A PREDICTIVE INDICATOR OF ICING DAMAGE RISK

Petr Musilek[1*], Afsaneh Esteki[1], Edward Lozowski[2]
[1] Dept. of Electrical and Computer Engineering, [2] Dept. of Earth and Atmospheric Sciences
University of Alberta Edmonton, AB, T6G 2V4, Canada
*Email: Petr.Musilek@ualberta.ca

***Abstract**:* The ability to predict severe ice storm events is an essential step to prevent or mitigate power grid outages caused by extreme wind and ice loads. We have shown previously that an Ice Accretion Forecasting System (IAFS) can predict severe ice storms several days in advance. However, identifying the storms' maximum intensities and localizing their epicentres remain challenges to be addressed. In this paper, we describe an icing risk indicator based on the observation that predicted freezing rain fields differ, when compared across time and space. This leads to a concept similar to pseudo-ensembles used for quantitative precipitation forecasts. In addition to precipitation, this new indicator must consider temperature, wind, and fraction of frozen precipitation. The final icing risk indicator is developed using a combination of icing forecasts shifted in time and space, weighted according to the relative distance from the area and time of interest. When combined with power line design parameters, it can provide a probabilistic forecast of areas likely to be affected by ice storms. Performance of the new indicator is illustrated using a case study of an icing event that caused widespread damage to the power distribution infrastructure.

1. INTRODUCTION

Prediction of icing events caused by freezing rain and their severity could help electric power companies and communities at risk to get prepared and take appropriate preventative measures. Hence, a system that can forecast ice accretion could decrease the costs associated with icing events. This motivation led to the development of ice accretion forecasting systems (IAFS) capable to predict approaching ice storms with lead time of several days [1]. However, identifying the storms' maximum intensities, localizing their epicentres, and determination of their exact timing remain challenges to be addressed. In this paper, we describe a predictive icing risk indicator that uses the concept of spatiotemporal neighbourhood to minimize the impact of spatial and temporal shifts of weather forecasts. It is developed using a combination of icing forecasts shifted in time and space, weighted according to the relative distance from the area and time of interest.

2. RESULTS AND DISCUSSION

The proposed Predictor of Icing Damage Risk (PIDR) expands the methodology of probabilistic precipitation forecasts [3]. In addition to precipitation, there are other conditions that determine whether, and how much, precipitation will accrete in the form of ice on structures. According to a simple model [2] commonly used in ice accretion studies [1], three variables have the greatest influence on potential ice accretion damage: precipitation rate and duration, and average wind speed. In addition, to diagnose occurrence and type of precipitation, averages of surface temperature and fraction of frozen precipitation are used as the inputs of the predictor.

Based on the nature of the accretion process, appropriate thresholds are selected for all variables. They signify values of the variables that, if exceeded, could lead to dangerous ice accretions. Individual grid points of a weather forecast are compared to these thresholds for exceedance. Ratios $N_{\text{exceed}}/N_{\text{total}}$ $\mathrm{N}_{\text{exceed}}/\mathrm{N}_{\text{total}}$ are then arranged into tables of probabilities that express likelihood that given variables will exceed their specified thresholds. In the final step, the tables are element-wise multiplied to provide the overall risk of icing damage on electric power transmission or distribution infrastructure.

PIDR was tested using a severe ice storm that took place in Newfoundland, Canada, in March 2010. The slowly moving storm brought large amounts of rain and freezing rain to the exposed northeastern coast of the island. The spatial distribution of risk, shown in Fig. 1, corresponds well to the locations of actual damage, and to the results of a detailed icing study [1].

