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

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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

		Production Losses	
Region	**Capacity (MW)**	**Ref. Year**	**Ref. Winter**
AB+MB	254	3.2%	5.7%
ON	688	3.5%	5.7%
QC	445	7.4%	12.4%
NB+NS	285	15.7%	26.5%
PEI+NL	96	3.4%	5.8%

From Lacroix & Tan, 2012

Method

- *Determine a reference production level*
- *Compare actual production with reference level*
- *Calculate losses*
- *Corresponding values in $*

Cold climate related production losses for wind farms in Canada

	Planed capacity (MW)	Annual Production (MWh)	Annual production loss (MWh)	Annual production loss (%)	Annual loss ($)
Existing wind farms	5260	14,284,490	1,009,626	6.6%	99,880,577
Future wind farms*	9804	26,624,557	1,143,787	4.12%	92,287,584
Total	15064	40,909,048	2,153,413	5.00%	192,168,161

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

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 ºC, 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

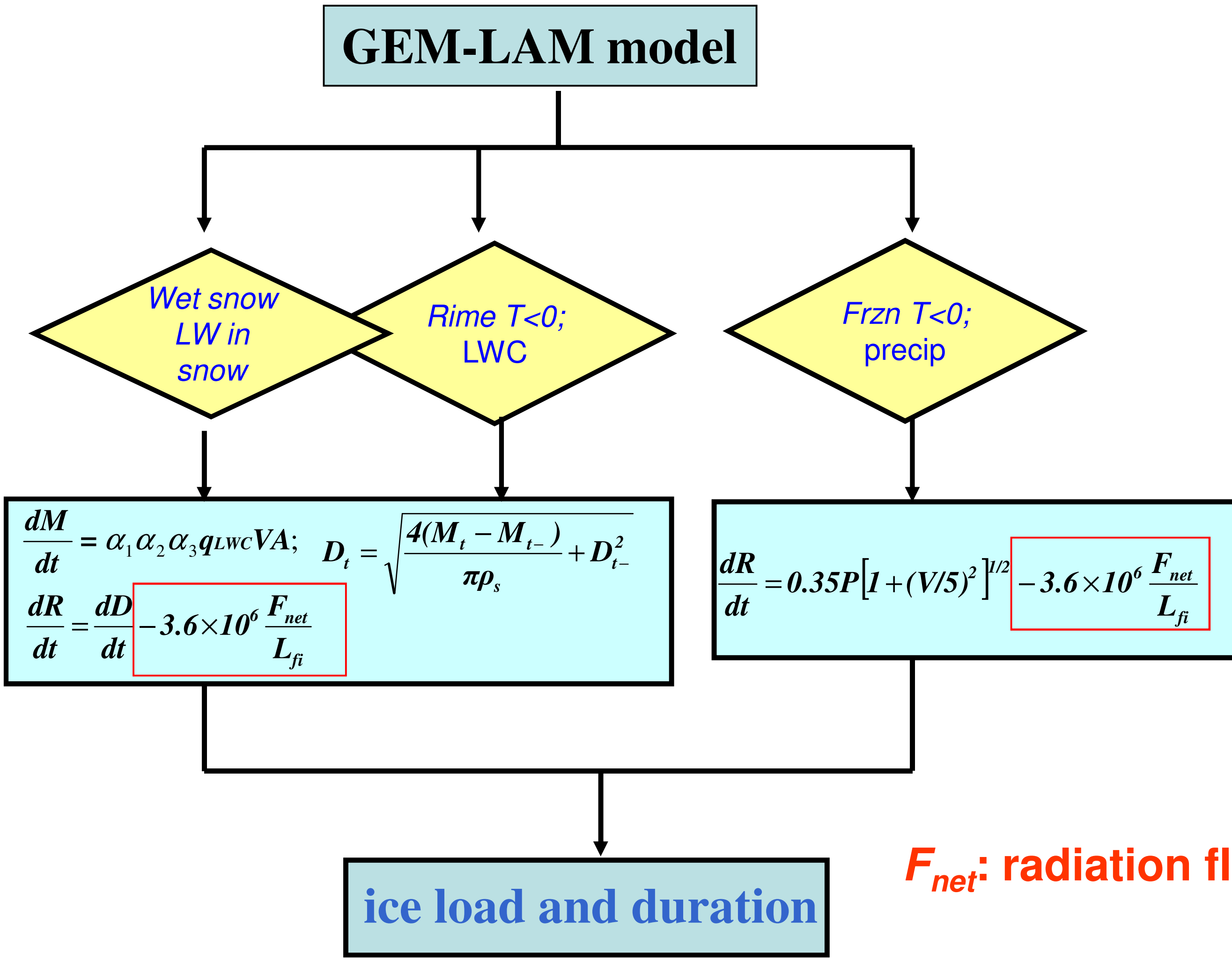
Introduction

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)



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: (44.3º N, 71.3º W) with elevation 1910 m

Climatology (1971-2000): T=-3° C; U=19ms^{-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

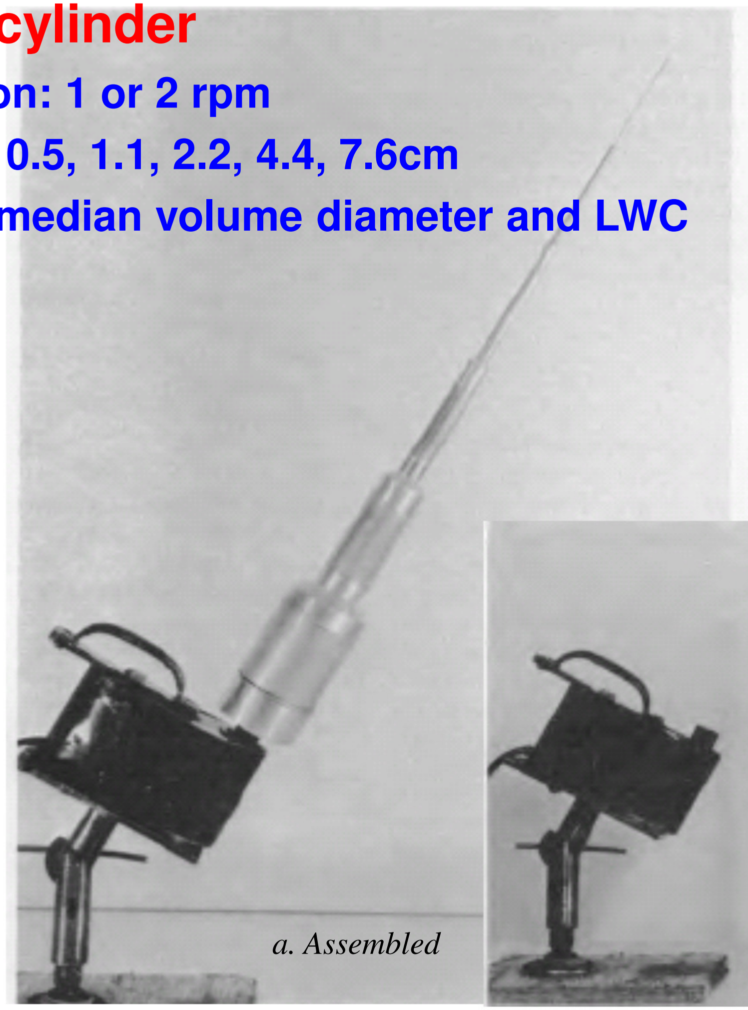
Observations

multicylinder

Rotation: 1 or 2 rpm

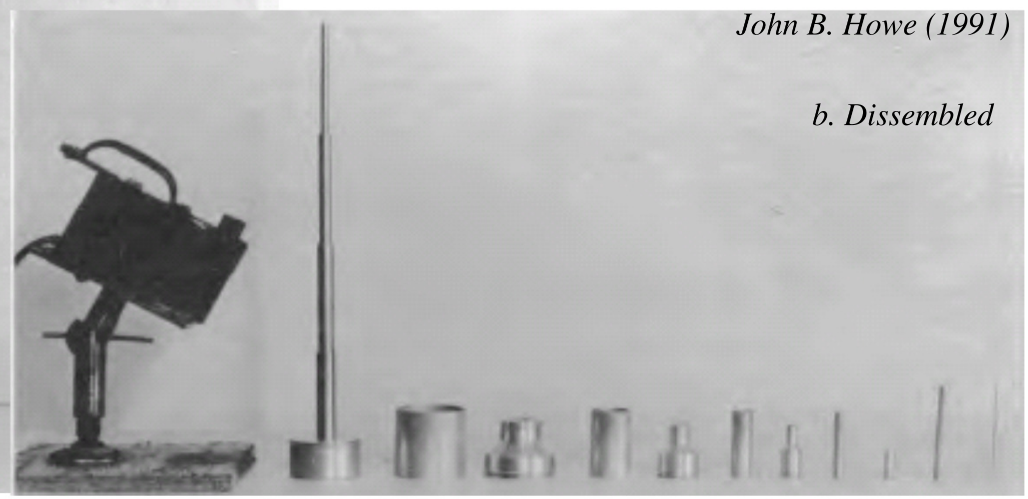
D: 0.2, 0.5, 1.1, 2.2, 4.4, 7.6cm

to get median volume diameter and LWC



a. Assembled

John B. Howe (1991)



b. Dissembled

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Observations

by CRREL personnel

Intensive observation dates:

Obs1: 11/27/1992 - 12/01/1992

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

Observations

Selected cases:

Obs1: 11/27/1992 - 12/01/1992

Obs2: 03/09/1994 - 03/15/1994 (SW)

Obs3: 02/09/1995 - 02/14/1995

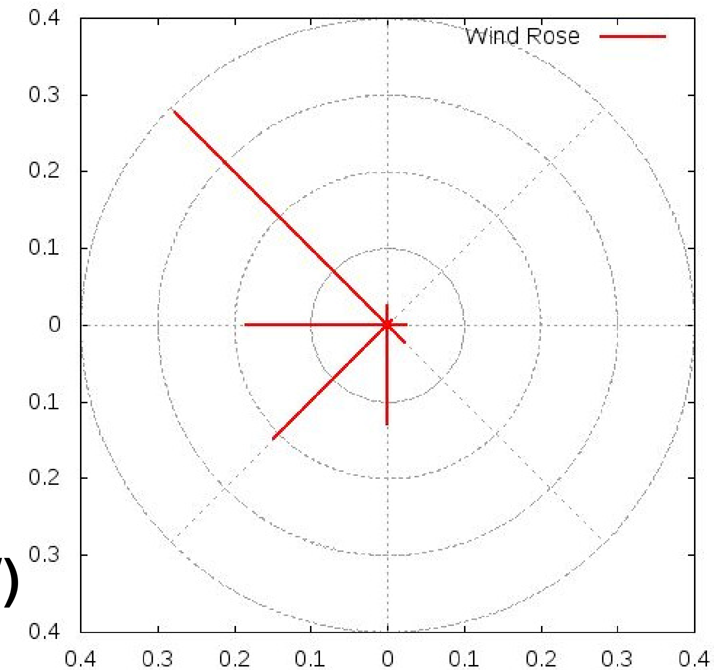
Obs4: 12/01/1995 - 12/04/1995

Obs5: 03/20/1996 - 03/26/1996 (NW)

Obs6: 12/06/1996 - 12/07/1996

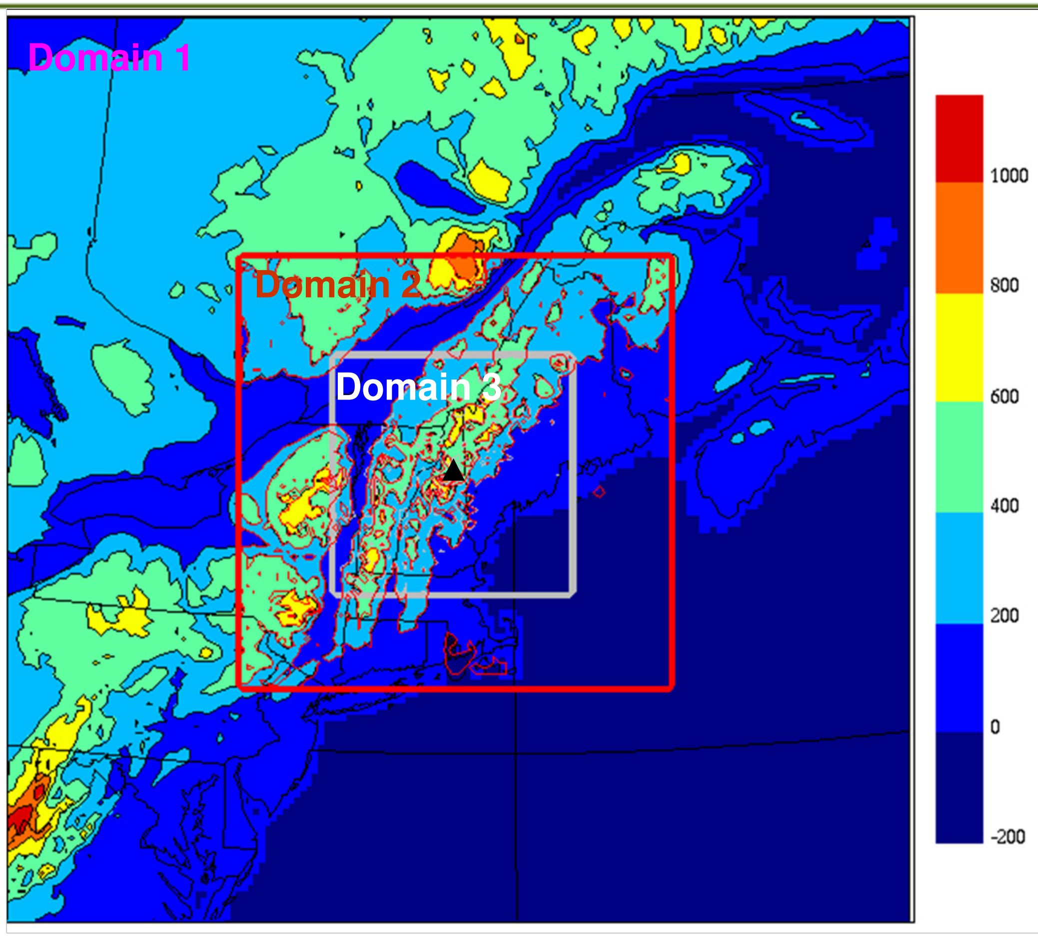
Obs7: 03/10/2011 - 03/13/2011 (S&W)

low level wind direction



Representative of the prevailing wind direction

Model- nested domains



Domain 1: 10km, 154x154

Domain 2: 3km, 234x234

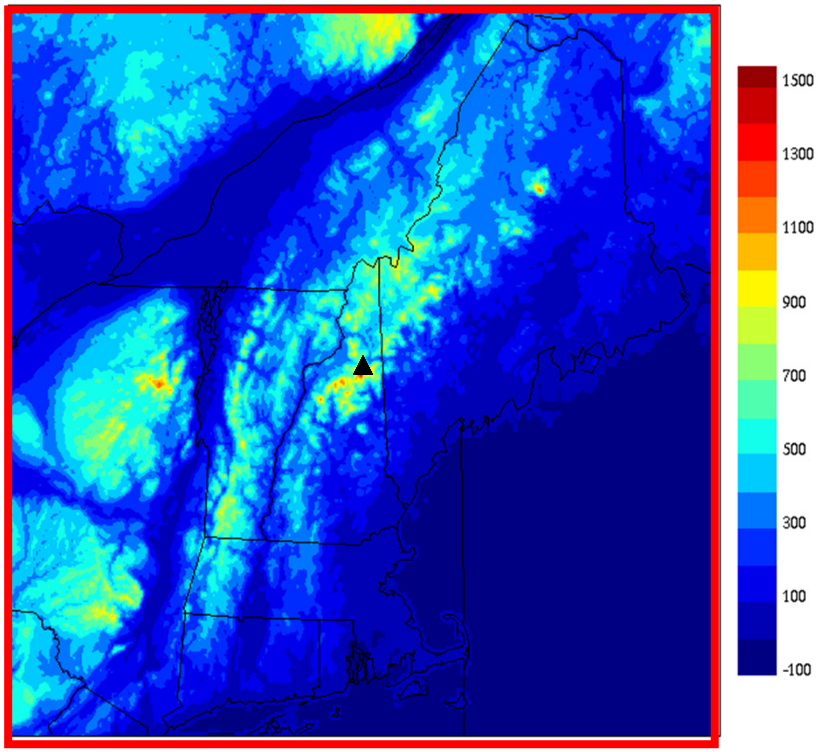
Domain 3: 1km, 414x414

▲ Mount Washington with elevation 1910 m

1020 m (10-km)

