Simulation of icing and evaluation of its impact on wind plant power loss

Jing Yang

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Outline

• Background on icing
• Models
  – Atmospheric model: GEM-LAM
  – Icing models: in-cloud icing, wet snow and freezing rain
• Applications of coupled model to icing events
  – Icing simulations over Mount Washington
    • Model settings and configuration
    • Observations vs simulation
  – Simulations over the Gaspé region
    • Description of observations
    • Comparison of simulated surface fields against observation
    • Comparison of simulated ice amount against power loss
• Summary and future work
Introduction - impacts

- Ice load breaks power lines and damages equipment
- Leads to load imbalances, causing wind turbines to shut off
- Decreases wind energy power production
- Affects (non-heated) anemometer measurements (leading to false wind speed measurements)
- Safety issues due to ice throw-up
# Introduction - power loss statistics

## Regional production losses of the 24 wind farms

<table>
<thead>
<tr>
<th>Region</th>
<th>Capacity (MW)</th>
<th>Ref. Year</th>
<th>Ref. Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB+MB</td>
<td>254</td>
<td>3.2%</td>
<td>5.7%</td>
</tr>
<tr>
<td>ON</td>
<td>688</td>
<td>3.5%</td>
<td>5.7%</td>
</tr>
<tr>
<td>QC</td>
<td>445</td>
<td>7.4%</td>
<td>12.4%</td>
</tr>
<tr>
<td>NB+NS</td>
<td>285</td>
<td>15.7%</td>
<td>26.5%</td>
</tr>
<tr>
<td>PEI+NL</td>
<td>96</td>
<td>3.4%</td>
<td>5.8%</td>
</tr>
</tbody>
</table>

*From Lacroix & Tan, 2012*

## Cold climate related production losses for wind farms in Canada

<table>
<thead>
<tr>
<th>Region</th>
<th>Planed capacity (MW)</th>
<th>Annual Production (MWh)</th>
<th>Annual production loss (MWh)</th>
<th>Annual loss ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing wind farms</td>
<td>5260</td>
<td>14,284,490</td>
<td>1,009,626</td>
<td>99,880,577</td>
</tr>
<tr>
<td>Future wind farms*</td>
<td>9804</td>
<td>26,624,557</td>
<td>1,143,787</td>
<td>92,287,584</td>
</tr>
<tr>
<td>Total</td>
<td>15064</td>
<td>40,909,048</td>
<td>2,153,413</td>
<td>192,168,161</td>
</tr>
</tbody>
</table>

* Under construction and planned, that will operate by 2012 and beyond

## Method

- Determine a reference production level
- Compare actual production with reference level
- Calculate losses
- Corresponding values in $
Introduction - icing types

focus on rime and glaze

- **Rime:** during in-cloud icing/fog, super-cooled droplets freeze quickly onto a substrate with \( T < 0 \, ^\circ\text{C} \), air bubbles trapped give opaque appearance.

- **Glaze:** freezing rain/drizzle hits a surface; a liquid layer forms on the accretion surface and freezing takes place beneath this layer; longer freezing time; no bubbles; transparent appearance.

- **Wet snow:** An agglomeration of flakes and a mixture of ice, water and air.

- **Frost:** Not important for turbine performance
Introduction

Note:
1. Icing normally occurs in coastal areas and high topography regions.

2. Ice growth rate depends on temperature, wind speed, LWC, median volume diameter of the particles; these fields can be obtained from a mesoscale model.
Model- icing models (riming, freezing rain, wet snow)

GEM-LAM model

Wet snow
LW in snow

Rime $T<0$;
LWC

Frzn $T<0$;
precip

\[
\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 q_{wc} V A; \quad D_t = \sqrt{\frac{4(M_t - M_{t-})}{\pi \rho_s}} + D_{t-}^2
\]

\[
\frac{dR}{dt} = \frac{dD}{dt} - 3.6 \times 10^6 \frac{F_{net}}{L_{fi}}
\]

\[
\frac{dR}{dt} = 0.35P \left[1 + \left(\frac{V}{5}\right)^2\right] \frac{1}{2} - 3.6 \times 10^6 \frac{F_{net}}{L_{fi}}
\]