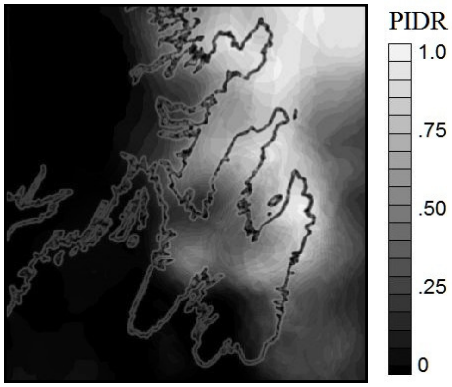


Figure 1: Spatial distribution of PIDR over Avalon peninsula, Newfoundland, on March 5, 2010, 21:00 UTC

3. CONCLUSIONS

The proposed predictor of icing damage risk can provide an early warning of approaching ice storms with a lead time of several days. Because it combines spatio-temporal and probabilistic approaches, this new predictor can identify areas of risk that may not be identified using a traditional, deterministic, single-point approach.

4. REFERENCES

[1] Hosek, J., Musilek, P., Lozowski, E., Pytlak, P., Forecasting severe ice storms using NWP: the March 2010 Newfoundland event, *Nat. Hazards Earth Syst. Sci.*, 2011

[2] Jones, K. F. (1998) A simple model for freezing rain ice loads. *Atmospheric Research*, 46:87-97.

[3] Theis, S.E., A. Hense and U. Damrath, Probabilistic precipitation forecasts from a deterministic model: A pragmatic approach. *Meteorol. Appl.*, 12: 257-268, 2005.

A Predictive Indicator of Icing Damage Risk

Petr Musilek, Afsaneh Esteki
Dept. of Electrical and Computer Engineering
University of Alberta
Edmonton, AB, T6G 2V4, Canada
Petr.Musilek@ualberta.ca

Edward Lozowski
Dept. of Earth and Atmospheric Sciences
University of Alberta
Edmonton, AB, T6G 2E3, Canada
Edward.Lozowski@ualberta.ca

Abstract— **The ability to predict severe ice storm events is an essential step to prevent or mitigate power grid outages caused by extreme wind and ice loads. We have shown previously that an Ice Accretion Forecasting System (IAFS) can predict severe ice storms up to three days in advance. The IAFS combines a numerical weather prediction model with an intelligent post-processor and a physical model of the ice accretion process. It can provide an early warning of an approaching ice storm. However, identifying the storms' maximum intensities and localizing their epicentres remain challenges to be addressed. In this paper, we describe an icing risk indicator based on the observation that predicted freezing rain fields differ, when compared across time and space. This leads to a concept similar to pseudo-ensembles used for quantitative precipitation forecasts. In addition to precipitation, this new indicator must consider temperature, wind, and fraction of frozen precipitation. All the components are distributed in space and evolve in time as the forecasts are updated. The final icing risk indicator is developed using a combination of time-shifted icing forecasts, weighted according to the forecast horizon and the relative distance from the area of interest. When combined with power line design parameters, it can provide a probabilistic forecast of areas likely to be affected by ice storms. Using the new indicator, the risk of icing damage to structures can be forecast up several days in advance. At the same time, this risk forecast can cover areas that may not be identified using a traditional deterministic approach. Performance of the new indicator is illustrated using a case study of an icing event that caused widespread damage to the power distribution infrastructure.**

***Keywords-** Icing, Risk, Probabilistic Forecast, Transmission Infrastructure, Overhead Lines*

I. INTRODUCTION

Meteorological conditions have a significant impact on the operability of power transmission lines, the integrity of their infrastructure, and the characteristics of transmission networks [3]. Weather phenomena that can cause transmission line failures and outages include extreme winds, lightning and ice loads. A study by the International Council on Large Electric Systems (CIGRE) concluded that ice accretion on power lines, winds or a combination of both, caused 87% of the total damage costs over 5 years starting from 1991 [8]. Although icing events are not common, they cost an annual average of \$313,000,000 in the U.S. alone. The extreme icing storm that hit Canada in January 1998 caused damage of \$1.44 billion - the largest insured loss in Canadian history. Millions of people were left without power, and there were 25 fatalities [9]. As another example, in December 2002 an ice storm hitting the eastern United States left more than 65% of Duke Power's 2.2 million customers without power for days. The post-storm recovery required 12,500 support personnel [4].