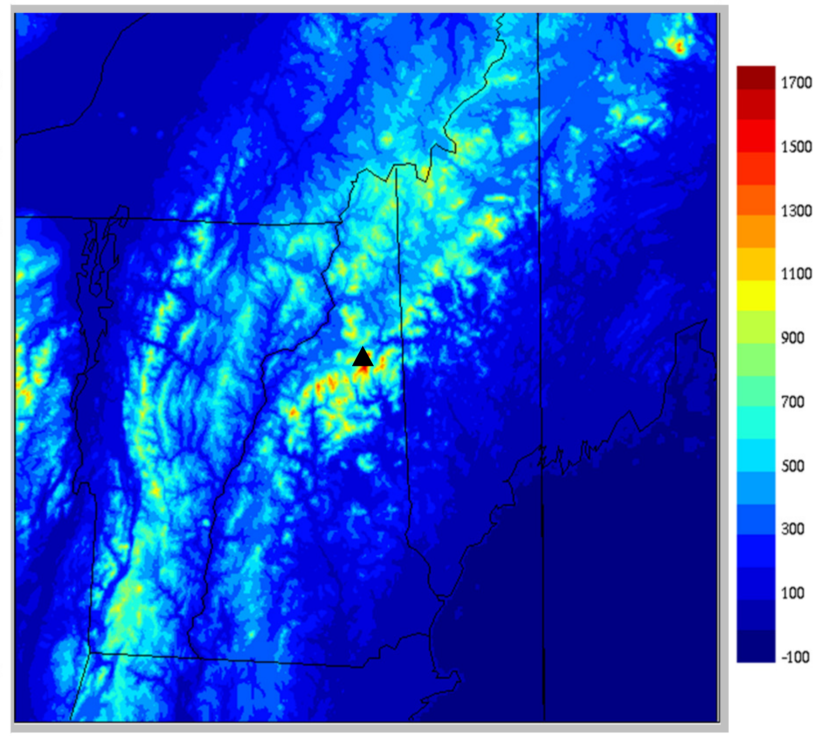
Model- sub-domains

Domain 2: 3km, 234x234



1560 m (3-km)

Domain 3: 1km, 414x414



1775 m (1-km)

▲ Mount Washington with elevation 1910 m

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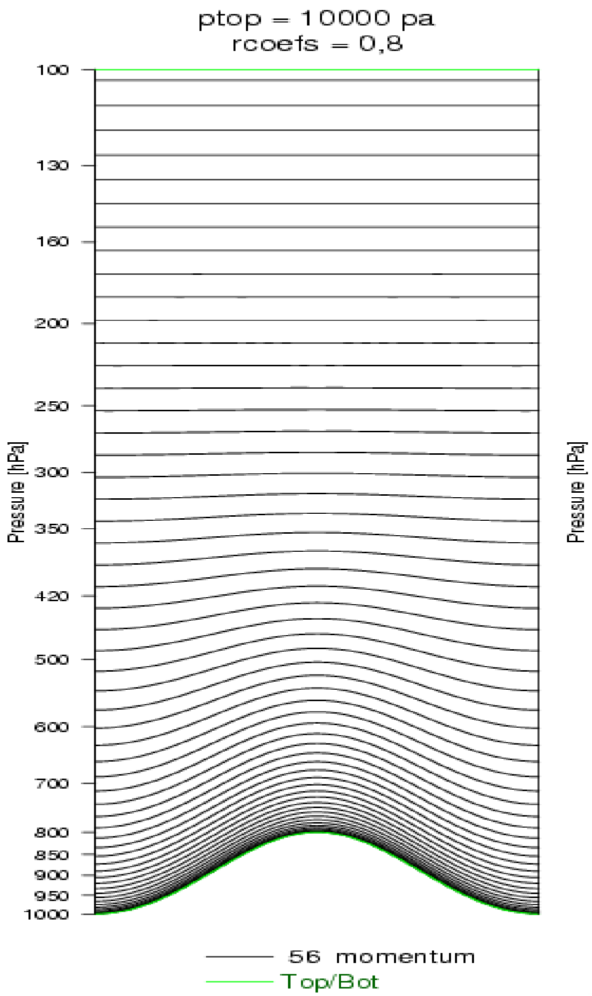
Model- vertical level settings

56 vertical levels

	Zm	Zt
...	...	...
0.9198	581	531
0.933	482	437
0.9451	392	352
0.9562	311	276
0.966	240	210
0.9745	179	154
0.9818	128	108
0.9875	87	72
0.9918	57	46
0.9949	36	28
0.997	21	16
0.9985	10	7
0.9995	3	1.5



Model- configuration

Initial and boundary conditions:

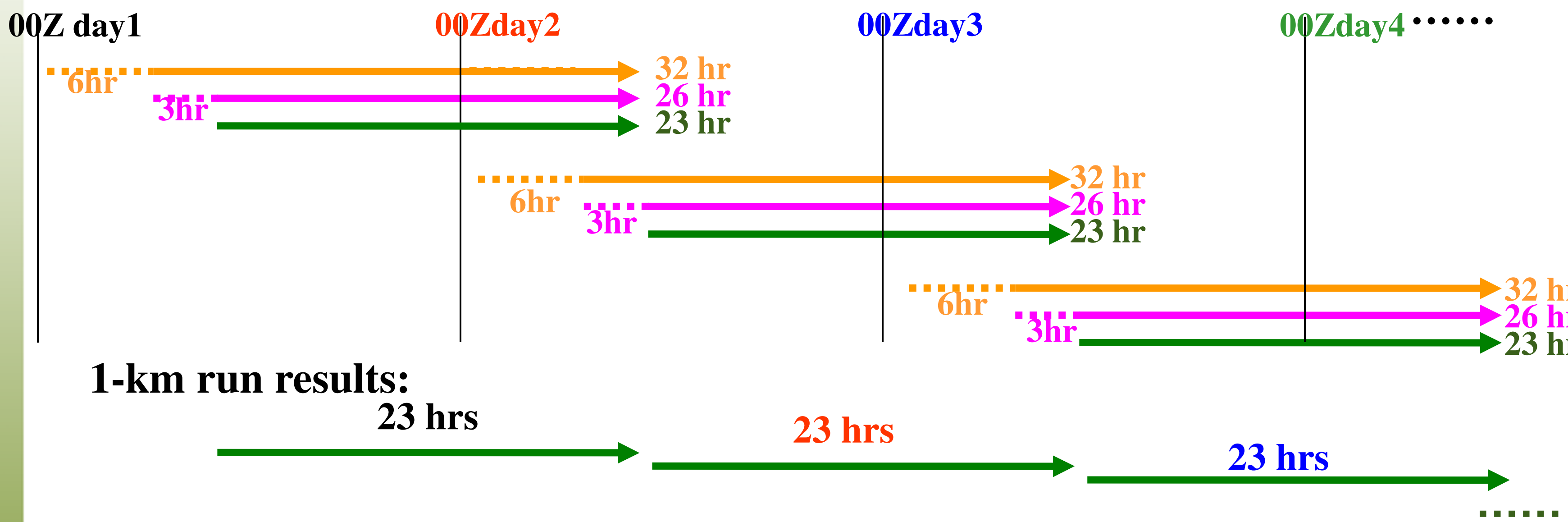
CMC 6-hourly regional analysis data, (~35km/16 levels)

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



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 (ºC)

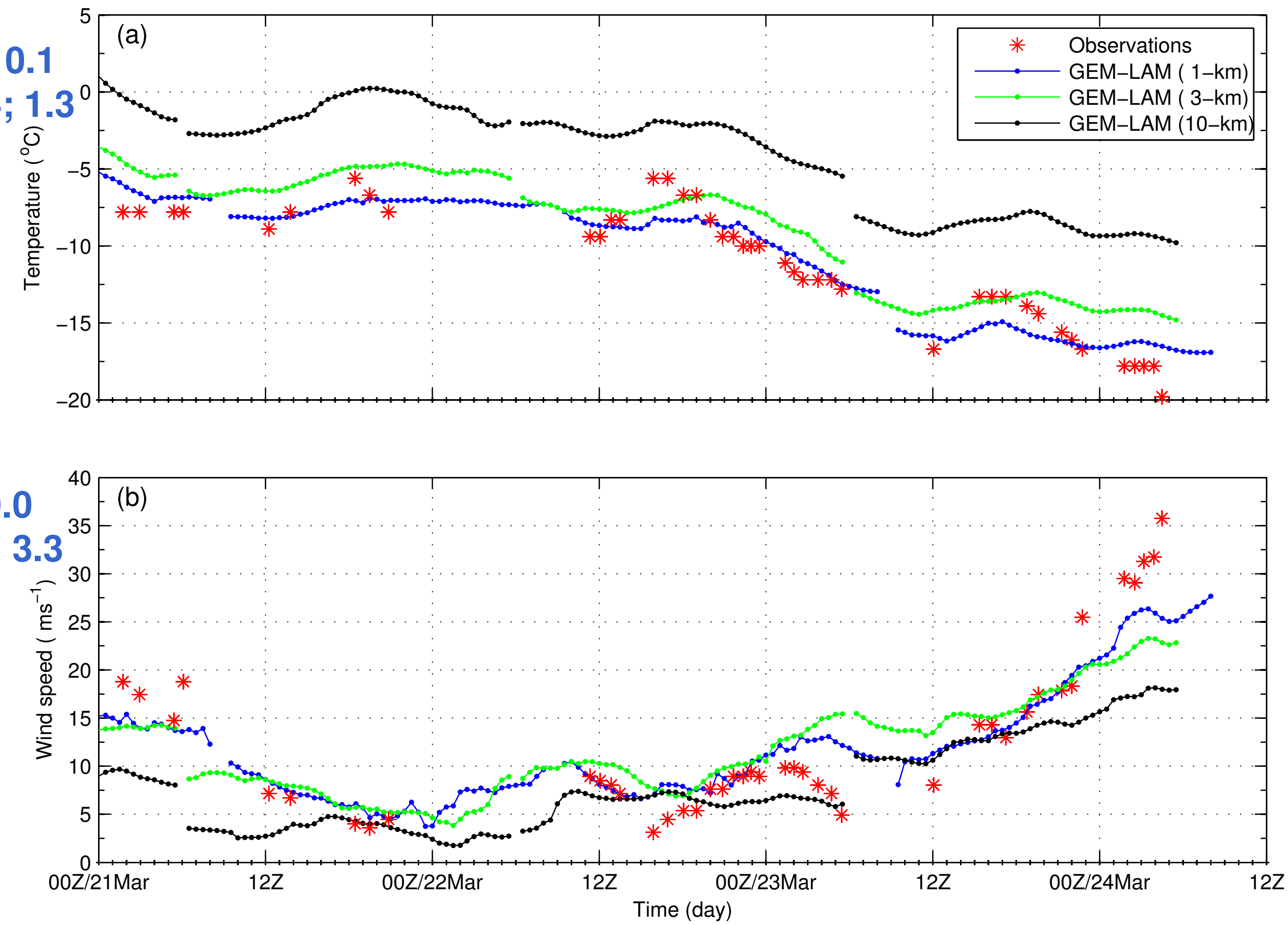
Bias: 6.7; 1.9; 0.1

RMSE:6.8; 2.4; 1.3

U (ms^{-1})

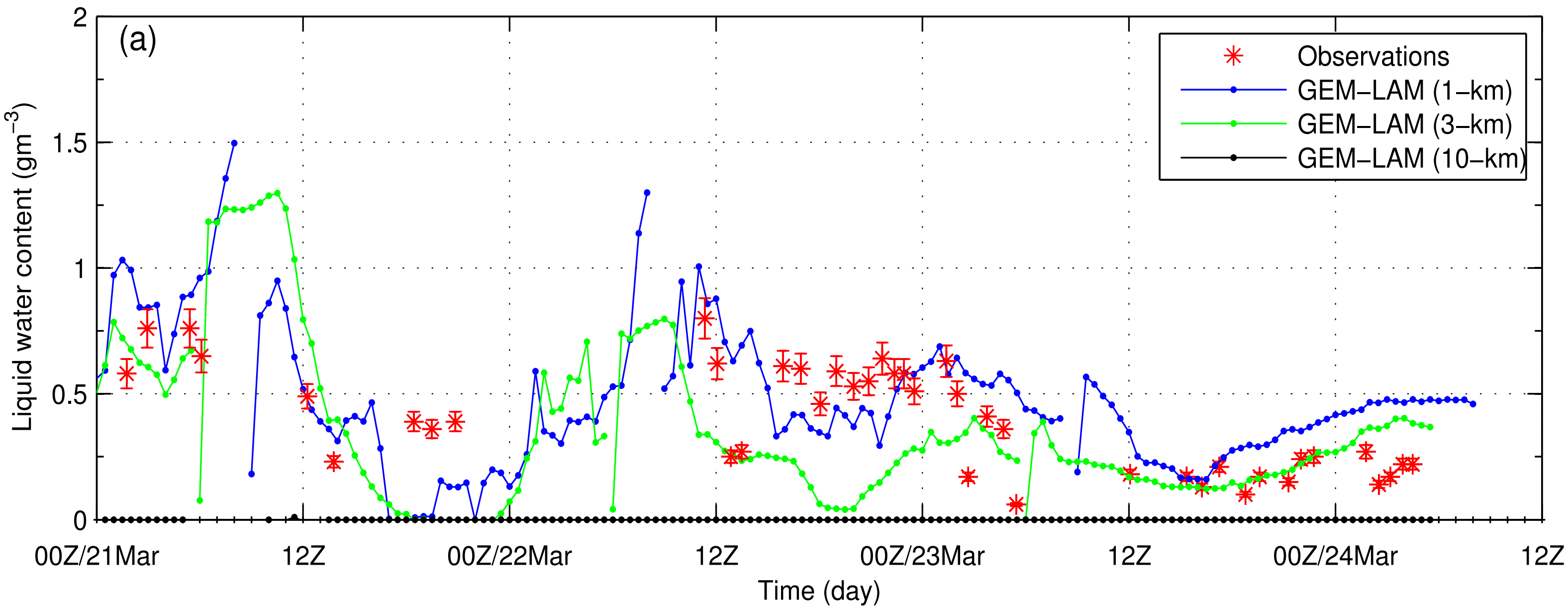
Bias: -3.6 0.4 0.0

RMSE:6.1; 4.5; 3.3



Simulation results- case 1 (Mar 1996, NW)

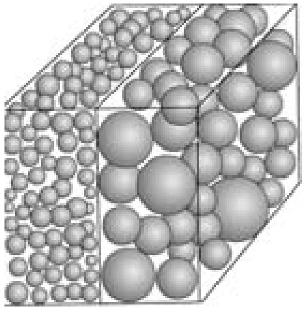
LWC (gm^{-3})
Bias: -0.39; -0.12; 0.08
RMSE:1.08; 0.26; 0.23



Simulation results- case 1 (Mar 1996, NW)