Ice load and duration

$F_{net}$: radiation flux term
Part 1- Mt Washington study

- Description of observations
- Simulation with GEM-LAM
  - Model settings and configuration
  - Simulated surface fields (Wind speed, Temp)
  - Simulated cloud liquid water content and particle diameter
- Summary
Mt Washington

**Location:** (44.3° N, 71.3° W) with elevation 1910 m

**Climatology** (1971-2000): $T=-3^\circ C$; $U=19\text{ ms}^{-1}$; clouds 55% of the time; heavy fogs 87% of days from Nov-Apr

**Measurements:**

- Wind speed (at 10.7 m) from heated, anti-iced anemometer.
- Temperature (at 4.6 m)
- Liquid Water Content
- Mean Volume Diameter
  - Multicylinder method (at 8m)

(from Christopher J. Morris)
**Observations**

**multicylinder**

Rotation: 1 or 2 rpm

D: 0.2, 0.5, 1.1, 2.2, 4.4, 7.6cm
to get median volume diameter and LWC
Observations

Intensive observation dates:

Obs2: 03/09/1994 - 03/15/1994
Obs3: 02/09/1995 - 02/14/1995
Obs4: 12/01/1995 - 12/04/1995
Obs5: 03/20/1996 - 03/26/1996
Obs6: 12/06/1996 - 12/07/1996
Obs7: 03/10/2011 - 03/13/2011

Multicylinder exposure duration: 7 - 23 mins

by CRREL personnel
Observations

Selected cases:

Obs2: 03/09/1994 - 03/15/1994 (SW)
Obs3: 02/09/1995 - 02/14/1995
Obs4: 12/01/1995 - 12/04/1995
Obs5: 03/20/1996 - 03/26/1996 (NW)
Obs6: 12/06/1996 - 12/07/1996
Obs7: 03/10/2011 - 03/13/2011 (S&W)

Representative of the prevailing wind direction
Model - nested domains

Domain 1: 10km, 154x154
Domain 2: 3km, 234x234
Domain 3: 1km, 414x414

▲▲▲▲
Mount Washington with elevation 1910 m

1020 m (10-km)
Model- sub-domains

Domain 2: 3km, 234x234

Domain 3: 1km, 414x414

Mount Washington with elevation 1910 m
Model - vertical level settings

56 vertical levels

<table>
<thead>
<tr>
<th>Zm</th>
<th>Zt</th>
</tr>
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<tr>
<td>...</td>
<td>...</td>
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<tr>
<td>0.9198</td>
<td>581</td>
</tr>
<tr>
<td>0.933</td>
<td>482</td>
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<tr>
<td>0.9451</td>
<td>392</td>
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<td>0.9562</td>
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<td>0.966</td>
<td>240</td>
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<td>0.9745</td>
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<td>0.9818</td>
<td>128</td>
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<tr>
<td>0.9875</td>
<td>87</td>
</tr>
<tr>
<td>0.9918</td>
<td>57</td>
</tr>
<tr>
<td>0.9949</td>
<td>36</td>
</tr>
<tr>
<td>0.997</td>
<td>21</td>
</tr>
<tr>
<td>0.9985</td>
<td>10</td>
</tr>
<tr>
<td>0.9995</td>
<td>3</td>
</tr>
</tbody>
</table>

Diagram: ptop = 10000 Pa, rcoeffs = 0.8

56 momentum
Top/Bot

Environment Canada

Canada
Model- configuration

Initial and boundary conditions:
CMC 6-hourly regional analysis data, (~35km/16 levels)

Physics scheme: (Physics library V5.2.0, GEM V4.2.0)