The prediction of icing events and their severity could help the electric power companies and communities at risk to prepared and take appropriate preventative measures. Site specific icing forecasts could also help utilities to better plan for recovery through appropriate staffing and dispatch of repair crews [4]. Hence, a system that can forecast ice accretion could decrease the costs associated with icing events. As a result, there is an increasing interest in the development of an Ice Accretion Forecasting Systems (IAFS).

We have shown previously that an IAFS can predict severe freezing rain ice storms several days in advance [6]. The IAFS combines a numerical weather prediction model, an intelligent post-processor and a physical model of the ice accretion process. It can provide an early warning of an approaching ice storm. However, identifying the storms' maximum intensities and localizing their epicentres remain challenges to be addressed. In this paper, we describe an icing risk indicator based on the observation that predicted freezing rain fields differ, when compared across time and space. The final, probabilistic Predictor of Icing Damage Risk (PIDR) is developed using a combination of deterministic, time-shifted icing forecasts, weighted according to the spatial and temporal distance from the area of interest.

This paper has five main sections. Section II provides background information about the problem, including ice accretion modeling, numerical weather prediction, and quantitative precipitation forecasting. The proposed icing risk indicator is described in detail in Section III, and applied to a recent ice storm event in section IV. Section V provides conclusions and suggestions for future work.

II. BACKGROUND

A. Modeling of Ice Accretion

Many models of ice accretion have been developed over the last sixty years [11]. They generally fall into two major categories: physical models and empirical models [12]. A physical model describes icing based on the associated physical processes of ice accretion. Such

---

This work has been supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

models usually rely on parameters that are difficult to measure, e.g. liquid water content and droplet size distribution [12]. Empirical models describe the accretion process based on observed weather and related experimental data [7], [10].

Most icing models estimate the amount of ice based on weather observations, under the assumption that freezing rain is actually falling [7]. Thus, in order to forecast the ice load on power lines, the occurrence of freezing rain must first be predicted. Then, once freezing precipitation has been forecast, an icing model can be engaged to forecast the ice accretion load [4], [16].

B. Numerical Weather Prediction

In order to implement an effective icing risk indicator, a Numerical Weather Prediction (NWP) system is used first, to forecast weather conditions in the area of interest. NWP models have evolved over the last half-century to become the state-of-the-art methodology for accurate, short-term weather forecasting [5], [13]. NWP systems generate the forecasts using gridded observations of the atmosphere as initial and boundary conditions. Forward time extrapolation is accomplished by solving spectral, finite element or finite difference forms of the mathematical equations that describe the thermodynamics and fluid mechanics of the atmosphere. Through a series of repeated calculations of the next state of the atmosphere, a forecast can be made, for a period of several days.

The Advanced Weather Research and Forecasting (WRF) system [19] is a modern, state-of-the-art NWP model. Its Advanced Research WRF (ARW) dynamic solver core, used for the simulations in this study, uses an Eulerian solver for the fully compressible, non-hydrostatic primitive equations. Because it is most often used as a regional NWP model, it must be first initialized with boundary conditions obtained from either a global or continental-scale model [18], before a forecast can be made.

C. Probabilistic Quantitative Precipitation Forecast

A Quantitative Precipitation Forecast (QPF) is the expected amount of precipitation accumulated over a specified time period in given area [1]. Theis *et al.* [20] described a simple procedure to obtain probabilistic precipitation forecasts from a deterministic model. The procedure is based on the hypothesis that the spatio-temporal neighborhood of a given point and time can be used to derive a probabilistic characterization of the precipitation forecast for that time and location. The authors introduce the concept of spatio-temporal neighborhood that is used in post-processing NWP forecasts. The post-processing procedure yields a *pseudo-ensemble* of deterministic precipitation forecasts that can be transformed into a probabilistic forecast.