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

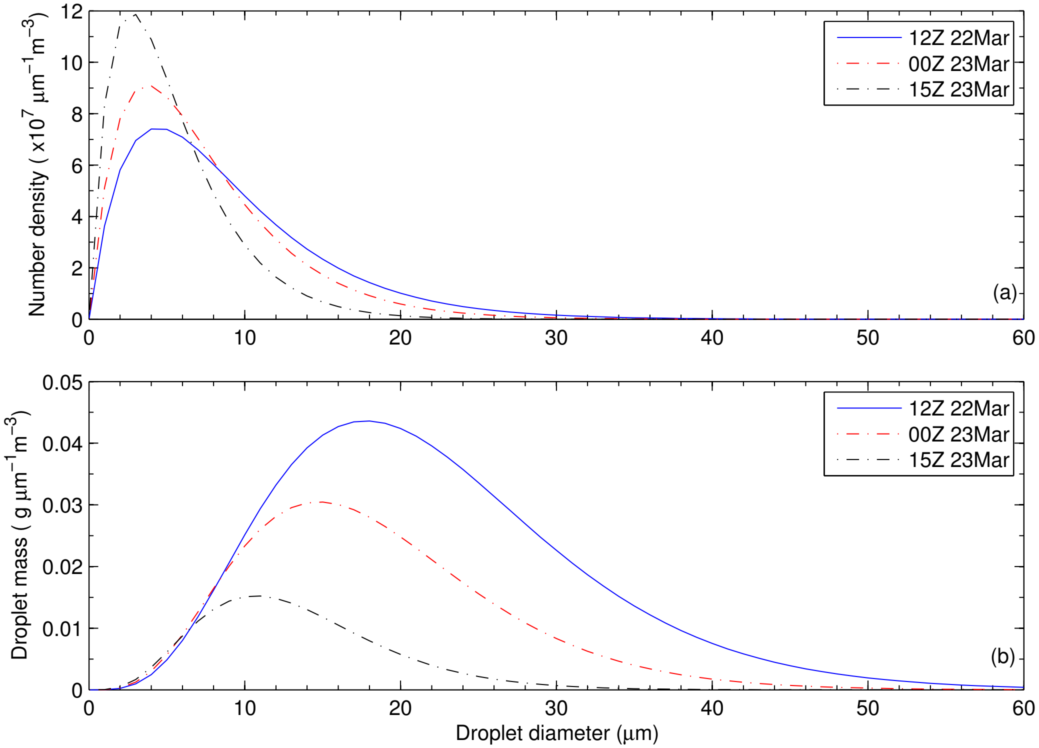
MVD: half of the cloud water is in larger droplets and half is in smaller droplets (calculated from droplet size distribution).



Size distribution

$$F(D) = \frac{N D^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)} e^{(-D/\beta)}$$

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



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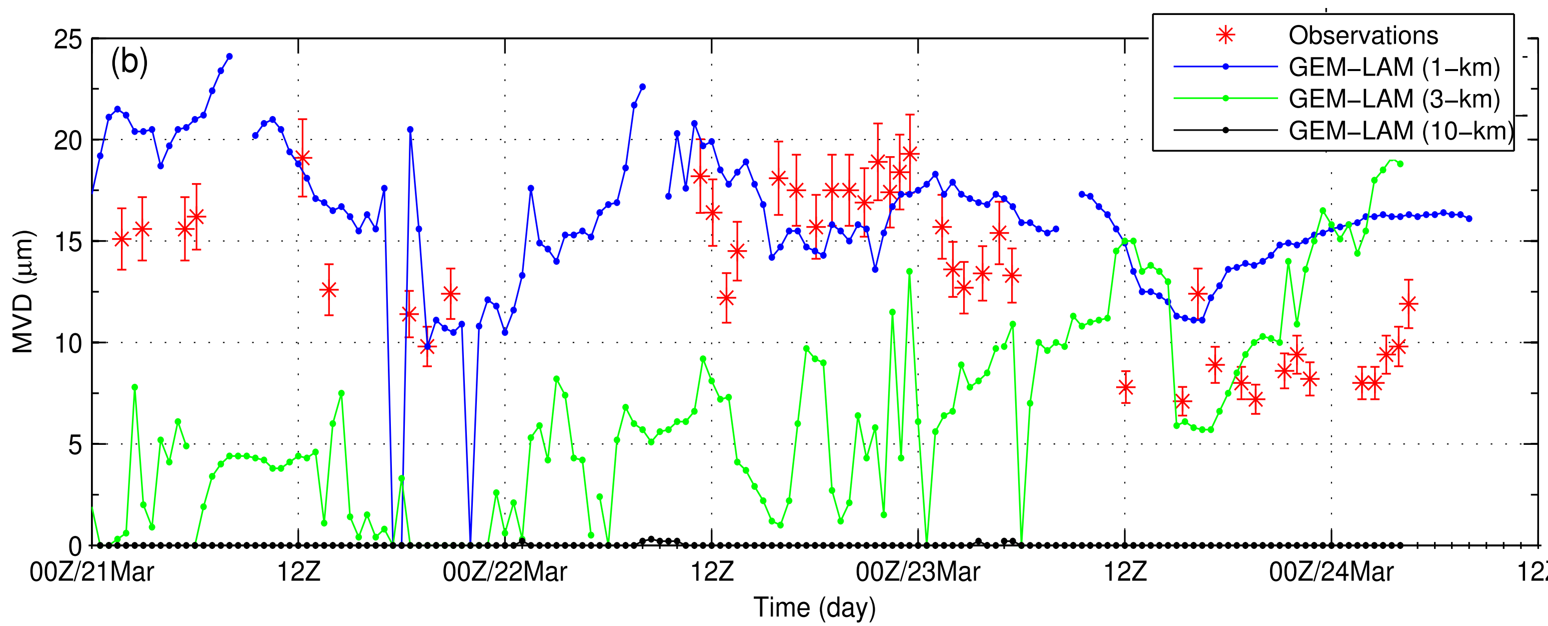
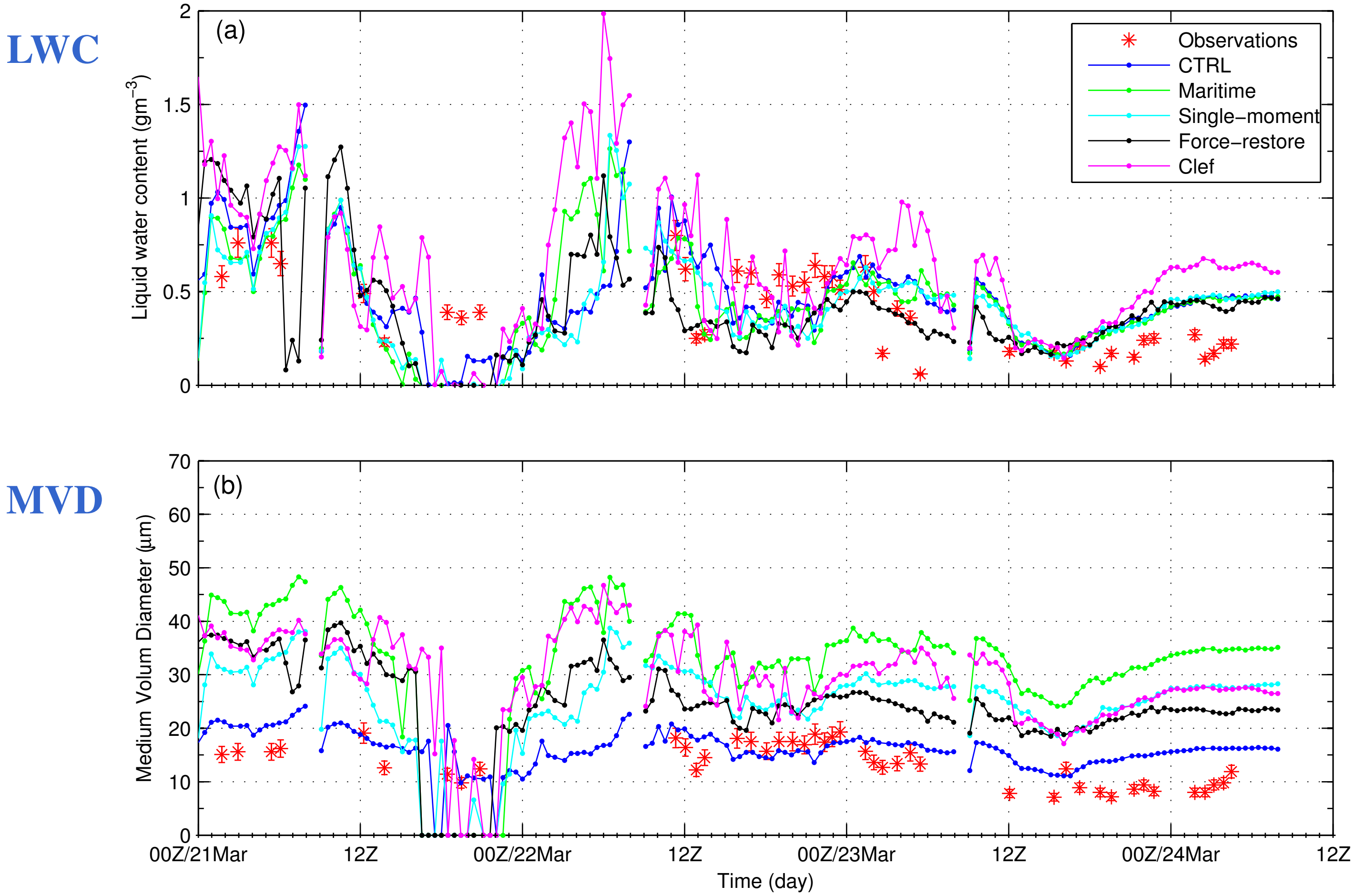
Simulation results- case 1 (Mar 1996, NW)

MVD (μ*m*)

Bias:-13.3, -5.5, 2.8   RMSE:13.8, 9.6, 4.6



Simulation results- case 1 (Mar 1996, NW)



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Simulation results- case 1 (Mar 1996, NW)

Simulated fields compared to observations for sensitivity tests (1-km simulation)

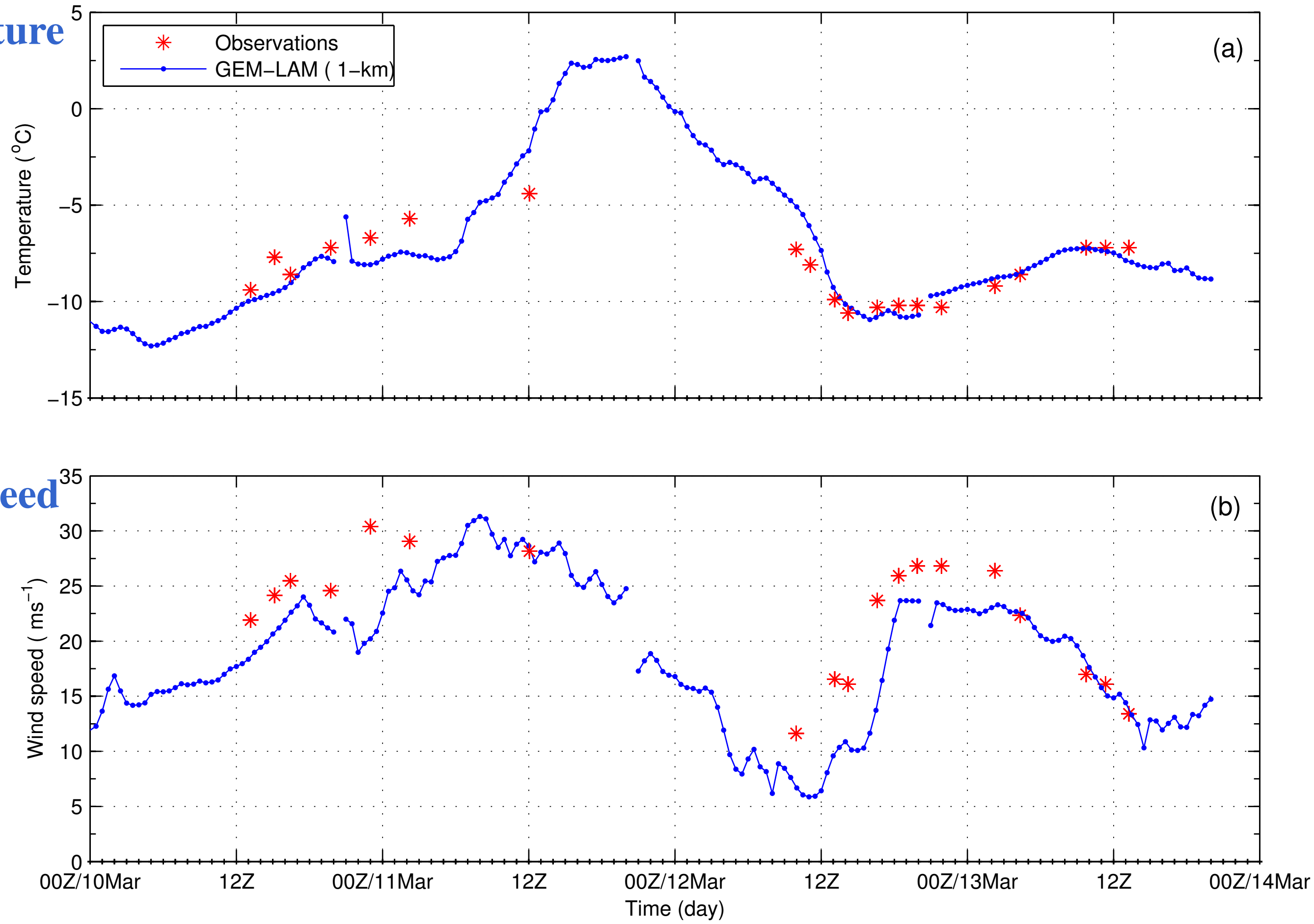
Schemes	RMSE				Bias			
	T (ºC)	V (m s^{-1})	LWC (g m^{-3})	MVD (μm)	T (ºC)	V (m s^{-1})	LWC (g m^{-3})	MVD (μm)
CTRL	*1.3*	*3.3*	*0.23*	*4.6*	*0.1*	*0.0*	*0.08*	*2.8*
Maritime(CCN)	1.3	3.3	0.22	20.6	0.2	0.1	0.03	18.4
Single-moment	1.3	3.4	0.23	13.5	0.2	0.2	0.02	11.2
Force-restore	1.6	3.4	0.25	12.4	0.8	0.3	0.01	10.0
Clef	1.4	3.7	0.36	16.1	0.4	-0.1	0.17	13.6

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)