Control Run:
• Surface: ISBA *(fix the analysis data, eg. calculating I1 from J2,HS)*
• Boundary layer: MOISTKE
• Implicit precipitation: Kain-Fritsch (only for 10-km run)
• Explicit precipitation: Milbrandt-Yau double moment scheme
• CCN type: Continent
Model - simulation strategy

1-km run results:

00Z day1

- 6hr
- 3hr

00Z day2

- 32 hr
- 26 hr
- 23 hr

00Z day3

- 32 hr
- 26 hr
- 23 hr

00Z day4

- 32 hr
- 26 hr
- 23 hr

Resolution | Time-step | Spin-up | Nesting interval
10km ~ 0.08993 | 300s | / | 6 hr
3km ~ 0.02698 | 60s | 6hr | 900s
1km ~ 0.008993 | 30s | 3hr | 600s
Simulation results - case 1 (Mar 1996, NW)

**T (°C)**
Bias: 6.7; 1.9; 0.1
RMSE: 6.8; 2.4; 1.3

**U (ms⁻¹)**
Bias: -3.6 0.4 0.0
RMSE: 6.1; 4.5; 3.3
Simulation results- case 1 (Mar 1996, NW)

**LWC (gm^{-3})**

Bias: -0.39; -0.12; 0.08
RMSE: 1.08; 0.26; 0.23

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Case 1 (Mar 1996, NW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEM-LAM (1−km)</td>
<td>Observations</td>
</tr>
<tr>
<td>GEM-LAM (3−km)</td>
<td>GEM-LAM (10−km)</td>
</tr>
</tbody>
</table>

**Graph:**

- Observations
- GEM-LAM (1−km)
- GEM-LAM (3−km)
- GEM-LAM (10−km)

**Legend:**

- Observations
- GEM-LAM (1−km)
- GEM-LAM (3−km)
- GEM-LAM (10−km)
**Simulation results- case 1 (Mar 1996, NW)**

**DMC:** Mass averaged diameter (output from gem-lam)

**MVD:** half of the cloud water is in larger droplets and half is in smaller droplets (calculated from droplet size distribution).

\[
F(D) = \frac{ND^{\alpha-1}}{\beta^{\alpha} \Gamma(\alpha)} e^{(-D/\beta)}
\]

\[
\int_{0}^{D_{mvd}} D^3 F(D) dD = \int_{D_{mvd}}^{\infty} D^3 F(D) dD
\]
Simulation results- case 1 (Mar 1996, NW)

MVD (µm)
Bias: -13.3, -5.5, 2.8  RMSE: 13.8, 9.6, 4.6

[b]Observations

GEM−LAM (1−km)
GEM−LAM (3−km)
GEM−LAM (10−km)

Simulation results-case 1 (Mar 1996, NW)
Simulation results - case 1 (Mar 1996, NW)
Simulation results- case 1 (Mar 1996, NW)

<table>
<thead>
<tr>
<th>Schemes</th>
<th>RMSE</th>
<th></th>
<th>Bias</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (ºC)</td>
<td>V (m s⁻¹)</td>
<td>LWC (g m⁻³)</td>
<td>MVD (µm)</td>
</tr>
<tr>
<td>CTRL</td>
<td>1.3</td>
<td>3.3</td>
<td>0.23</td>
<td>4.6</td>
</tr>
<tr>
<td>Maritime(CC N)</td>
<td>1.3</td>
<td>3.3</td>
<td>0.22</td>
<td>20.6</td>
</tr>
<tr>
<td>Single-moment</td>
<td>1.3</td>
<td>3.4</td>
<td>0.23</td>
<td>13.5</td>
</tr>
<tr>
<td>Force-restore</td>
<td>1.6</td>
<td>3.4</td>
<td>0.25</td>
<td>12.4</td>
</tr>
<tr>
<td>Clef</td>
<td>1.4</td>
<td>3.7</td>
<td>0.36</td>
<td>16.1</td>
</tr>
</tbody>
</table>