In the study described in this paper, we extend the methodology of pseudo-ensembles to meteorological variables relevant to ice accretion, namely, precipitation type, air temperature and wind speed.

III. PREDICTOR OF ICING DAMAGE RISK

The proposed predictor (PIDR) expands the methodology of probabilistic precipitation forecasts [20]. In addition to precipitation, there are other conditions that determine whether, and how much, precipitation will accrete in the form of ice on structures. In the accretion model of Jones [7], often used in ice accretion studies [4], [6], [16], three variables have the greatest influence on the ice accretion process: precipitation rate and duration (or equivalently, total accumulated freezing precipitation), and wind speed. Two additional, important variables must be taken into account, although they do not appear explicitly in the simple model [7], because it implicitly assumes the occurrence of freezing rain. They are surface temperature and precipitation type (rain, freezing rain, freezing mix, ice pellets, graupel, snow).

Similarly to QPF described in [20], one must begin by determining appropriate variable thresholds that indicate the critical values that may lead to icing damage, if exceeded. Based on the nature of ice accretion and the damage it inflicts on power systems, the following thresholds have been selected for initial implementation of the predictor:

- Surface air Temperature $\overline{T} < 1°\mathrm{C}$,
- Accumulated precipitation $\sum P > 0.8 \cdot R_{eq}^{\max}$,
- Fraction of frozen precipitation $\overline{SR} < 0.465$,
- Wind speed $\overline{W} > 10\ \mathrm{ms}^{-1}$,

where values with an overbar $(\overline{\cdots})$ are averaged over the duration of the precipitation event.

The temperature threshold is derived from the necessary condition for ice accretion, namely that the temperature must be below the freezing point. The actual value of the threshold is adjusted to +1°C to account for a possible warm bias of the NWP model [15]. The threshold for accumulated precipitation is set equal to 80% of the ice thickness for which the structures located in the region of interest were designed. This follows from the fact that, for precipitation rates that lead to potentially dangerous ice loads and wind speeds in excess of 10 ms^{-1}, the rate of accretion exceeds the precipitation rate by a small margin of about 25% [14]. The threshold for the fraction of frozen precipitation is set according to the Ramer algorithm [17] modified to work with the NWP model. In [16], accretion effectiveness linearly decreases between SR values of 0 and 0.93. The value used as the threshold is a simple average of these two boundaries. The threshold for wind speed was selected to represent a typical value that may lead to dangerous accretions when a substantial amount of freezing precipitation falls over a prolonged period of time, i.e. 10 ms^{-1}. In this initial study, all threshold values were selected subjectively, based on experience. In future work, these values should be optimized to reflect actual meteorological conditions and ice accretions, observed in a range of icing events.

A. Neighborhoods

After the thresholds have been determined, individual grid points of the NWP model output are compared to their respective thresholds for exceedance. In addition to the points themselves, their spatiotemporal neighborhoods are also included in the analysis. The spatial neighborhood used for this initial study is shown in Fig. 1. For each grid point, the number of forecasts within the neighborhood which are greater (or less) than the corresponding threshold, N_{exceed}, is divided by the total number of grid points within the neighborhood, N_{total}. The weights of points within a neighborhood decrease with increasing distance from the central grid point. The weighs are based on a spatial Gaussian distribution, and normalized so that the ratio directly expresses the probability of exceedance of the threshold.

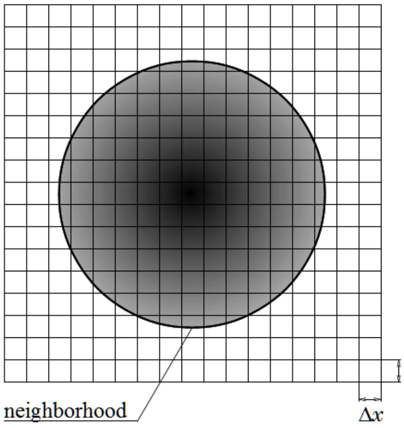


Figure 1. Spatial neighborhood; the grid represents points where forecasts are available; shading inside the neighborhood represents relative weights of grid points derived from a 2D Gaussian distribution.

