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# IN-CLOUD ICING SIMULATION WITH GEM-LAM MODEL

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***Abstract**:* In-cloud icing on structures such as transmission lines and wind turbines is an important consideration for both design and for operations. The objectives of this research project are two fold: 1) to explore the possibility of using an atmospheric mesoscale model for in cloud icing simulations and 2) to provide a database of model icing simulations for a climatological study of rime icing. The regional GEM-LAM mesoscale model of the Canadian Meteorological Center (CMC) was used to model historical icing events during which observational data are available in Mount Washington. The Milbrandt-Yau explicit precipitation scheme is used in GEM-LAM, which predicts the mixing ratio, number concentration of individual hydrometeors and gives the particle size distribution and cloud liquid water content. The microphysical variables, together with temperature and wind speed, are important inputs for driving icing models, which are used to simulate ice accretion on transmission lines and wind turbines. An important first step in this work involves comparing the GEM-LAM simulated cloud moisture properties and other meteorological data with available near-surface observational data. Detailed comparisons of the GEM-LAM runs with Mount Washington observational data will be presented along with a discussion of the next steps of the research.

## 1. INTRODUCTION

In-cloud icing is a common phenomenon observed in coastal areas and high elevations, where water vapor pressure is easily saturated which provides favorable conditions for cloud droplet formation and temperatures are often below freezing. It affects both transmission lines and the blades of wind turbines. Numerical modeling is a useful tool to study icing on wind turbines. In this paper, the regional GEM-LAM (Global Environmental Multiscale-Limited Area Model) mesoscale model of the Canadian Meteorological Center (CMC) was used to model an in-cloud icing event that occurred in December 1996 at the summit of Mount Washington in the United States.

## 2. MODEL DESCRIPTION AND STRATEGY

The simulation is designed using a triple-nested grid, with horizontal grid spacings of 10-km, 3-km and 1-km, and 62 vertical levels. CMC analysis data are used as the initial conditions and the lateral boundary conditions for the domain of the 10-km coarse-resolution run. The 3-km simulation was initialized six hours after the 10-km run to allow for model spin-up, with the boundary conditions supplied by interpolating from the 10-km run outputs. Similarly, for the 1-km run, the spin-up time is three hours and lateral boundary conditions were derived from the 3-km simulation results. The Milbrandt-Yau scheme [1] is used to treat grid-scale cloud and precipitation in all three runs. This explicit precipitation scheme is a bulk microphysics scheme, within which hydrometeor size distribution of each category is represented by an analytical function.

## 3. OBSERVATION AND SIMULATION RESULTS

In-cloud icing event which occurred on Mount Washington on 7 December 1996 was simulated with GEM-LAM, and the results were compared with the observation. The modelled wind speed and air temperature from the 1-km run are given in Fig. 1, showing that the model wind follows the evolution of the observed ~11m wind quite well. Also, there is a good agreement between simulated temperature and observed values, with differences of 2ºC or less. Figure 2 compares the time evolution of simulated liquid water content with observations. The simulated value was generally smaller than the observed value at 8 m above ground from 0000 to 0900 LST, and larger after that.

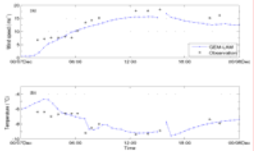

**Figure 1:** Comparison of observed and simulated (a) wind speed (unit: $ms^{-1}$) and (b) temperature (unit: ºC).

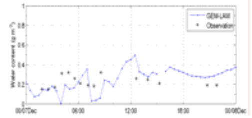

**Figure 2:** Comparison of observed and simulated liquid water content (unit: $gm^{-3}$).

## 4. CONCLUDING REMARKS

This paper describes an in-cloud icing event which occurred on Mount Washington, and the GEM-LAM model was used to simulate this case. The modelled temperature and wind speed compared favourably to field observations. The Milbrandt-Yau explicit precipitation scheme used in GEM-LAM gave reasonable liquid water content and cloud droplet diameters between 2 and 170 µm. This validation is important, and it is the first step to determine the in-cloud icing amount.