RMSE and bias for MVD are larger for sensitivity test; However, less changes for LWC, except for CLEF.
Simulation results - case 2 (Mar 2011, S&W)

(a) Temperature

(b) Wind speed
Simulation results- case 2 (Mar 2011, S&W)

(a) Liquid water content (gm$^{-3}$)

(b) MVD ($\mu$m)

Observations
GEM–LAM (1–km)
Simulation results - case 3 (Mar 1994, SW)

Temperature

(a)

Wind speed

(b)
Simulation results- case 3 (Mar 1994, SW)

LWC

(a)

Liquid water content (gm$^{-3}$)

MVD

(b)

MMD (µm)

Observations

GEM–LAM(Polluted)

GEM–LAM(Ctrl)
Simulation results - three cases

Temperature

Wind speed

LWC

MVD
Model- icing models (riming, freezing rain, wet snow)

GEM-LAM model

Wet snow
LW in snow

Rime T<0;
LWC

Frzn T<0;
precip

\[ \frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 q_{1,wc} VA; \]
\[ D_t = \frac{\sqrt{4(M_t - M_{t-1})}}{\pi p_s} + D_{t-1} \]

\[ \frac{dR}{dt} = \frac{dD}{dt} - 3.6 \times 10^6 \frac{F_{net}}{L_{fr}} \]

Ice load and duration
Model- collision efficiency and icing rate (case 1)

(a) Collision efficiency

(b) Icing rate

- GEM–LAM
- Multicylinder
- Cylinder 3
Model: collision efficiency and icing rate (case 2)

(a) Collision efficiency

(b) Icing rate
Model - collision efficiency and icing rate (case 3)

(a) Collision efficiency

(b) Icing rate
Summary- for icing simulation in Mt Washington

1. In-cloud icing events on Mount Washington simulated with GEM-LAM
2. Calculated MVD from GEM-LAM droplet size distribution.
3. Compared meteorological (T, U, V, HU), cloud fields (LWC, MVD), and icing rate with measure data, and calculated RMSE:
   - surface wind speed (4.6 m s$^{-1}$);
   - air temperature (1.6 °C);
   - liquid water content (0.23 g m$^{-3}$);
   - MVD (5.8 µm);
   - icing rate: (1.53 g m$^{-1}$ min$^{-1}$)
4. Sensitivity tests show T, U, and V fields to be robust; LWC and MVD are sensitive to physics schemes; MVD is very sensitive to CCN.
Part 2. Simulation over Gaspé

- Observations from wind power plants
- Model and simulation strategy
- Comparison of simulations with observations
  - For a freezing rain event (glaze)
  - For an in-cloud icing event (rime)
  - In terms of meteorological fields
  - In terms of power loss
- Summary
# Observations - 27 icing events

## Icing events at a Wind Power Plant (Jan 2008 to Dec 2010)

<table>
<thead>
<tr>
<th>Case#</th>
<th>Time</th>
<th>Case#</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30/04/2008 21:00</td>
<td>12</td>
<td>20/03/2008 23:00</td>
</tr>
<tr>
<td>2</td>
<td>12/12/2008 20:00</td>
<td>13</td>
<td>13/04/2008 18:00</td>
</tr>
<tr>
<td>3</td>
<td>27/11/2009 14:00</td>
<td>14</td>
<td>12/02/2009 19:00*</td>
</tr>
<tr>
<td>4</td>
<td>11/12/2009 05:00</td>
<td>15</td>
<td>14/02/009 19:00</td>
</tr>
<tr>
<td>5</td>
<td>15/12/2009 23:00</td>
<td>16</td>
<td>02/03/2009 16:00</td>
</tr>
<tr>
<td>6</td>
<td>21/12/2009 01:00</td>
<td>17</td>
<td>05/04/2009 01:00</td>
</tr>
<tr>
<td>7</td>
<td>14/02/2010 15:00</td>
<td>18</td>
<td>13/04/2009 00:00</td>
</tr>
<tr>
<td>8</td>
<td>30/03/2010 10:00</td>
<td>19</td>
<td>25/01/2010 14:00</td>
</tr>
<tr>
<td>9</td>
<td>31/03/2010 05:00</td>
<td>20</td>
<td>20/02/2010 00:00</td>
</tr>
<tr>
<td>10</td>
<td>18/02/2009 10:00</td>
<td>21</td>
<td>28/02/2010 18:00</td>
</tr>
<tr>
<td>11</td>
<td>23/02/2009 06:00</td>
<td>22</td>
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</tr>
<tr>
<td>25</td>
<td>09/01/2008 13:00</td>
<td>23</td>
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</tr>
<tr>
<td>26</td>
<td>29/01/2008 05:00*</td>
<td>24</td>
<td>27/12/2010 09:00</td>
</tr>
<tr>
<td>27</td>
<td>08/11/2008 09:00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Icing types:**