Temperature

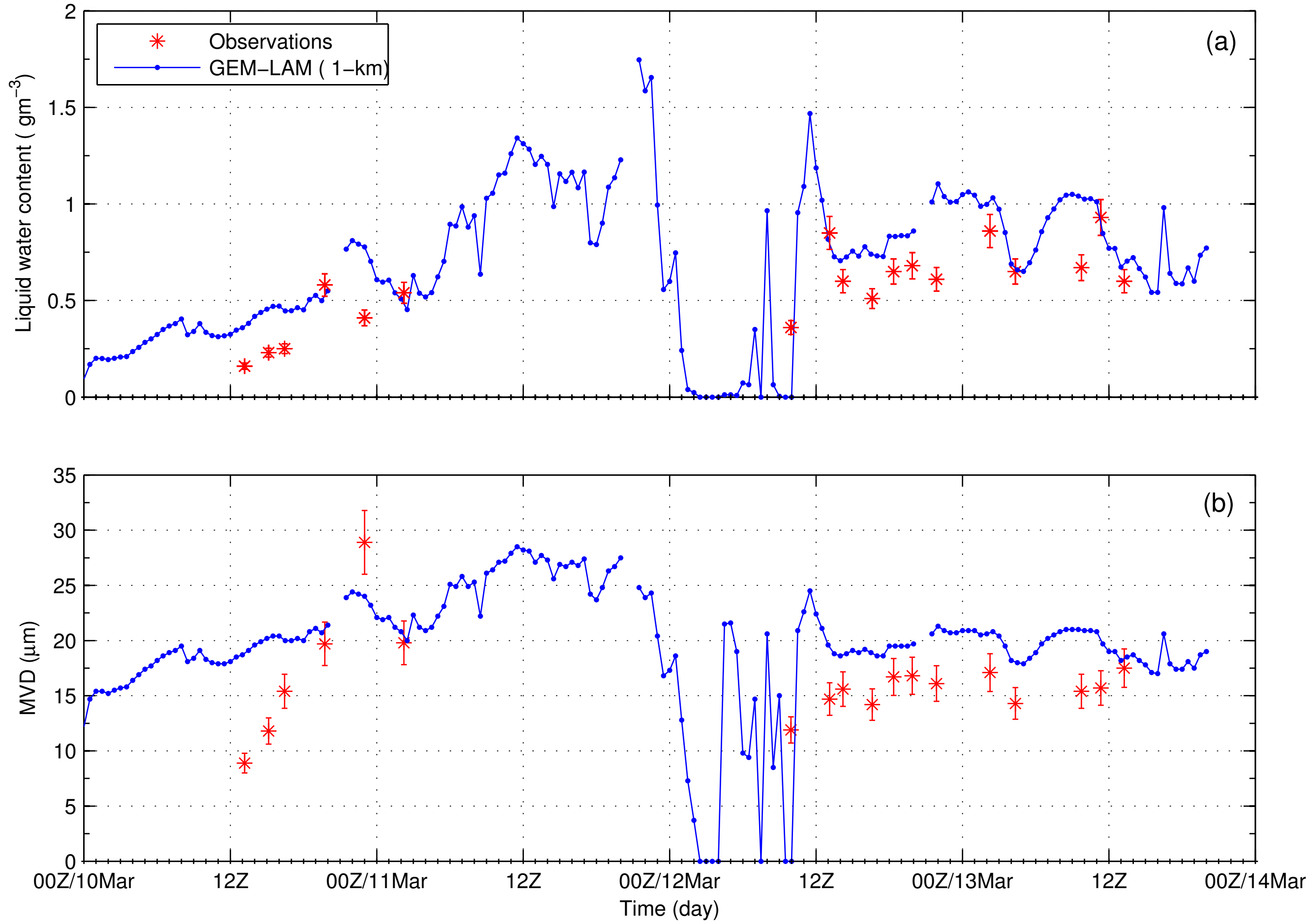
Wind speed



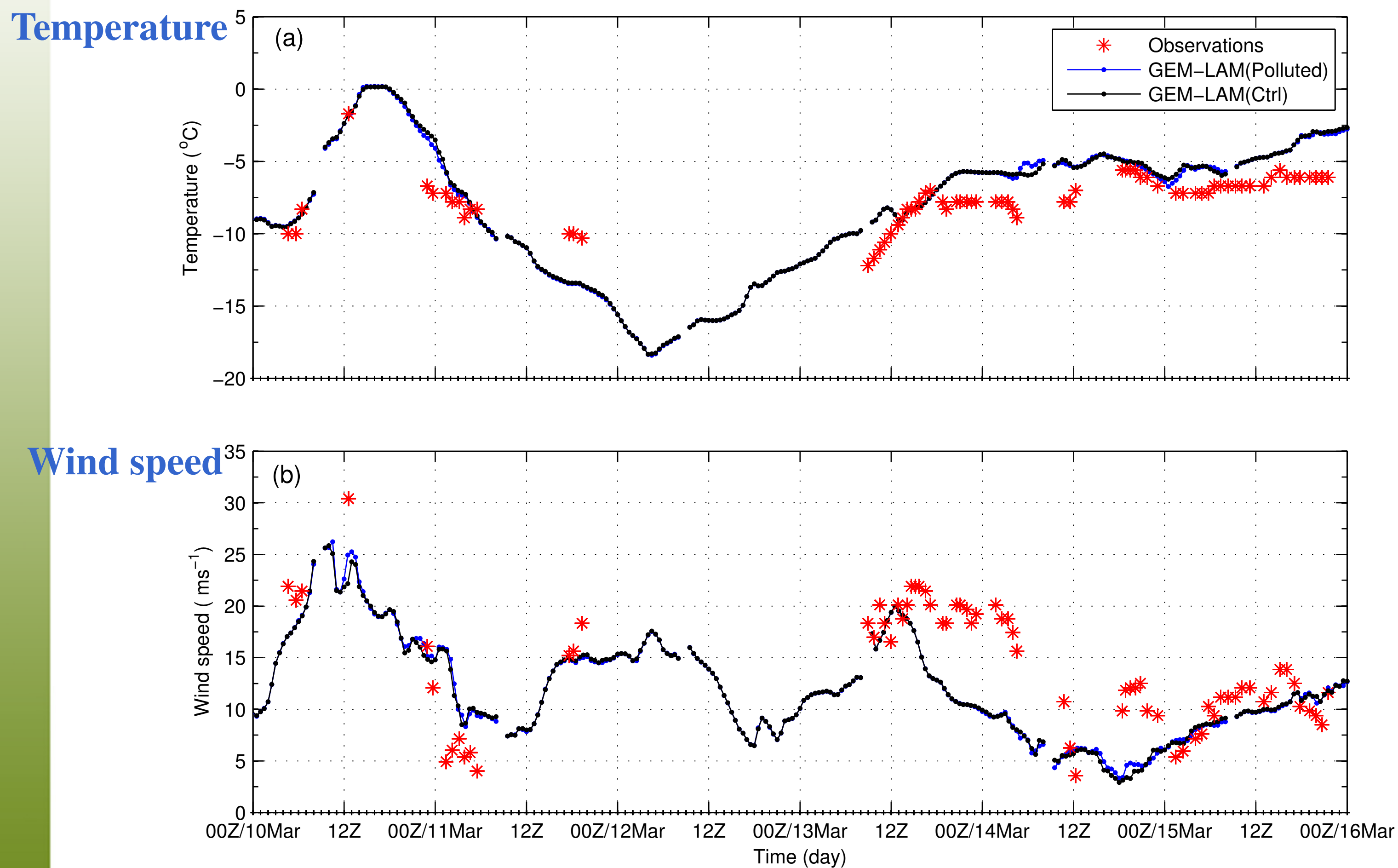
Simulation results- case 2 (Mar 2011, S&W)

LWC

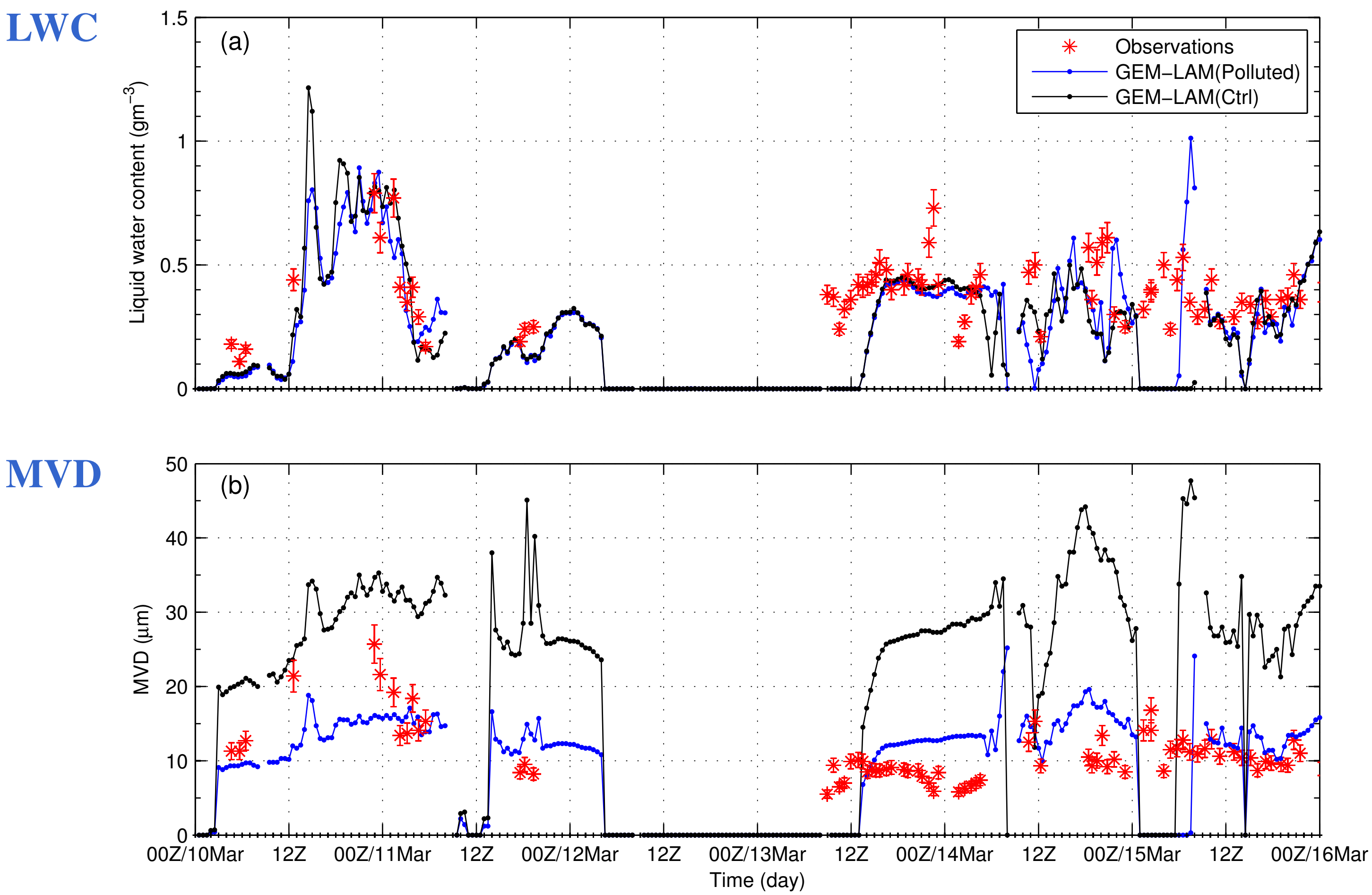
MVD



Simulation results- case 3 (Mar 1994, SW)



Simulation results- case 3 (Mar 1994, SW)