A temporal neighborhood is also defined, to take into account forecasts before and after the specific time for which PIDR is determined, i.e. $t_{i-2}, t_{i-1}, t_i, t_{i+1}, t_{i+2}$. The first meteorological variable to consider is precipitation. This is quite straightforward, because WRF provides cumulative amount of precipitation as a direct output variable, RAINNC. However, because each simulation starts from RAINNC=0, forecasts with shorter lead times miss earlier precipitation, and hence their RAINNC has a negative bias. For this reason, precipitation forecasts with a later time horizon are initialized with values of RAINNC by their predecessors, at the time of their start. This procedure is shown in Fig.2.

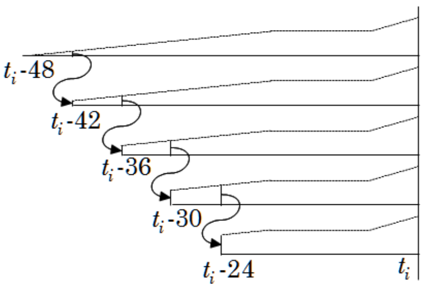


Figure 2. Initialization of RAINNC from preceeding forecasts

The next variable is temperature. WRF outputs a value T2, which is the model temperature at a height of 2 m above the surface. However, the use of instantaneous values would be meaningless: ice accretion is a slow process that takes hours or days to accumulate ice of mass that poses danger to structures. Therefore, Instead of simply taking the value of $T(t_i)$, an average over the duration of the precipitation event is considered

$$\overline{T} = \frac{\sum_{i=0}^{H} T(t_{i-H})}{H+1}, \tag{1}$$

where H is the duration of the precipitation event. Fraction of frozen precipitation and wind speed are treated in a similar way, i.e.

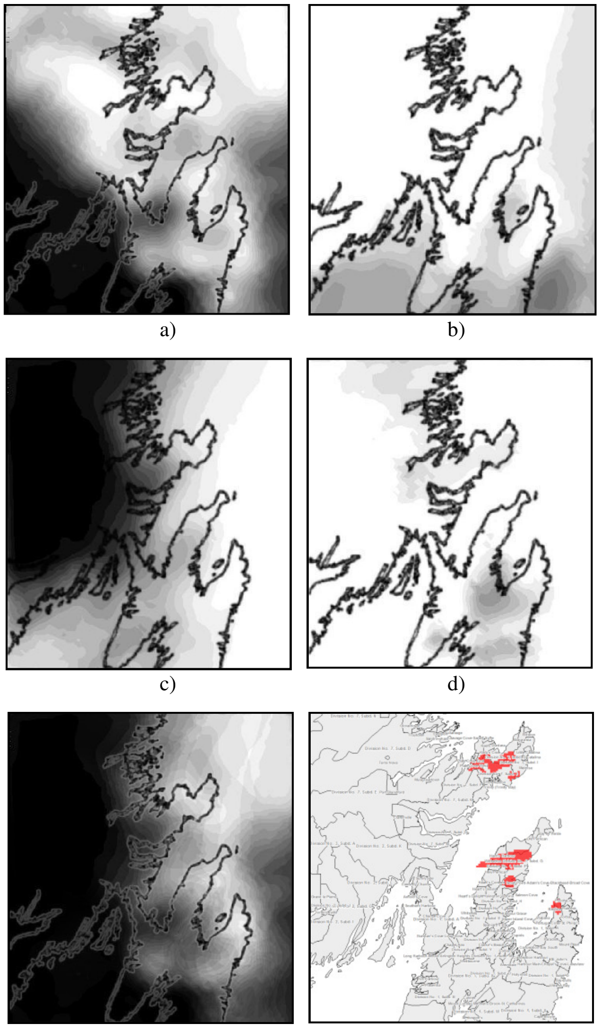
$$\overline{SR} = \frac{\sum_{i=0}^{H} SR(t_{i-H})}{H+1} \text{ and } \overline{W} = \frac{\sum_{i=0}^{H} W(t_{i-H})}{H+1}. \tag{2}$$