## 5. REFERENCES

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# IN-CLOUD ICING SIMULATION WITH GEM-LAM MODEL

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***Abstract*—In-cloud icing on structures such as transmission lines and wind turbines is an important consideration for both design (to withstand the load) and for operations (decreased efficiency of wind turbines, galloping of transmission line conductors). This physical phenomenon often occurs in coastal areas and over high terrain, where there are virtually no systematic observations. The objectives of this research project are two fold: 1) to explore the possibility of using an atmospheric mesoscale model for in cloud icing simulations and 2) to provide a database of model icing simulations for a climatological study of in-cloud icing. The regional GEM-LAM mesoscale model of the Canadian Meteorological Center (CMC) was used to model historical icing events during which observational data are available in Canada and in the United States (e.g. Mount Washington observatory). The simulation is designed using a triple-nested grid, with horizontal grid spacings of 10-km, 3-km and 1-km, and 62 vertical levels. This allowed us to get high resolution results in time and space. CMC analysis data are used as the initial conditions and the lateral boundary conditions for the domain of the 10-km coarse-resolution run. The 3-km simulation was initialized six hours after the 10-km run to allow for model spin-up, with the boundary conditions supplied by interpolating from the 10-km run outputs. Similarly, for the 1-km run, the spin-up time is three hours and lateral boundary conditions were derived from the 3-km simulation results. A newly developed sophisticated microphysics scheme (Milbrandt-Yau) is used in GEM-LAM. This explicit precipitation scheme predicts the mixing ratio, number concentration of individual hydrometeors (such as cloud droplets, rain droplets, ice, snow, graupel, and hail) and gives the detailed temporal evolution of the particle size distribution and cloud liquid water content. The microphysical variables, together with other meteorological variables, such as temperature and wind speed are important inputs for driving icing models, which are used to simulate ice accretion on transmission lines and wind turbines. An important first step in this work involves comparing the GEM-LAM simulated cloud moisture properties and other meteorological data with available near-surface observational data. Detailed comparisons of the GEM-LAM runs with Mount Washington observational data will be presented along with a discussion of the next steps of the research.**

***Keywords-icing simulation; GEM-LAM; partilce size distribution; liquid water content.***

## I. INTRODUCTION

In-cloud icing is a common phenomenon observed in coastal areas and high elevations, where water vapor pressure is easily saturated which provides favorable conditions for cloud droplet formation and temperatures are often below freezing. It affects both transmission lines [1] and the blades of wind turbines, which are usually installed in these high wind resource regions. The icing of rotor blades and control wind gauges results in wind turbine performance degradation and/or safety shutdowns. Because of this, not only must turbines be designed to withstand the ice load, but it is also necessary to predict icing occurrence and amount for the proper turbine operation.

Field studies are invaluable in research on in-cloud icing. However, they are done infrequently at a limited number of sites. This sparseness of direct measurements contributes to the difficulties in climatological studies of in-cloud icing. As a result, numerical modeling has become a useful tool to complement field measurements in the study of icing on wind turbines. For icing models, sufficiently accurate input data are important to determine the onset, duration and amount of icing [2]. The important meteorological factors include wind speed, temperature, cloud droplet size distribution and liquid water content, which can be obtained from NWP (Numerical Weather Prediction) models with sophisticated cloud microphysics schemes. In this paper, the regional GEM-LAM (Global Environmental Multiscale-Limited Area Model) mesoscale model of the Canadian Meteorological Center (CMC) was used to model an in-cloud icing event that occurred in December 1996 at the summit of Mount Washington in the United

States. The model description and strategy used are described in Section II. To gauge the performance of the GEM-LAM model, a comparison is made between results of model simulations and observations in Section III. Concluding remarks are given in Section IV.

## II. MODEL DESCRIPTION

GEM-LAM is a non-hydrostatic atmospheric model consisting of a dynamical core and various physics packages [3][4]. The governing equations are fully-compressible and give pressure, temperature, specific humidity, horizontal winds, vertical velocity as well as mixing ratio of cloud water, rain water, and ice substances. They are integrated using a semi-Lagrangian and semi-implicit numerical scheme. A terrain following log-hydrostatic-pressure coordinate system is used in the vertical. The physics packages include solar and infrared radiation treated interactively with clouds, a planetary boundary layer parameterization based on a time dependent turbulent kinetic energy with fully implicit vertical diffusion, and a stratified surface layer based on similarity theory.