Simulation results- three cases

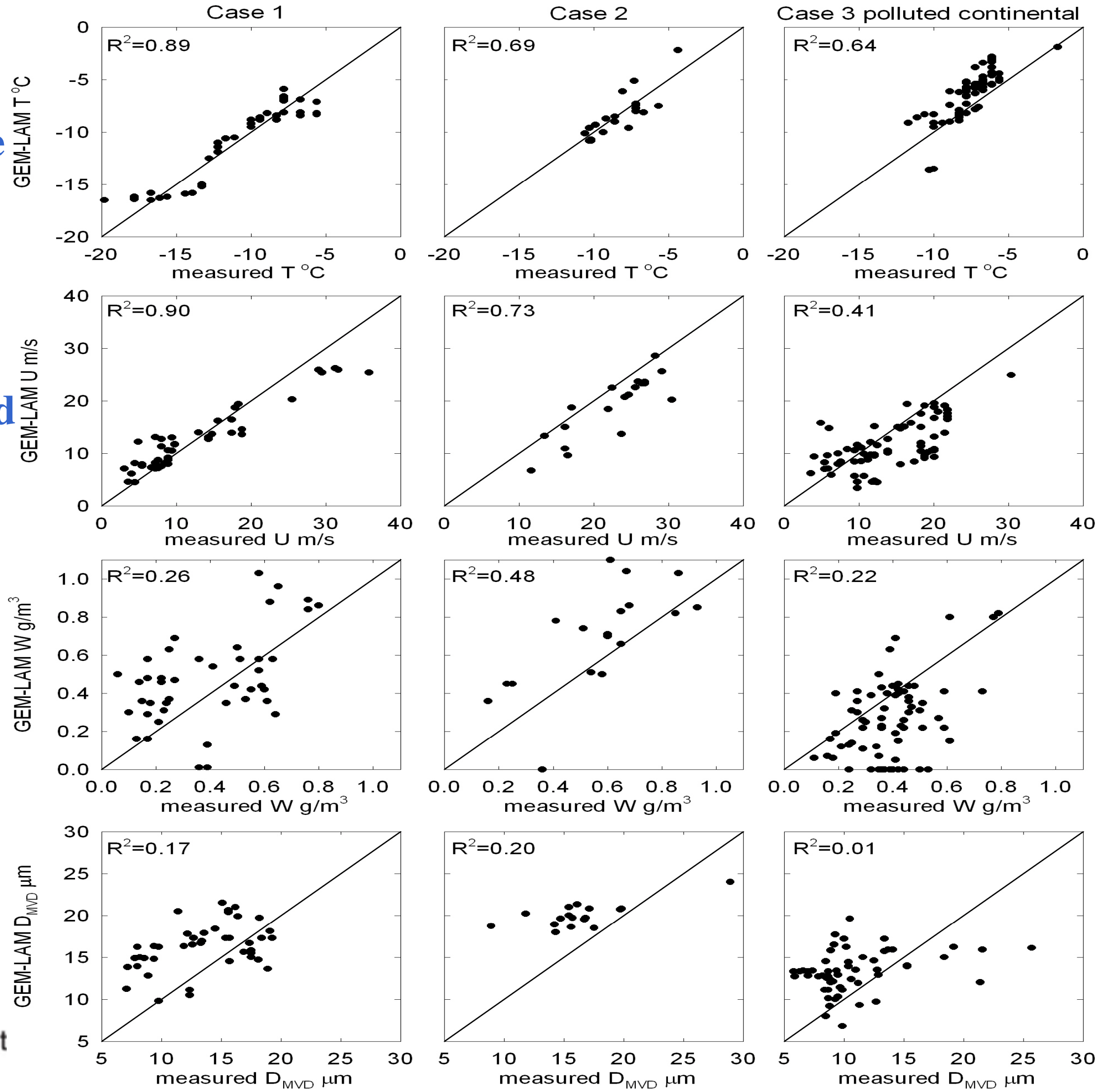
R^2

Temperature

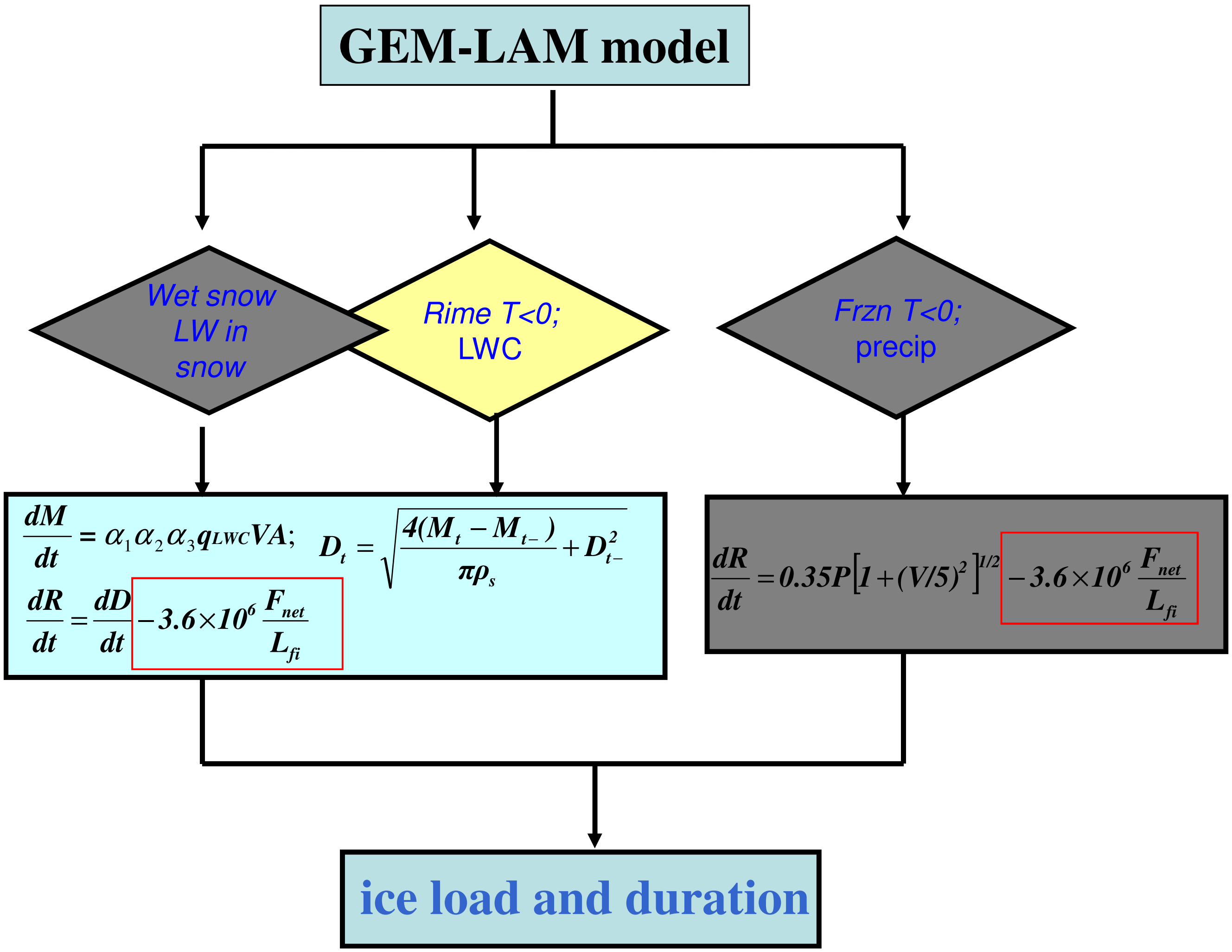
Wind speed

LWC

MVD



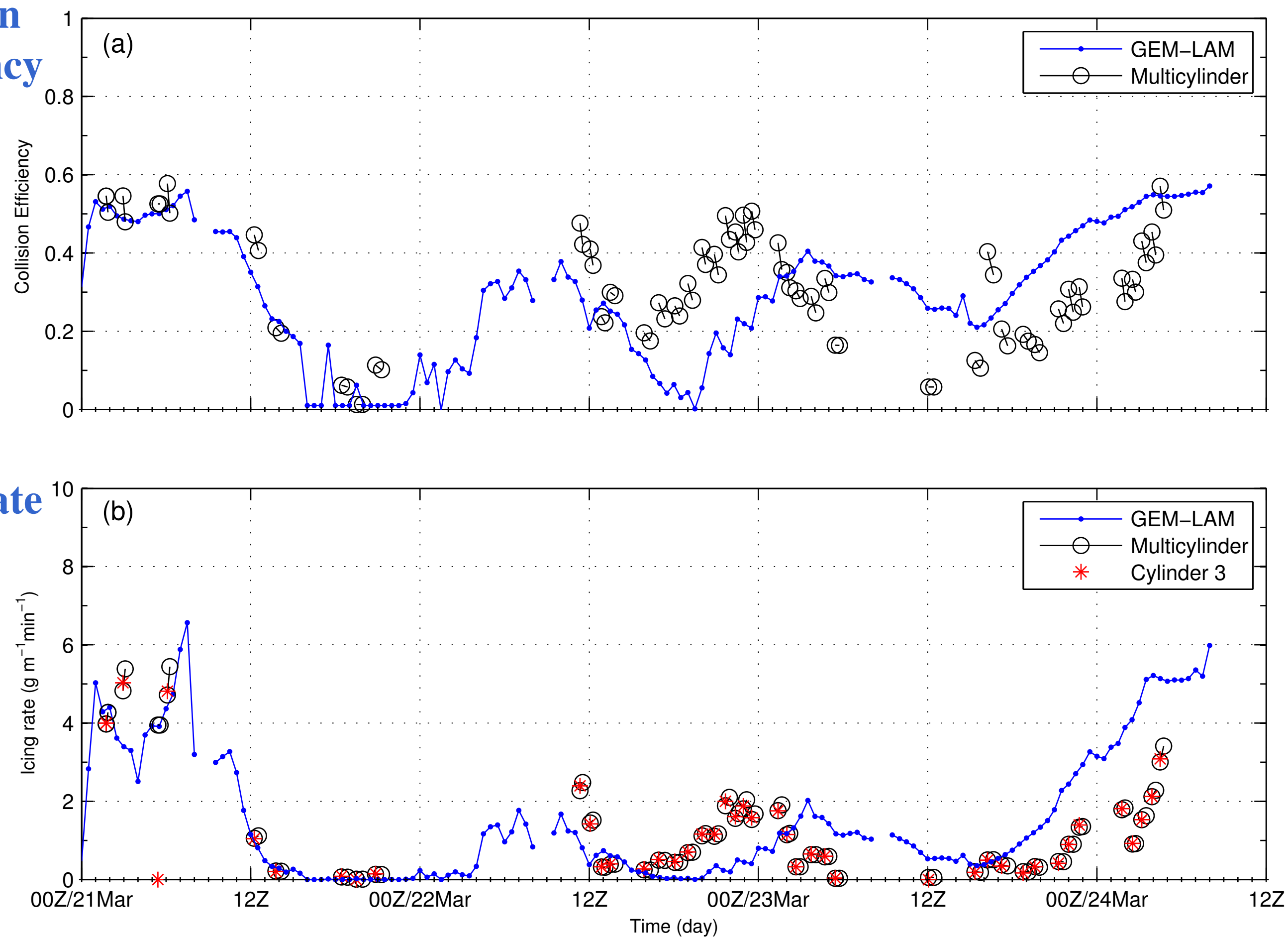
Model- icing models (riming,freezing rain,wet snow)



Model- collision efficiency and icing rate (case 1)

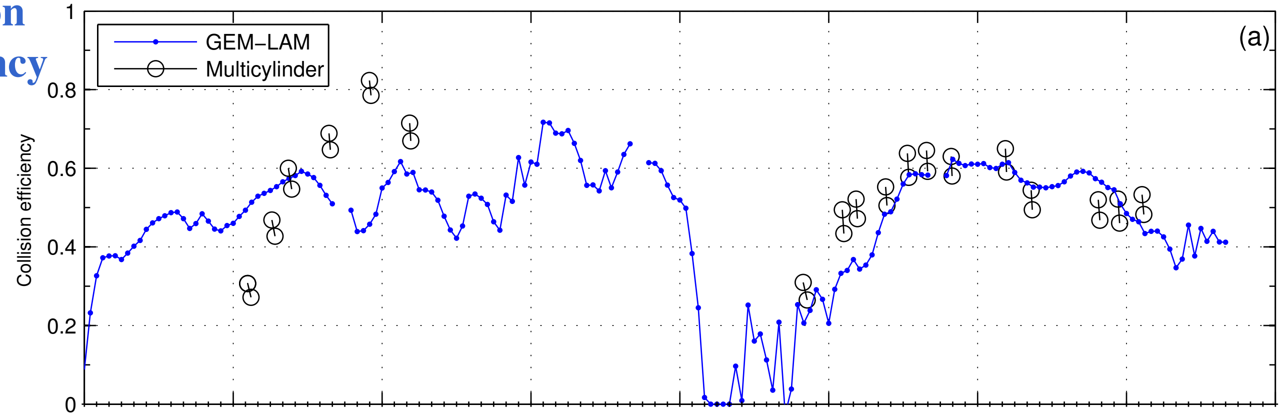
collision efficiency

icing rate

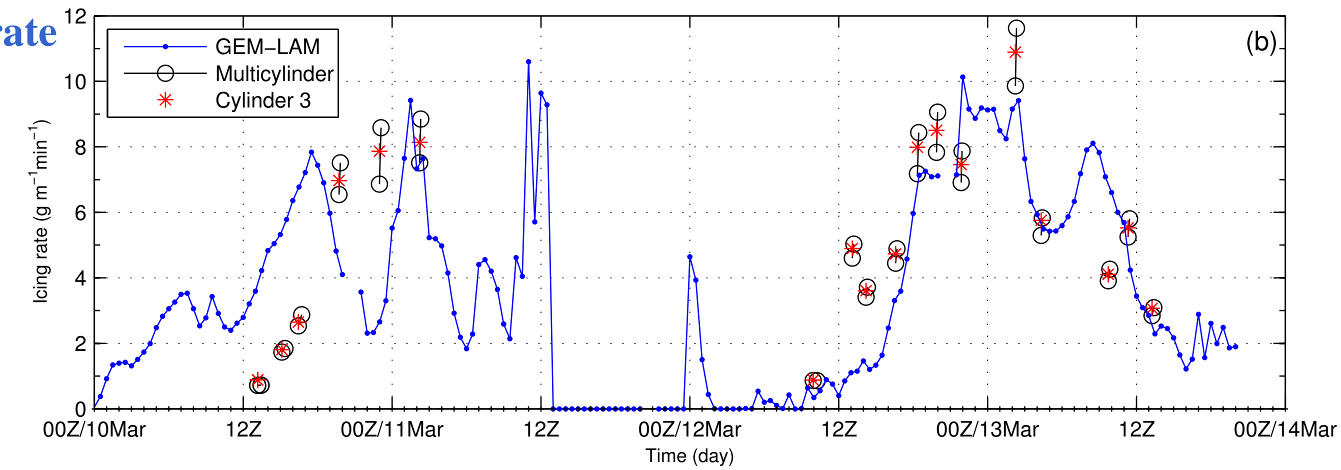


Model- collision efficiency and icing rate (case 2)

collision efficiency



icing rate



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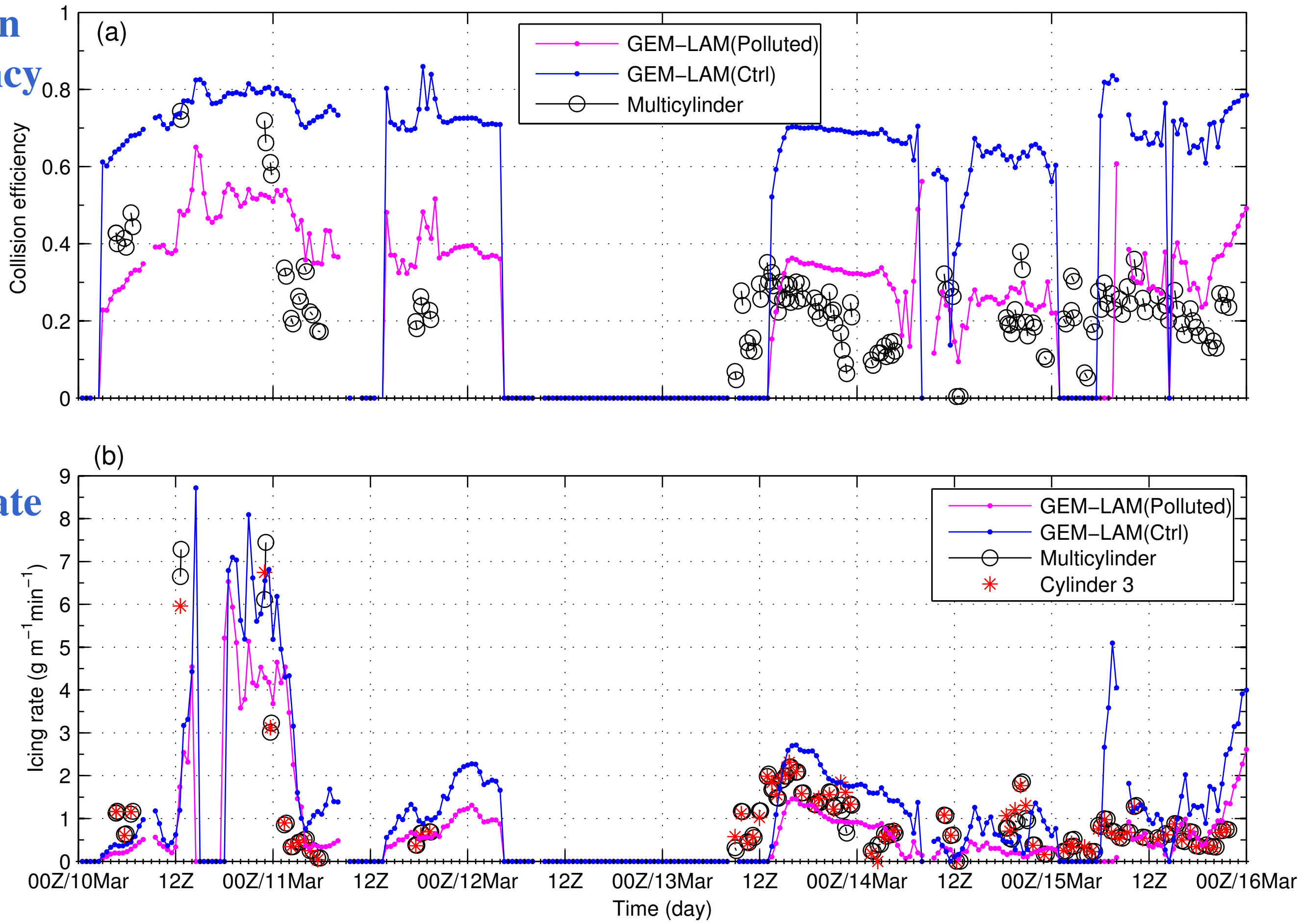
Model- collision efficiency and icing rate (case 3)

collision efficiency

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 ^{o}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

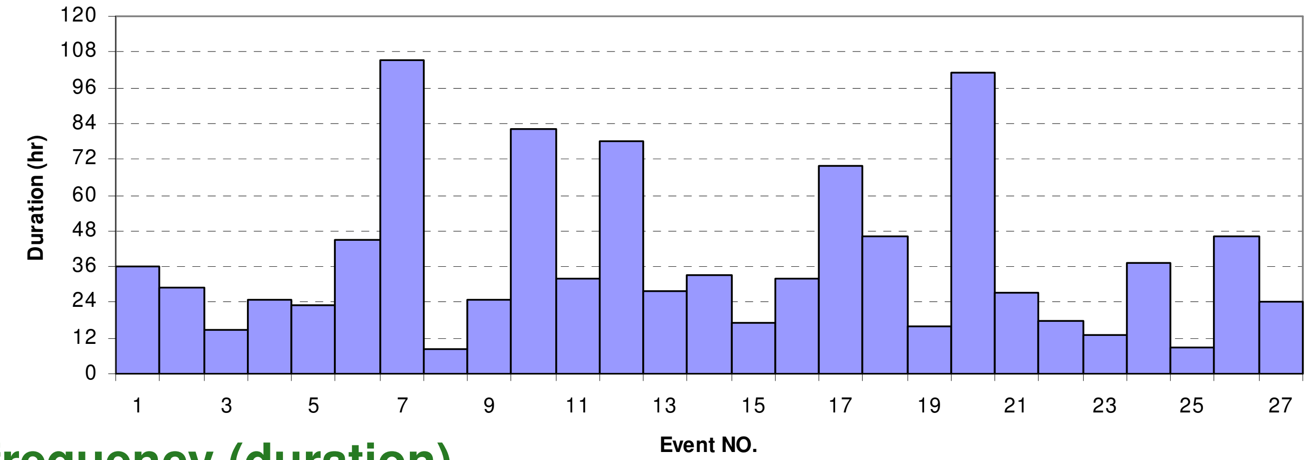
Icing events at a Wind Power Plant (Jan 2008 to Dec 2010)