Ratios $N_{\text{exceed}}/N_{\text{total}}$ are then arranged to form tables of probabilities. Each cell, corresponding to a particular location on the forecast grid, expresses the likelihood that a given variable will exceed the specified threshold. Assuming statistical independence of the four variables, individual elements of the four tables are multiplied. This provides a table of the overall risks of icing damage on electric power transmission or distribution infrastructure.

IV. APPLICATION

To illustrate the operation of PIDR, it was applied to a severe ice storm that took place in Newfoundland, Canada, in March 2010. This ice storm has been recently simulated and analyzed [6], providing an ideal case to prove the concept of PIDR. The storm hit southeastern Newfoundland on March 5, and brought rain and freezing rain to the exposed northeastern coast of the island. The slowly moving storm produced rain for about two days. A detailed description of the storm can be found in [6]. The storm was simulated using the WRF model with three nested domains. Only the intermediate domain, with a grid size of $\Delta x=\Delta y=3.6$ km and dimensions of 64×79 grid points, was used for this study. In order to reproduce the conditions of a real forecast, initial and boundary conditions were obtained from the North American Model (NAM) data products, which are based on global model forecasts.

The simulated forecast with horizon of 24 hours was used for this illustration. The value of precipitation threshold was set to 15.2mm. This value is 80% of the severe icing category threshold, assigned to northeastern Newfoundland by the overhead systems design standard [2]. This procedure yielded the four probability tables visualized in Fig. 3. The table of $\Sigma P>15.2$mm in Fig. 3a, showed significant potential for damaging ice accretions over the entire northern half of the island. This was confirmed by the average temperatures over the duration of the precipitation event, cf. Fig 3b. However, only the eastern part of the precipitation field had predominantly liquid precipitation, as shown in Fig. 3c. Finally, see Fig. 3d, the average wind speed during the precipitation event was sufficient to produce dangerous accretions. It should be noted that PIDR currently only considers ice loads, not combined wind-and-ice loads.



a) b) c) d) e) f)

Figure 3. Probability of a) $\Sigma P > 15.2$mm, b) $\overline{T} < 1$°C, c) $\overline{SR} < 0.465$, d) $\overline{W} > 10$ ms^{-1}, e) resulting PIDR; f) map of areas affected by the ice storm of March 4-5, 2011 [for scale cf. Fig. 1]

The final risk grid, shown in Figure 3e, is obtained using the element-wise product of all four tables. Comparison with a map of the areas most affected by the ice storm, shown in Fig. 3f, indicates a good match.

V. CONCLUSIONS

This paper introduced the concept of a predictive indicator of icing damage risk (PIDR). This predictor examines the spatio-temporal neighborhood of each point forecast, using thresholds to identify meteorological conditions that could lead to severe ice accretions on power transmission and distribution infrastructure. The concept was tested using a severe ice storm that took place in Newfoundland, Canada, in March 2010.

Future work will concentrate on examining the assumption of statistical independence of meteorological variables, and possible modification of the aggregation procedure. Further improvements will involve optimization of the size and resolution of the neighborhood, and tuning of the thresholds using data collected from other ice storms.

REFERENCES

[1] Bushong, J. S., "Quantitative Precipitation Forecast: Generation and Verification at the Southeast River Forecast Center", *Georgia Water Resources Conference*, 1999, http://www.srh.noaa.gov/media/serfc/presentations/qpf_generation.pdf, Retrieved 11/02/07.