The simulation is designed using a triple-nested grid (Fig. 1), with a primary simulation domain at horizontal resolution of 10-km, with the domain size 155x155. The other two nested domains have finer resolutions of 3-km and 1-km, with the domain size 246x246 (Fig. 1b) and 414x414 (Fig. 1c), respectively. As can be seen from Fig.1, finer-scale variations in topographic gradient is resolved by the high resolution of 1-km, and the topography over Mount Washington is very close to the real height. For all these three domains, there are 62 vertical levels. The spin-up times for 3-km and 1-km runs are six and three hours. Time steps for three simulations are 5min, 1min and 30s, respectively. GEM-LAM was first initialized with the Canadian Meteorological Centre (CMC) regional analysis for the 10-km run, and the lateral boundary conditions were updated every 6 h. The output of this run provides the initial and boundary condition for the next cascade run. The Kain-Fritcsh scheme is used as convection precipitation scheme for the first run, and the Milbrandt-Yau scheme is used to treat grid-scale cloud and precipitation in all three runs [5]. This explicit precipitation scheme is a bulk microphysics scheme, within which hydrometeor size distribution of each category is represented by an analytical function. Microphysical growth rates are formulated in two moments of the size distribution, i.e., particle number concentration and mixing ratio. In contrast to single-moment bulk schemes, the total number concentrations of hydrometeors are predictive quantities in this newly developed scheme, and the mean-mass hydrometeors for each category are diagnosed from these predictive variables.

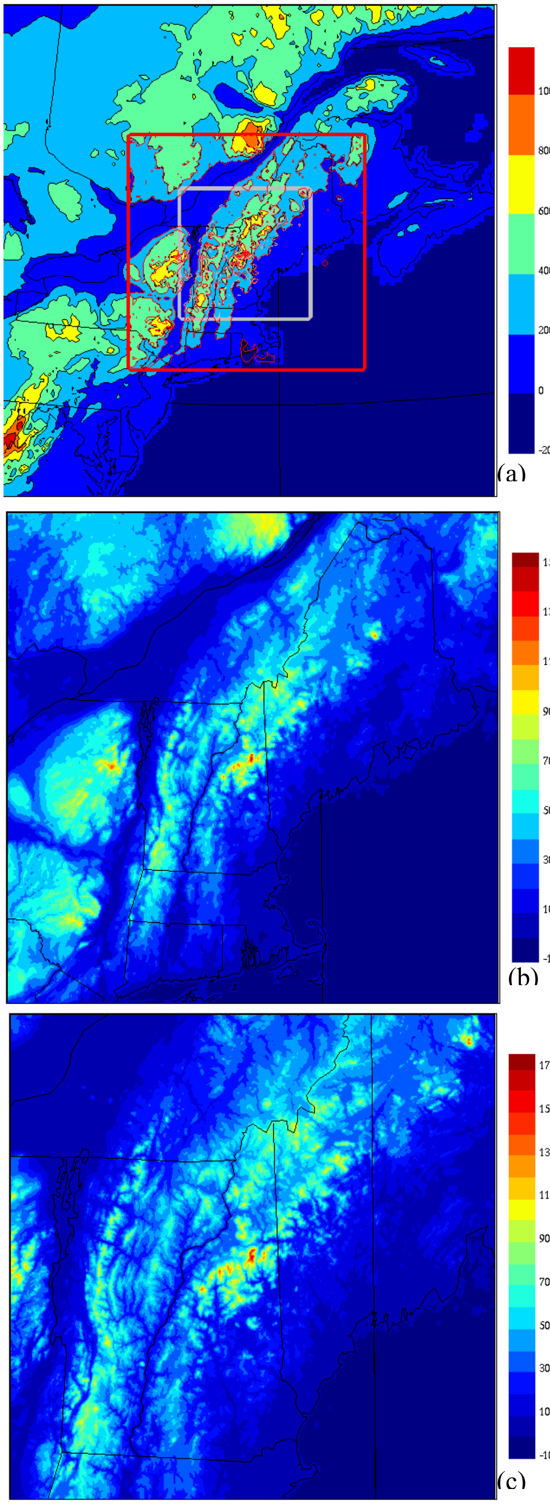

Figure 1. (a) Geographical domain covered by three domains. The coarse resolution of the large domain provides boundary conditions to the nested high resolution (b) domain 2 and (c) domain 3 over Mount Washington.

## III. OBSERVATION AND SIMULATION RESULTS

To explore the possibility of using an atmospheric mesoscale model for in-cloud icing simulations and providing a database of model icing simulations for a climatological study of in-cloud icing, the first step is to determine the validity of GEM-LAM in simulating cloud moisture properties and other meteorological parameters by comparing with available near-surface observational data. To this end, the in-cloud icing event which occurred on Mount Washington on 7 December 1996 was simulated, and the results were compared with the observation.