- Freezing rain
- Wet snow
- Rimming

*Denotes icing event not directly related to wind turbine operation.
Observations - icing duration

Duration (defined by power loss)

Events frequency (duration)
Observations- average values for 4 types

Statistical analysis of these 27 icing events:

<table>
<thead>
<tr>
<th>Type</th>
<th>No</th>
<th>Dur (hr)</th>
<th>Loss (MWh)</th>
<th>Loss_p (%)</th>
<th>Turbine</th>
<th>Average values at meteorological tower of farm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>FR</td>
<td>9</td>
<td>311</td>
<td>192.0</td>
<td>59.72</td>
<td>5.80</td>
<td>6.87</td>
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<tr>
<td>WS</td>
<td>2</td>
<td>114</td>
<td>17.9</td>
<td>21.77</td>
<td>6.98</td>
<td>8.41</td>
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<tr>
<td>Riming</td>
<td>3</td>
<td>79</td>
<td>27.9</td>
<td>42.01</td>
<td>6.00</td>
<td>1.08</td>
</tr>
<tr>
<td>Total</td>
<td>27</td>
<td>1020</td>
<td>536.9</td>
<td>49.43</td>
<td>7.19</td>
<td>8.63</td>
</tr>
</tbody>
</table>

Loss = theoretical generated power – real generated power, unit: MWh
Loss_p = Loss / theoretical generated power, unit: %.
Observations - temperature and relative humidity

@10-m meteorological tower

Point: average value over the total duration of each icing event (27)
Observations- power and power loss

Perte_p > 60% : Event 1, 3, 6, 7, 9, 12, 14, 17, 21, 26
Observations - wind speed

Wind speed @ meteorological tower

- Heated anemometer
- Unheated anemometer
- Difference

Missing value in Heated Anemometer at NO. 1, 2, 12, 13, 25, 26, 27
Perte_p > 60% : Event 1, 3, 6, 7, 9, 12, 14, 17, 21, 26
Wind difference > 5m/s: Event 3, 6, 7, 10, 11, 14, 15, 17, 18, 21, 22, 24
Therefore, NO. 3, 6, 7, 14, 17, 21, and/or No. 1, 12, 26 (Missing values)
# Observations

## Icing events at a Wind Power Plant (Jan 2008 to Dec 2010)

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<td>5</td>
<td>15/12/2009 23:00</td>
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<tr>
<td>6</td>
<td><strong>21/12/2009 01:00</strong></td>
</tr>
<tr>
<td>7</td>
<td><strong>14/02/2010 15:00</strong></td>
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<tr>
<td>8</td>
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<tr>
<td>24</td>
<td>27/12/2010 09:00</td>
</tr>
</tbody>
</table>

- **freezing rain**
- **wet snow**
- **riming**
GEM-LAM configuration

Double-nested domain
Domain 1: 15km, 138x110
Domain 2: 2.5km, 465x345

Initial and boundary conditions
CMC regional analysis;
hourly regional forecast data
(~15km/58 levels).