Type	Case#	Time
freezing rain	1	30/04/2008 21:00
freezing rain	2	12/12/2008 20:00
freezing rain	3	27/11/2009 14:00
freezing rain	4	11/12/2009 05:00
freezing rain	5	15/12/2009 23:00
freezing rain	6	21/12/2009 01:00
freezing rain	7	14/02/2010 15:00
freezing rain	8	30/03/2010 10:00
freezing rain	9	31/03/2010 05:00
wet snow	10	18/02/2009 10:00
wet snow	11	23/02/2009 06:00
riming	25	09/01/2008 13:00
riming	26	29/01/2008 05:00*
riming	27	08/11/2008 09:00

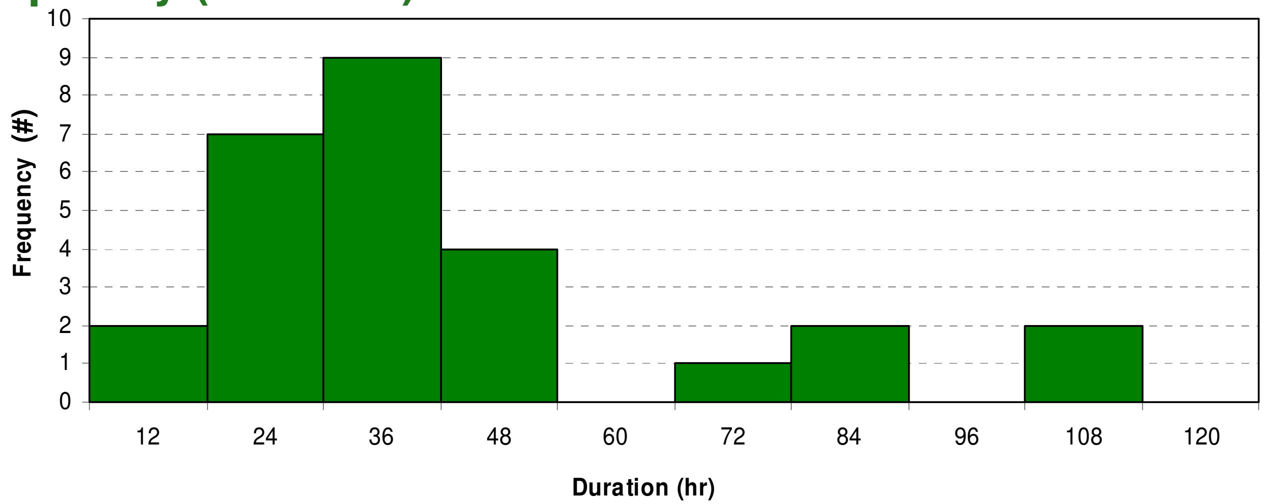
Type	Case#	Time
freezing rain or wet snow	12	20/03/2008 23:00
freezing rain or wet snow	13	13/04/2008 18:00
freezing rain or wet snow	14	12/02/2009 19:00*
freezing rain or wet snow	15	14/02/009 19:00
freezing rain or wet snow	16	02/03/2009 16:00
freezing rain or wet snow	17	05/04/2009 01:00
freezing rain or wet snow	18	13/04/2009 00:00
freezing rain or wet snow	19	25/01/2010 14:00
freezing rain or wet snow	20	20/02/2010 00:00
freezing rain or wet snow	21	28/02/2010 18:00
freezing rain or wet snow	22	02/03/2010 01:00
freezing rain or wet snow	23	24/11/2010 23:00
freezing rain or wet snow	24	27/12/2010 09:00

Observations- icing duration

Duration (defined by power loss)



Events frequency (duration)



Observations- average values for 4 types

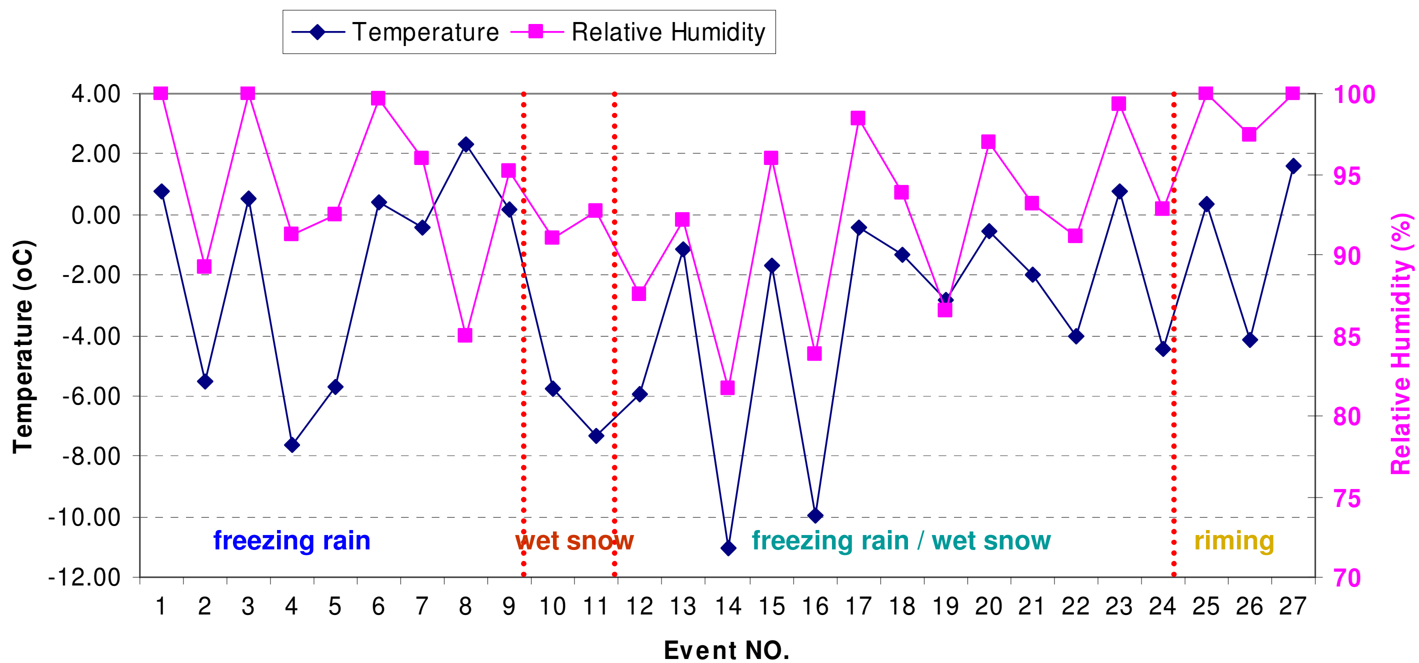
Statistical analysis of these 27 icing events:

Type	No	Dur (hr)	Loss (MWh)	Loss_p (%)	Turbine	Average values at meteorological tower of farm				
					V	V_h	V_{nh}	T	RH	P
FR	9	311	192.0	59.72	5.80	6.87	2.02	-1.46	96	961
WS	2	114	17.9	21.77	6.98	8.41	2.99	-6.23	92	961
FR/WS	13	516	299.1	51.20	7.99	9.76	3.13	-3.26	92	961
Riming	3	79	27.9	42.01	6.00		1.08	-1.89	98	968
Total	27	1020	536.9	49.43	7.19	8.63	2.62	-2.94	94	961

Loss = theoretical generated power – real generated power, unit: MWh
Loss_p = Loss / theoretical generated power, unit: %.

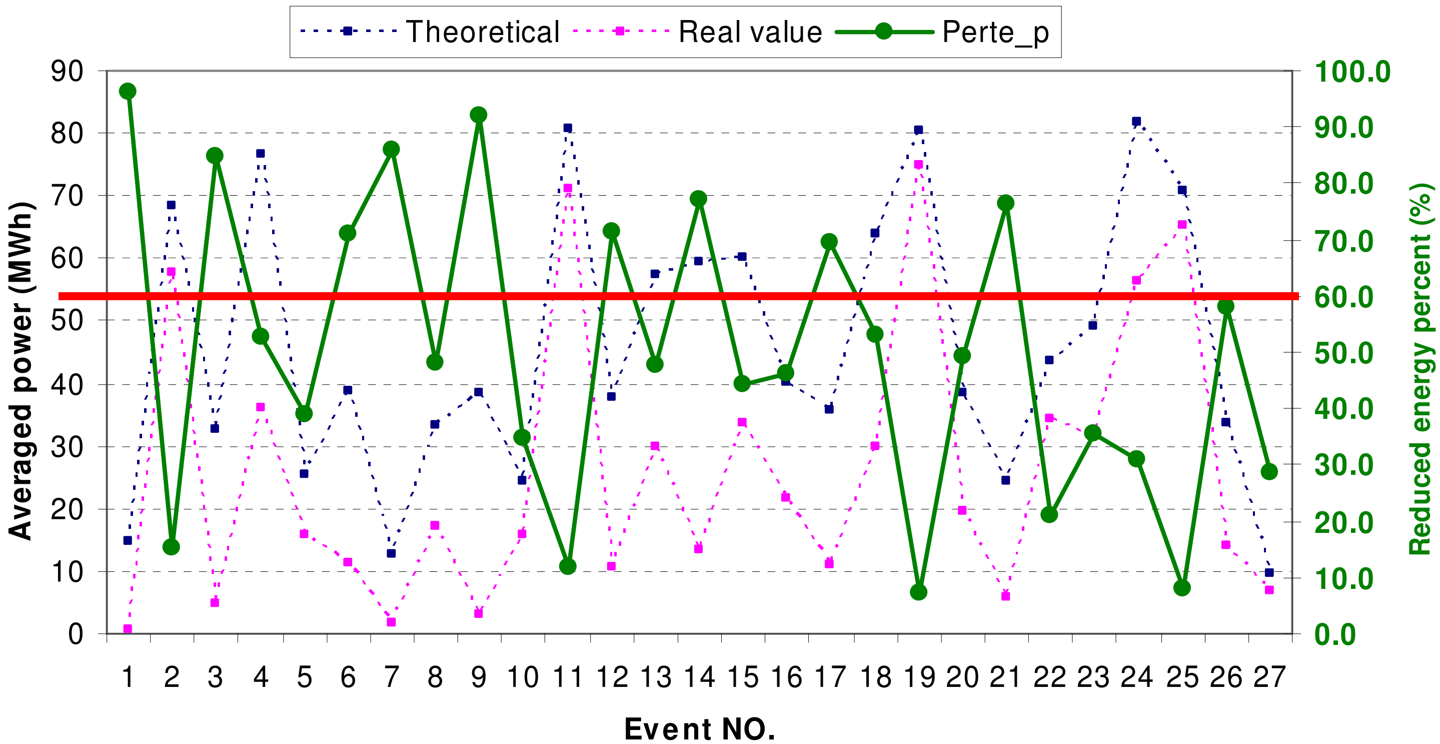
Observations- temperature and relative humidity

@10-m meteorological tower



Point: average value over the total duration of each icing event (27)

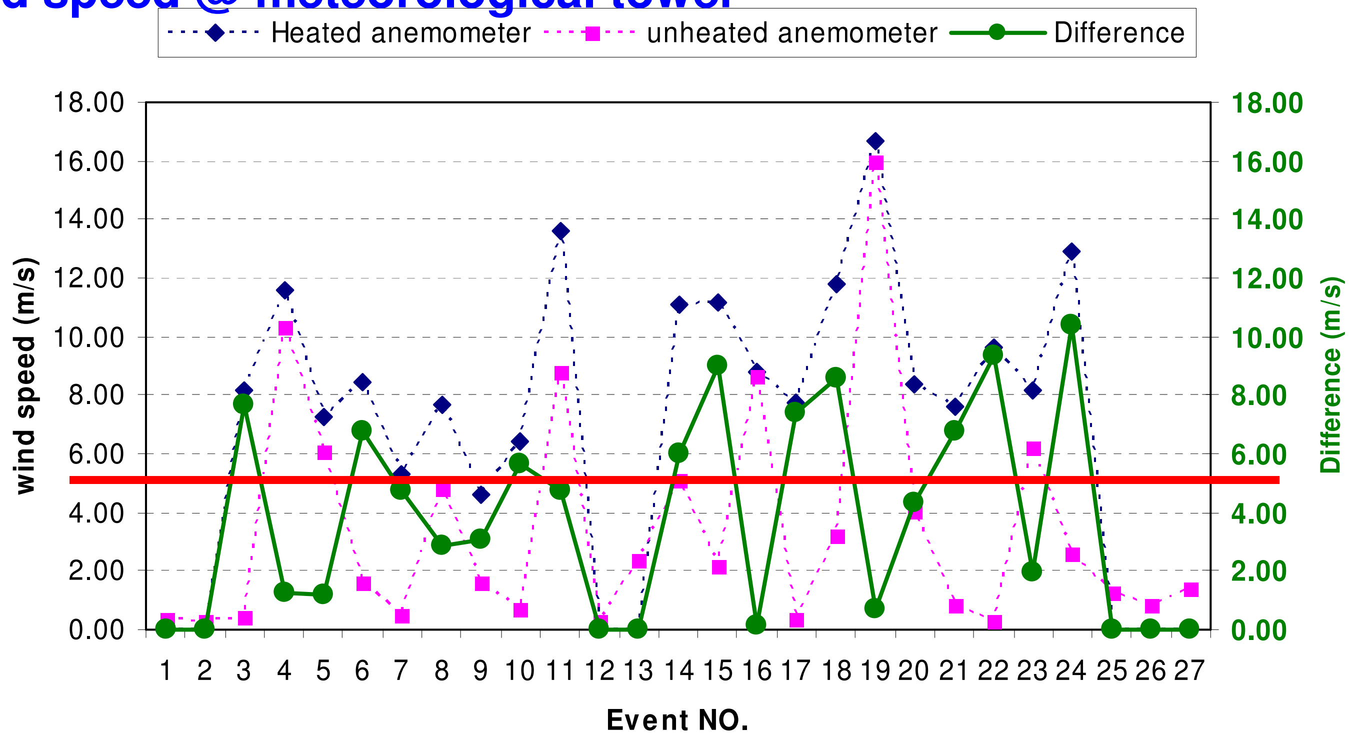
Observations- power and power loss



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

Observations- wind speed

Wind speed @ meteorological tower



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)

Type	Case#	Time
freezing rain	1	30/04/2008 21:00
freezing rain	2	12/12/2008 20:00
freezing rain	***3***	***27/11/2009 14:00***
freezing rain	4	11/12/2009 05:00
freezing rain	5	15/12/2009 23:00
freezing rain	***6***	***21/12/2009 01:00***
freezing rain	***7***	***14/02/2010 15:00****
freezing rain	8	30/03/2010 10:00
freezing rain	9	31/03/2010 05:00
wet snow	10	18/02/2009 10:00
wet snow	11	23/02/2009 06:00
riming	25	09/01/2008 13:00
riming	***26***	***29/01/2008 05:00***
riming	***27***	***08/11/2008 09:00***

Type	Case#	Time
freezing rain or wet snow	12	20/03/2008 23:00
freezing rain or wet snow	13	13/04/2008 18:00
freezing rain or wet snow	***14***	***12/02/2009 19:00***
freezing rain or wet snow	15	14/02/009 19:00
freezing rain or wet snow	16	02/03/2009 16:00
freezing rain or wet snow	***17***	***05/04/2009 01:00****
freezing rain or wet snow	18	13/04/2009 00:00
freezing rain or wet snow	19	25/01/2010 14:00
freezing rain or wet snow	20	20/02/2010 00:00
freezing rain or wet snow	***21***	***28/02/2010 18:00***
freezing rain or wet snow	22	02/03/2010 01:00
freezing rain or wet snow	23	24/11/2010 23:00
freezing rain or wet snow	24	27/12/2010 09:00