Mount Washington (44.267ºN, 71.3ºW), located in New Hampshire, is the highest peak in the northeastern United States with height of 1910m. Although the steep topographic gradient over this region poses a challenge for the simulation, the high resolution geophysical fields from CMC resolve the topography well. Because the summit is above the tree line and is covered by snow in the winter, the surface roughness length is corrected with the snow coverage and snow depth from the CMC analysis data. This avoids a significant wind reduction near the ground, which otherwise would occur due to an overly large surface roughness length. For a typical forested location the roughness length would be several meters, while for this simulation we used a roughness length of 0.01 m.

Clouds both above and below the summit, as well as intermittent fog with a little riming were reported starting in the morning of 6 December. Beginning shortly after midnight on 7 December the fog became persistent, and multicylinder runs were carried out to measure liquid water content and Median Volume Diameter (MVD). Details of the multicylinder analysis are given in [6]. The near surface temperature varied between -6ºC and -9ºC during the multicylinder runs, with the coldest temperature at around noon (Fig. 2). The wind speed increased during the daytime, reaching values of nearly 20 $ms^{-1}$ at noon. The reported wind speeds were measured at 11 m above ground and are the average for each multicylinder run, with durations between 10 and 35 minutes (averaging 25 minutes) in these conditions.

The modelled wind speed and air temperature from the 1-km run are also given in Fig. 2. The simulated values were obtained from half-hourly model output interpolated to the location of the summit of Mount Washington. Note the comparison in Figure 2 is between instantaneous simulated winds from a model with 1-km resolution, and measured winds averaged over ~25 minutes. Nevertheless, Fig. 2 shows that the model wind follows the evolution of the observed ~11m wind quite well. Also, there is a good agreement between simulated temperature and observed values, with differences of 2ºC or less.

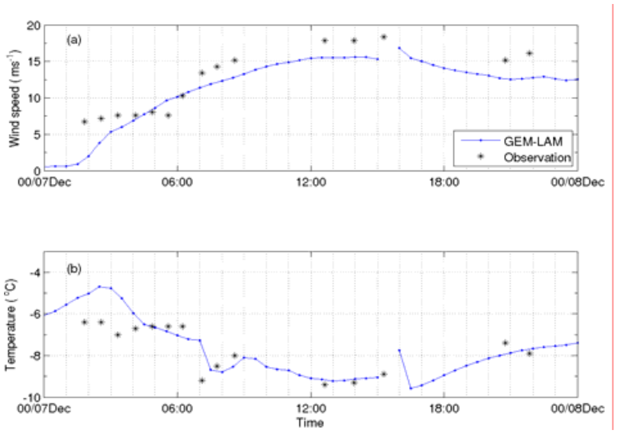

Figure 2. Comparison of observed and simulated (a) wind speed (unit: $ms^{-1}$) and (b) temperature (unit: ºC).

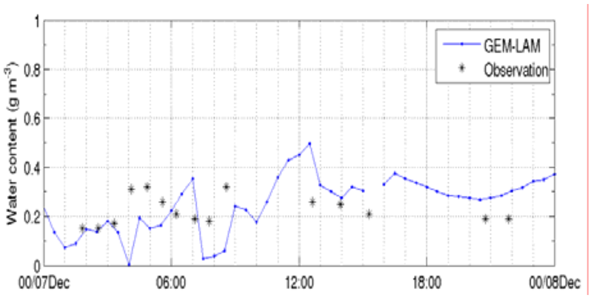

Figure 3. Comparison of observed and simulated liquid water content (unit: $gm^{-3}$).

Figure 3 compares the time evolution of simulated liquid water content with observations. The simulated liquid water content was generally smaller than the observed value at 8 m above ground from 0000 to 0900 LST, and larger after that. This is because the relatively dry air was advected from the northeast to Mount Washington during the early time of the model simulation, resulting in less cloud droplet formation. A cyclone from the south was seen to move northeast, and the surface winds over New Hampshire became southerly at 1900 LST on 7 December, bringing humid air and contributing to the cloud formation.