Study cases (8):
1. Freezing rain/wet snow
   04-08 Apr, 2009.
2. Riming, 14-19Feb, 2010
Case 1 (Freezing rain/Wet snow)

Case 1: Freezing rain / Wet snow

Time:  4 Apr - 8 Apr, 2009

Results:

  Compare simulated meteorological fields to observations

  Compare ice amount to power loss
Case 1 – Model vs. Obs.

Observed (10-min) and simulated (half hourly) pressure, RH and T from 4 to 8 Apr, 2009
Case 1 – Model vs. Obs. (wind speed)

Ensem Ave. of wind speed @ 67 turbines

Wind speed at met tower

![Graph showing wind speed over time for Case 1 - Model vs. Obs. (wind speed). The graph compares observed and modeled wind speeds at different time intervals.]
Case 1 – Obs. (power loss)
Case 1 – Model icing vs. Obs. power loss

Icing rate

Accumulated

Power loss in percentage

Time (day)
Case 1 – Model icing vs. Obs. power loss

Standardized icing amount and power loss from 4 to 8 Apr, 2009

Positive correlation: $r = 0.6$
Case 2 (Riming/freezing rain)

Case 2: Riming/freezing rain

Time: 14 - 19 Feb, 2010

Results:

- Compare simulated meteorological fields to observations
- Compare simulated precipitation & LWC to power loss
- Compare simulated icing amount to power loss
Case 2 – Model vs. Obs. (RH, T, UV)

RH

Temperature

Wind speed
Case 2 – Model Pr&LWC vs. Obs. power loss

Precipitation

LWC

Power loss
Case 2 – Model icing vs. Obs. power loss

Icing rate

Accumulated ice amount

Power loss
## Simulation results of 8 cases

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
<th>Start-up</th>
<th>Duration (hr)</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Icing</td>
<td>Power loss</td>
<td>Icing</td>
<td>Power loss</td>
</tr>
<tr>
<td>1</td>
<td>4-9 Apr, 2009</td>
<td>11Z, 04 Apr</td>
<td>16Z, 04 Apr</td>
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<td>05Z, 08 Nov</td>
<td>20Z, 07 Nov</td>
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<td>11-16 Feb, 2009</td>
<td>10Z, 11 Feb</td>
<td>13Z, 11 Feb</td>
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<td>5</td>
<td>27 Nov-1 Dec, 2009</td>
<td>14Z, 27 Nov</td>
<td>14Z, 27 Nov</td>
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<td>7</td>
<td>27 Feb-3 Mar, 2010</td>
<td>06Z, 28 Feb</td>
<td>13Z, 28 Feb</td>
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<tr>
<td>8</td>
<td>30 Mar-3 Apr, 2010</td>
<td>04Z, 30 Mar</td>
<td>06Z, 30 Mar</td>
<td>54</td>
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</table>
1. Validated GEM-LAM simulation results with available observations during icing events at two sites;
2. GEM-LAM capture the time evolution of meteorological conditions of the icing events well;
3. Cloud-related fields are sensitive to microphysics schemes and CCN;
4. Improved icing models to account for radiation fluxes;
5. GEM-LAM captures the start-up and duration of icing events (accumulated ice amount and duration from GEM-LAM matches observed power loss);
6. This can be used for forecasts of wind power and ice storms.
Future work

1. To develop wind energy production forecast system by considering icing impacts.
   • Obtain empirical relationship from statistical analysis of historical icing events (from a database of model icing simulations)
   • Apply this to wind energy forecast

2. To develop an atlas of icing amount and occurrence frequency for all of Canada.
   • Use observation data from a wind farm to validate Single Column Model (SCM)
   • Develop and couple icing load models to SCM
   • Use coupled model and downscaling method to get high resolution meteorological and cloud related fields
   • Develop icing map over Canada

3. To propose probabilistic approach for ice loads in Canada (feasibility of ensemble forecast system).
Thanks for your attention!
incubation time

meteorological icing

instrumental icing

recovery time

period of data loss

loss in production