GEM-LAM configuration

Double-nested domain

Domain 1: 15km, 138x110

Domain 2: 2.5km, 465x345

Initial and boundary conditions

CMC regional analysis;

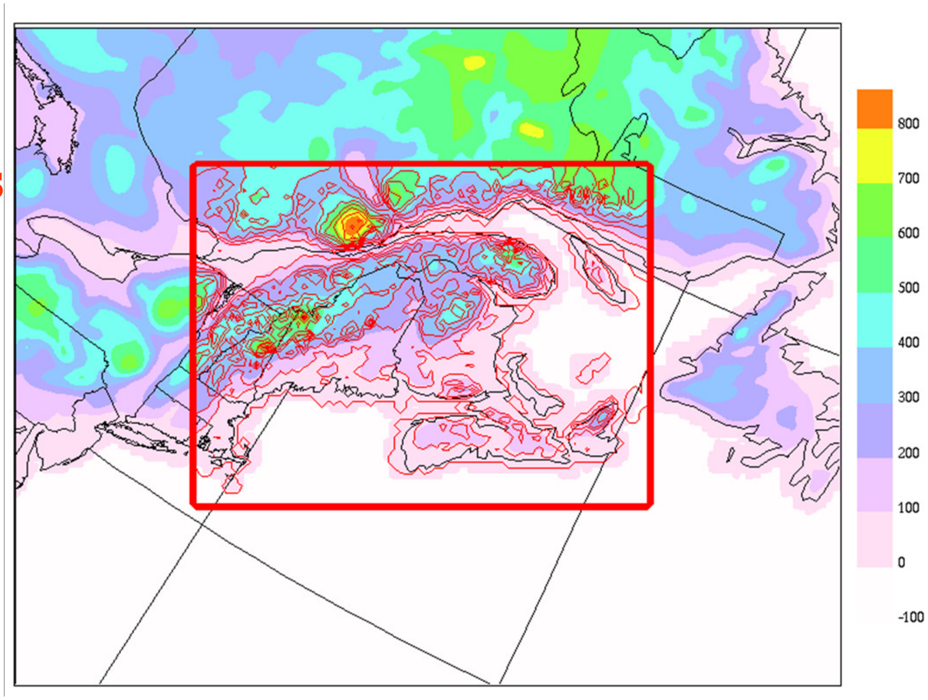
hourly regional forecast data

(~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**

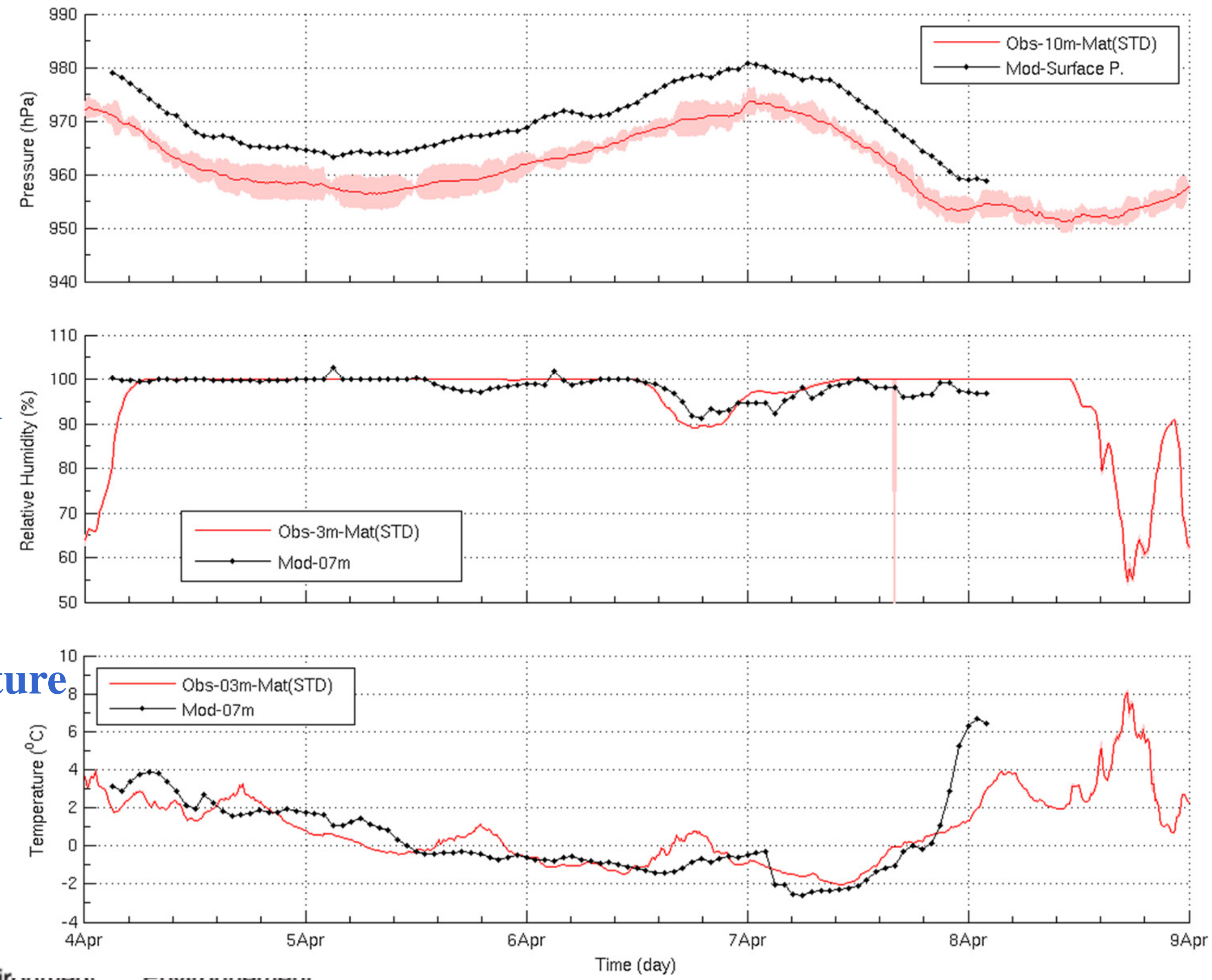
Case 1 – Model vs. Obs.

Observed (10-min) and simulated (half hourly) pressure, RH and T from 4 to 8 Apr, 2009

Pressure

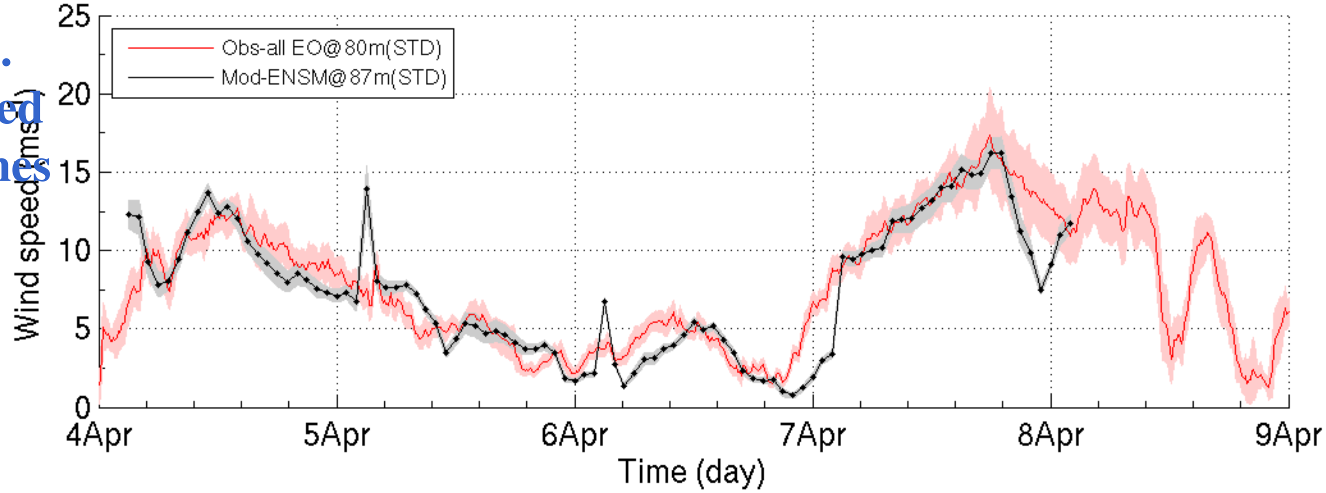
Relative Humidity

Temperature

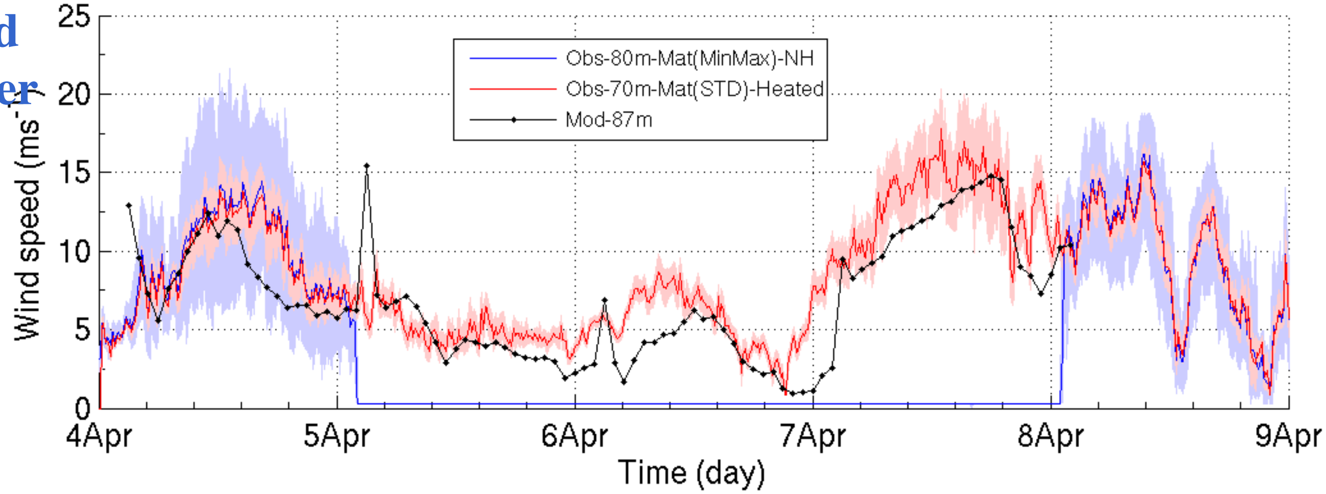


Case 1 – Model vs. Obs. (wind speed)

Ensem Ave.
of wind speed
@ 67 turbines

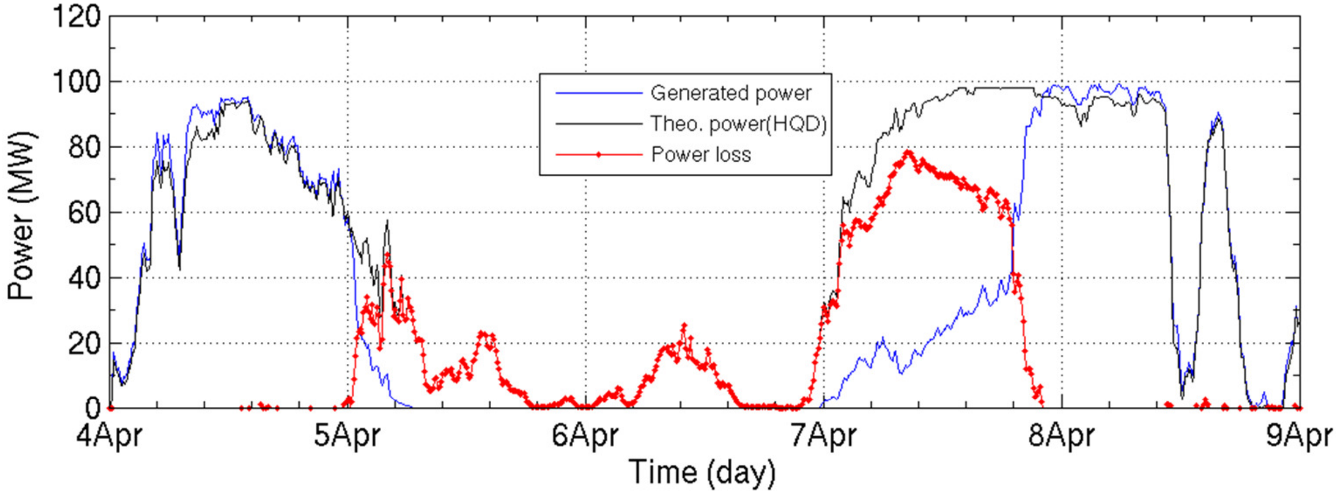


Wind speed
at met tower

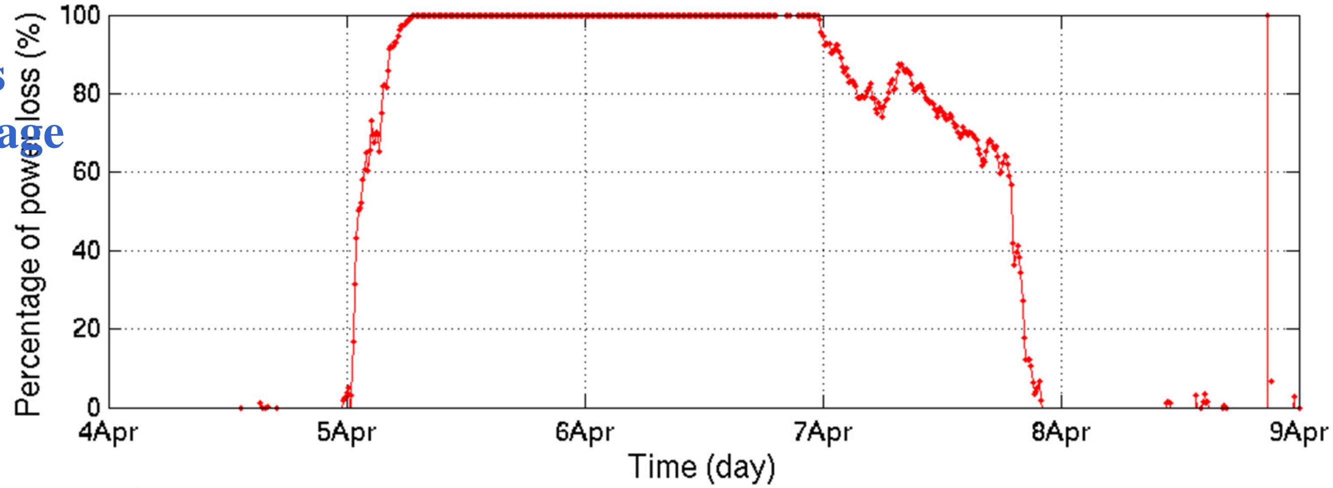


Case 1 – Obs. (power loss)