[2] Canadian Standards Association, *Overhead systems*, 8th edition. Technical Report C22.3 No. 1-06, October 2006.

[3] Crocombette, C., “The weather impact on the transmission of electricity in France,” *8th European conference on Application of Meteorology*, ECEAM07, Spain, 2007.

[4] DeGaetano, T., Belcher, B. N., Spier, P. L., 2008: Short-Term Ice Accretion Forecasts for Electric Utilities Using the Weather Research and Forecasting Model and a Modified Precipitation-Type Algorithm. *Weather and Forecasting*, 23(5), 838-853.

[5] Environmental Modeling Center, “The GFS atmospheric model,” *NCEP Office note 442*, Global Climate and Weather Modeling Branch, EMC, Camp Springs, Maryland, 2003.

[6] Hosek, J., Musilek, P., Lozowski, E., Pytlak, P., Forecasting severe ice storms using numerical weather prediction: the March 2010 Newfoundland event, Nat. Hazards Earth Syst. Sci., 2011

[7] Jones, K. F. (1998) A simple model for freezing rain ice loads. *Atmospheric Research*, 46:87-97.

[8] Kiessling, F., Nefzger, P., Noslasco J., Kaintzyk, U., *Overhead Power Lines: Planning, Design, Construction*, Springer, 2003.

[9] Lecomte, E., Pang, A., Russell, J., “Ice Storm ’98,” ICRL *Research Paper Series*, No. 1, 1998

[10] Makkonen, L., 1998: Modeling power line icing in freezing precipitation. *Atmospheric Research*, 43, 131-142.

[11] Makkonen, L., Lozowski, E., 2005: Fifty years of progress in modelling the accumulation of atmospheric ice on power network equipment, In Proc. *IWAIS 2005*, Montréal, Quebec, June 2005

[12] McComber P. Druez J., De Lafontaine J., Paradis A., Laflamme, J. N., Estimation of Transmission Line Icing at Different Sites Using a Neural Network, Proc. *ISOPE 1999*, Brest, pp. 599-606

[13] Molteni, F., Buizza, R., Palmer, T. N., and Petroliagis, T., “The ECMWF ensemble prediction system: Methodology and validation,” *Quart. J. Roy. Meteorol. Soc.*, vol. 122, no. 529, Part A, pp. 73–119, Jan 1996.

[14] Musilek, P., Pilot Study - Modeling and Forecasting Icing Events Using Regular Weather Models, Report No. T073700-3344, CEATI International, Montreal, QC, August 2010 (122 pages)

[15] Pyle, M. E., Janjic, Z., Black, T. ., Ferrier, B., An overview of real time WRF testing at NCEP, In *Proc. 5th MM5/WRF Users Workshop*, NCAR, June 22-25, Boulder, CO, 2004 (4 pages)

[16] Pytlak, P., Musilek, P., Lozowski, E., and Arnold, D.: Evolutionary Optimization of an Ice Accretion Forecasting System (IAFS), Mon. Weather Rev., 138, 2913–2929, 2010.

[17] Ramer, J.: An empirical technique for diagnosing precipitation type from model output, *5th International Conf. On Aviation Weather Systems*, Vienna, VA. AMS, 227–230, 1993.

[18] Rogers, E. et al., The NCEP North American mesoscale modeling system: Recent changes and future plans. Preprints of *23rd Conf. on Weather Analysis and Forecasting/19th Conf. on NWP*, Amer. Meteor. Soc., Omaha, NE. paper 2A.4, 2009

[19] Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M., Huang, H., Wang, W., and Powers, J. G., *A description of the advanced research WRF version 3*, NCAR Tech. Note NCAR/TN-475+STR, 113 pp., 2008.

[20] Theis, S.E., A. Hense and U. Damrath, Probabilistic precipitation forecasts from a deterministic model: A pragmatic approach. Meteorol. Appl., 12: 257-268, 2005.