Mean mass diameter is one of the output fields from the Milbrandt-Yau cloud physics scheme. This diameter is diagnosed from the cloud mixing ratio and total number concentration. However, the observation gives the Median Volume Diameter ($D_{mvd}$), which is the droplet diameter for which half the volume of cloud water is in smaller droplets and half is in bigger droplets

$$\int_0^{D_{mvd}} D^3 F(D)dD = \int_{D_{mvd}}^{\infty} D^3 F(D)dD\,. \tag{1}$$

Here, $F(D)$ ($m^3m^{-1}$) is the droplet number concentration of diameter $D$(m). In the Milbrandt-Yau scheme within GEM-LAM, cloud droplets are assumed to follow gamma size distribution

$$F(D) = \frac{ND^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)}\exp(-D/\beta)\,, \tag{2}$$

whereas $\alpha$ and $\beta$ (m) are respectively the dimensionless shape parameter and the scale parameter of the distribution, and $N$ ($m^{-3}$) is the total number concentration. Substituting (2) into (1), gives the following equation for $D_{mvd}$

$$\gamma(\alpha+3, D_{mvd}) = \Gamma(\alpha+3, D_{mvd})\,. \tag{3}$$

In (3), $\gamma$ and $\Gamma$ are lower and upper incomplete gamma functions respectively. With the simulated droplet size distribution, $D_{mvd}$ can then be calculated through numerical iteration. Figure 4 gives the droplet size distribution and the third moment of the spectrum at 0100, 0500, 1000 and 1500 LST on 7 December. In comparison to the early hours on 7 Dec, the droplet spectrum after 0600 LST became narrower, and shifted to the small droplet size. The third moment of size distribution determines $D_{mvd}$, which is depicted in Fig. 5 as well as mean mass diameter from GEM-LAM and the observed $D_{mvd}$. The simulated value is larger than the observed at most time. Nevertheless, the order of magnitude is same, and there is moderately good agreement between the simulated and observed values. The large oscillations of $D_{mvd}$ in the GEM-LAM prior to 0600 LST is related to the oscillating cloud number concentration, which may be due to the saturation adjustment technique to avoid over-condensation (or over-evaporation) in one time step.

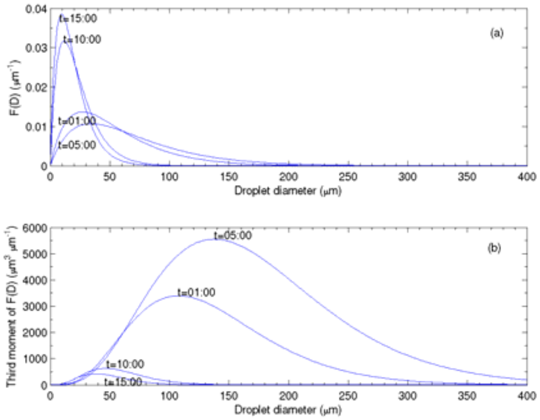

Figure 4. (a) Droplet size distribution *F(D)*(unit: $\mu m^{-3}$) and (b) the third moment of droplet size distribution $D^3F(D)$ at 0100, 0500, 1000 and 1500 on 7 December,1996.

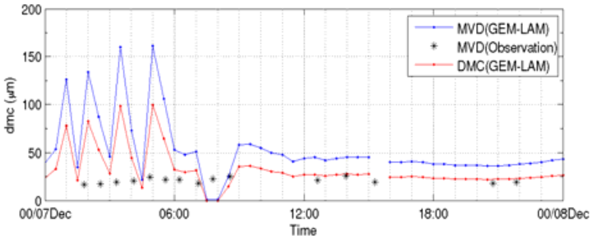

Figure 5. Comparison of observed and simulated cloud droplet diameter (unit: μm) .

## IV. CONCLUDING REMARKS

This paper describes an in-cloud icing event which occurred on Mount Washington, and the GEM-LAM model used to simulate this case. The modelled temperature and wind speed compared favourably to field observations. The Milbrandt-Yau explicit precipitation scheme used in GEM-LAM gave liquid water contents between 0 and 0.5 g $m^{-3}$, compared to observed values between 0.15 and 0.32 g $m^{-3}$, and $D_{mvd}$s of between 2 μm and 170 μm, compared with observed $D_{\mathrm{mvd}}$s between 16 and 26 μm. This validation effort is important, and it is the first step in simulating in-cloud icing. The results of the icing simulation will be presented in the conference.

## ACKNOWLEDGMENTS

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