D. Site-by-Site Analysis

To evaluate if the global method retained is equally representative for each individual station, Tab. VI presents the site-by-site results for the temperature, freezing rain forecast and relative humidity method (RH ≥ 97 %). Although there are some variations between sites, the results resemble those of the global analysis. Next, the best method for each site was found. This was done in order to see if the application of a global method to the individual sites yielded significantly different results from finding and applying the best method for each site. Tab. VII shows the results of the best method at each site for maximum CSI.

For the best individual methods, the temperature, freezing rain forecast and relative humidity method performs best for four of the six stations. For three stations, this method also gives the smallest ERR_{aep} value. For all stations, the CSI and ERR_{aep} values of Tab. VII are similar to those in Tab. VI. Therefore, applying the global method chosen here to the individual sites does not deteriorate the results.

There does not seem to be a noteworthy difference between the results of the coastal sites (Gaspé and Mont-Joli), the sites closer to urban centers (Mirabel and Québec), and the in-land sites (Chibougamau and Bagotville).

TABLE VI: RESULTS OF THE *T,FRZ,RH* METHOD FOR EACH STATION WITH RH ≥ 97 %

Station name	**CSI**	**ERR_{aep} (%)**	**D_h (h)**	**POD**	**FAR**
Gaspé	0.31	0.51	96	0.52	0.47
Mont-Joli	0.29	0.26	135	0.54	0.52
Québec	0.29	-0.07	255	0.59	0.57
Chibougamau	0.35	-0.62	42	0.51	0.39
Mirabel	0.33	-0.24	201	0.59	0.54
Bagotville	0.39	0.01	99	0.62	0.45
Global analysis	**0.33**	**-0.02**	**138**	**0.56**	**0.49**

TABLE VII: MAXIMAL CSI RESULTS FOR BEST INDIVIDUAL STATION METHODS (RH = RELATIVE HUMIDITY, LWC = LIQUID WATER CONTENT, AND FRZ = FREEZING RAIN FORECAST)

Station name	**Best method per site**	**CSI**	**ERR_{aep} (%)**	**D_h (h)**	**POD**	**FAR**	**Parameter value for max. CSI**
Gaspé	*T,FRZ,RH*	0.32	0.47	45	0.51	0.48	RH ≥ 98 %
Mt-Joli	*T,FRZ,RH*	0.32	0.20	60	0.52	0.47	RH ≥ 100 %
Québec	*T,FRZ,RH*	0.32	-0.22	-60	0.43	0.43	RH ≥ 100 %
Chibou.	*T,LWC*	0.36	-0.74	-120	0.40	0.20	LWC ≥ 0.12 g/m^3
Mirabel	*T,FRZ,RH*	0.40	-0.48	-138	0.47	0.30	RH ≥ 100 %
Bagot.	*T,FRZ,LWC*	0.42	-0.01	-9	0.56	0.34	LWC ≥ 0.12 g/m^3

Before continuing to the monthly analysis, it is interesting to look at the D_h column of Tab. VI. Dividing D_h by the number of actual icing hours and multiplying by 100 gives the percentage of over or underprediction of icing hours. There is an overprediction in the number of hours of 46 % for Gaspé, 69 % for Mont-Joli, 79 % for Québec, 11 % for Chibougamau, 50 % for Mirabel, and 29 % for Bagotville. It could be interesting to try to reduce these overpredictions as well as the differences between sites. However, this might need an evaluation based on different or extra performance criteria.

E. Monthly Analysis

The final analysis consists of looking at the predicted and real monthly distributions of icing hours. Fig. 2-4, on the next page, illustrate the real and predicted monthly icing hours for selected stations. The figures show that there are no erroneous icing event predictions for the hottest months of the year. In addition, they illustrate how the chosen method adapts to the icing climate and monthly distribution of the different sites.

V. CONCLUSION

With reanalysis data from the NARR dataset, some icing event prediction methods were tested. The results were compared to four years of meteorological airport data from six stations for validation. The prediction methods tested included two-parameter and three-parameter methods using temperature, relative humidity, cloud height, liquid water content, visibility and a freezing rain forecast. The performance of the tested methods was evaluated with two indices: the CSI, which describes the simultaneity of the predicted and actual icing events, and the ERR_{aep}, which represents an estimated error in the annual energy production of wind turbines for the icing periods.

Of the methods tested, it was shown that those using cloud base height and visibility had poor results and that those using relative humidity, liquid water content and the freezing rain forecast were more accurate. Without going into a detailed sensitivity analysis on the parameter values, it was nonetheless noted that the results are sensitive to the parameter limits chosen.

As for the different types of icing, the maximum attainable

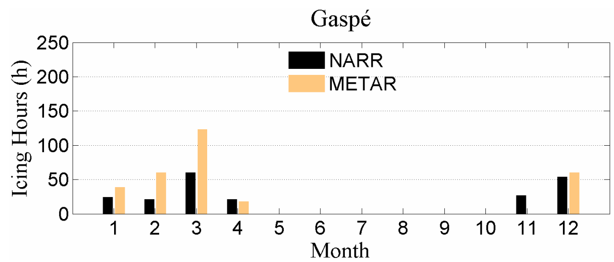

Fig. 2 Plot of the monthly distribution of predicted (NARR) and actual (METAR) icing hours for the Gaspé airport.

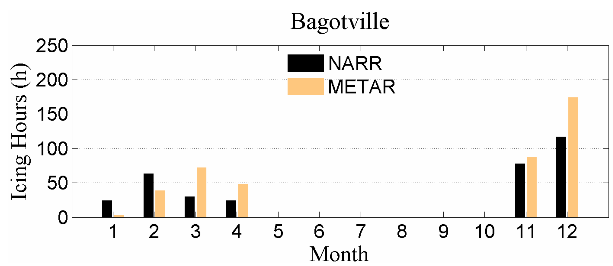

Fig. 3 Plot of the monthly distribution of predicted (NARR) and actual (METAR) icing hours for the Bagotville airport.

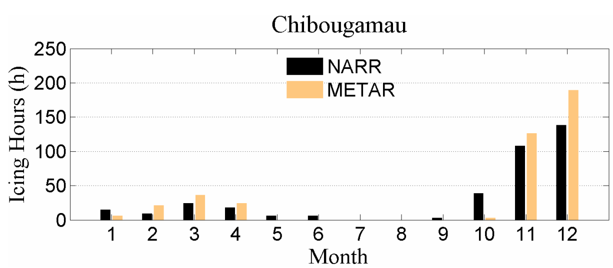

Fig. 4 Plot of the monthly distribution of predicted (NARR) and actual (METAR) icing hours for the Chibougamau airport.

CSI for precipitation icing events was much higher than that of in-cloud icing events. It was however possible to reach a low ERR_{aep} value for both types of icing.

The three-parameter method using temperature, freezing rain forecast and relative humidity (RH ≥ 97 %) was considered to perform best for the combination of both indices in a global analysis of the six stations. It was shown that the method also gave adequate results when applied to each station individually and that the method predicted the monthly distribution of icing hours relatively well.

At present, the proposed method is a valuable tool for predicting the annual mean number of icing hours or events for the wind energy industry. It correctly predicts over half of the total number of actual icing events and gives a small ERR_{aep} value. Nonetheless, with the relative error between predicted and actual icing hours varying from 79 % at the Québec airport to 11 % at the Chibougamau airport, and with the difficulty in identifying in-cloud icing events, it could be interesting to investigate other parameter combinations to see if further improvements can be made.

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