Power loss



Power loss in percentage

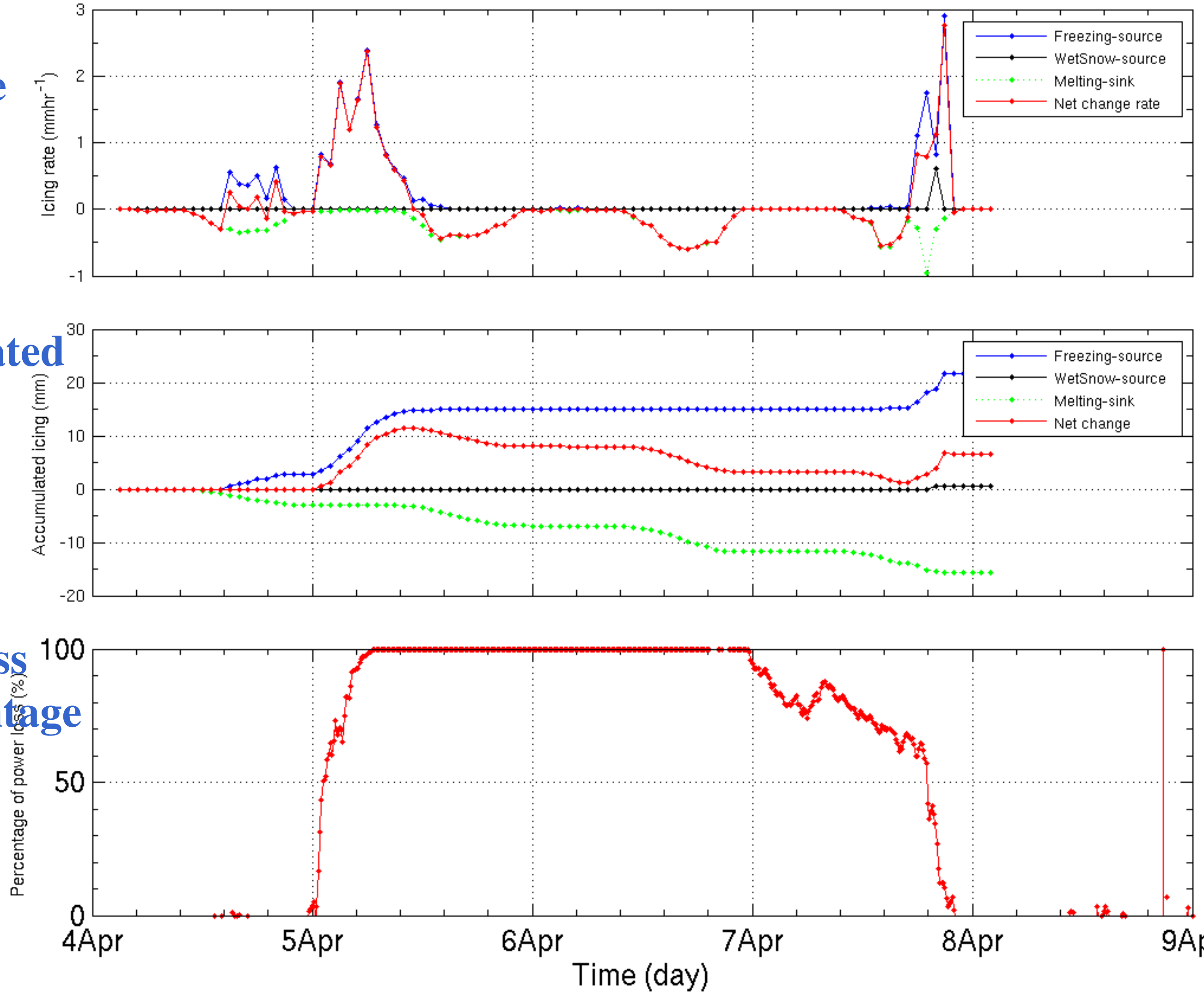


Case 1 – Model icing vs. Obs. power loss

Icing rate

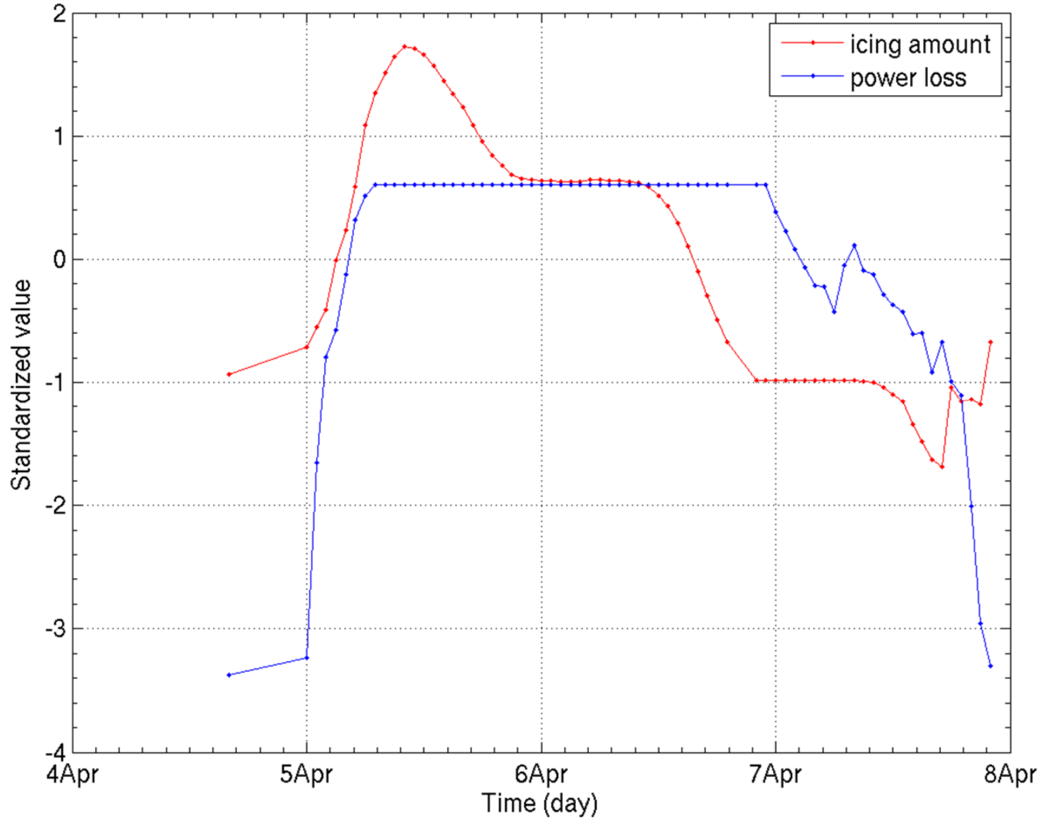
Accumulated

Power loss in percentage



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

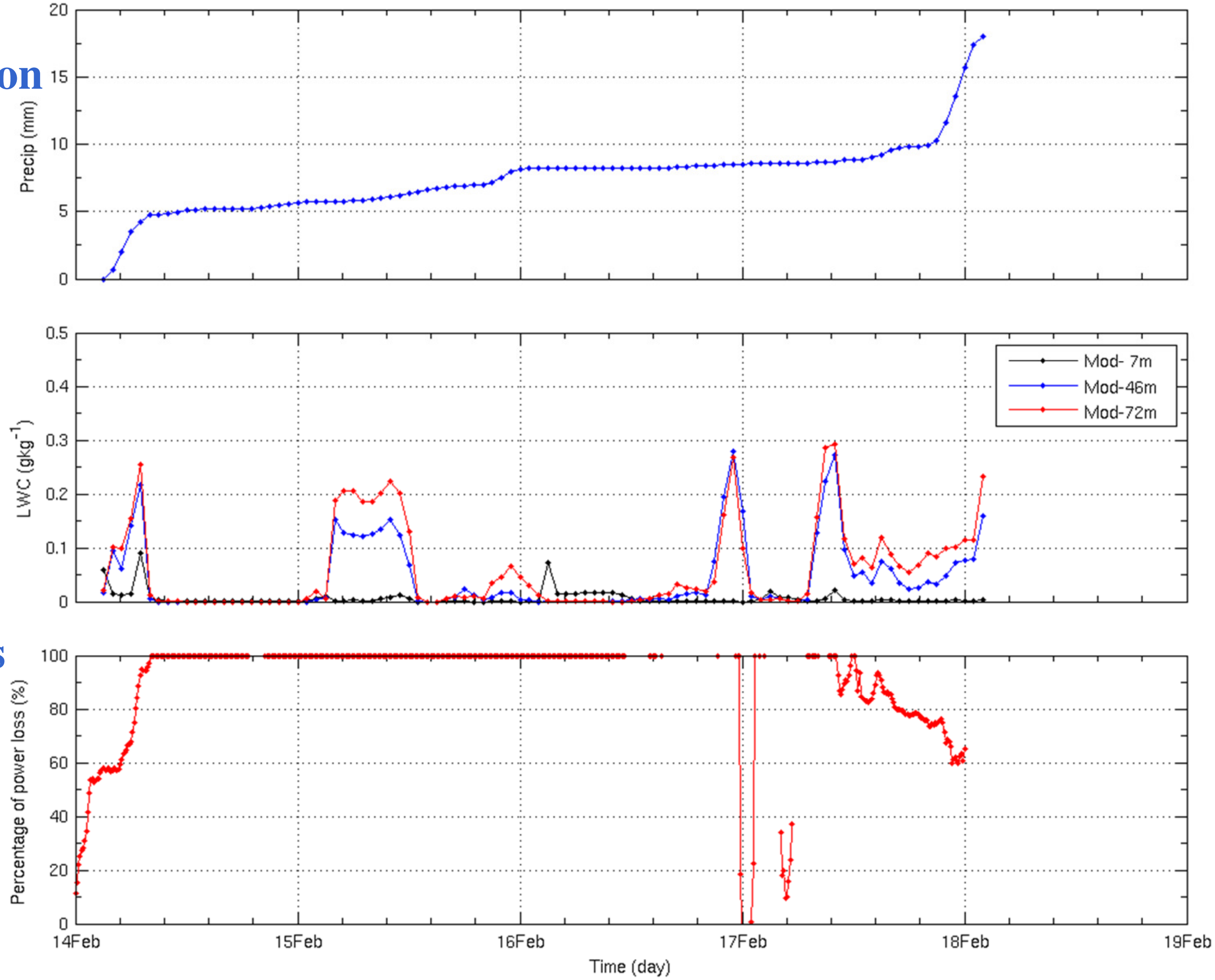
Wind speed

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

Precipitation

LWC

Power loss

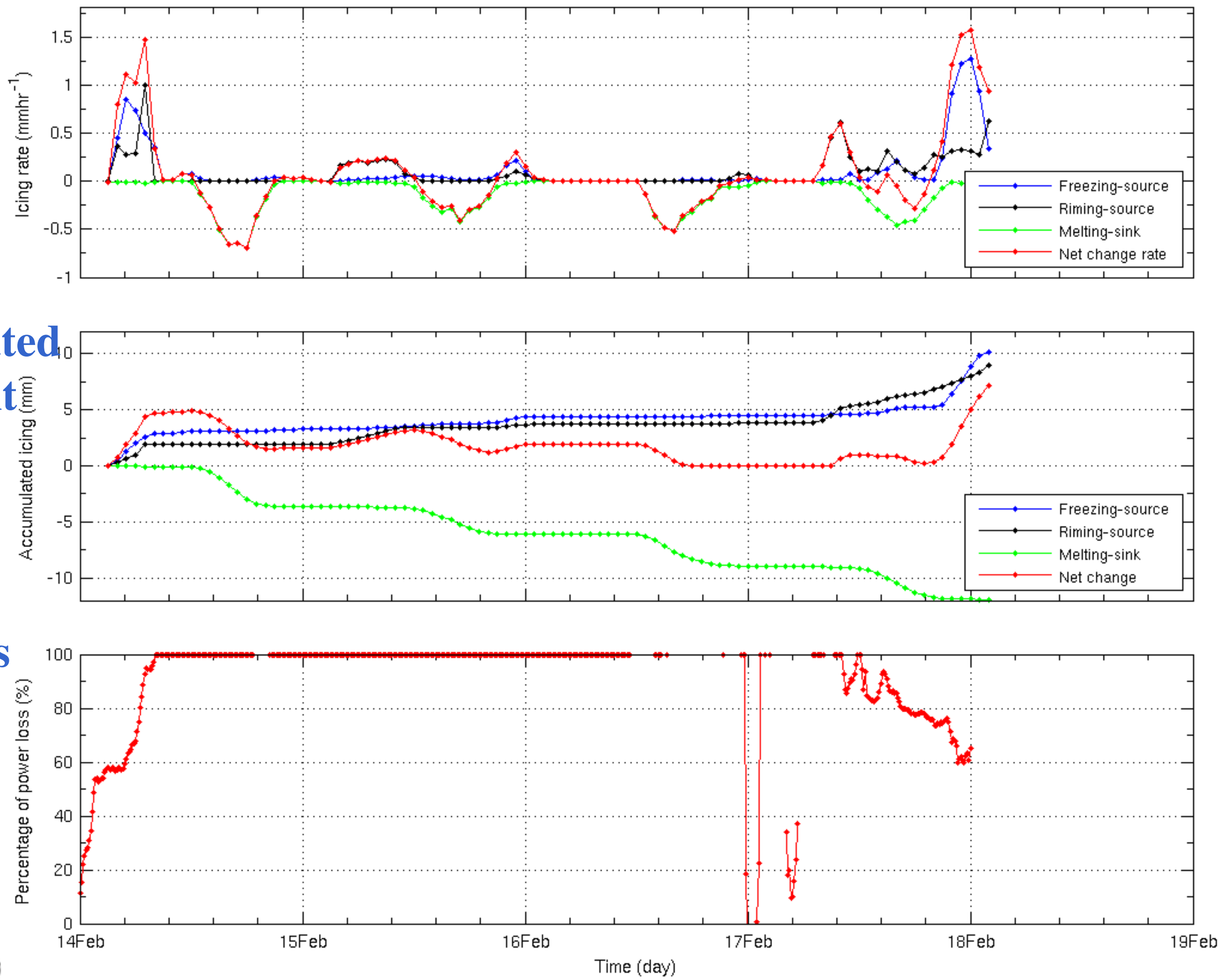


Case 2 – Model icing vs. Obs. power loss

Icing rate

Accumulated ice amount

Power loss



Simulation results of 8 cases

	Date	Start-up		Duration (hr)	
		Icing	Power loss	Icing	Power loss
1	4-9Apr, 2009	11Z, 04 Apr	16Z, 04 Apr	88	70
2	14-18 Feb, 2010	00Z,14 Feb	03Z, 14Feb	78	74
3	07-11 Nov, 2008	05Z, 08 Nov	20Z, 07 Nov	68	54
4	11-16 Feb, 2009	10Z, 11 Feb	13Z, 11 Feb	111	76
5	27Nov-1Dec,2009	14Z, 27 Nov	14Z, 27 Nov	81	65
6	20-24 Dec, 2009	14Z, 20 Dec	19Z, 20 Dec	64	63
7	27Feb-3Mar, 2010	06Z, 28 Feb	13Z, 28 Feb	64	54
8	30Mar-3Apr, 2010	04Z, 30 Mar	06Z, 30 Mar	54	51

Summary

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.

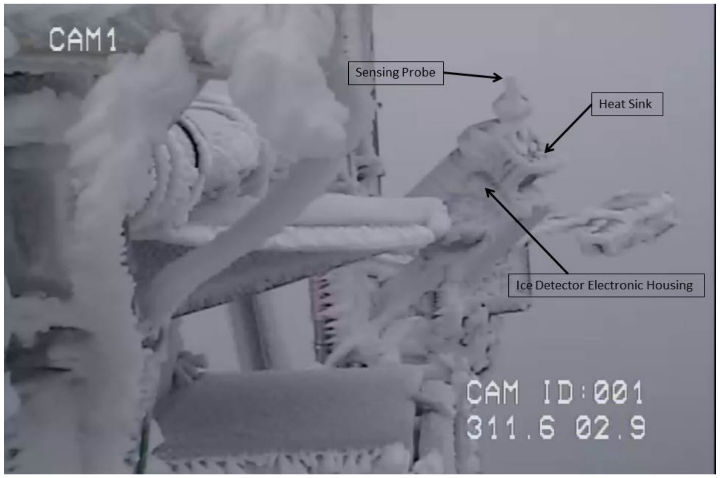
Future work

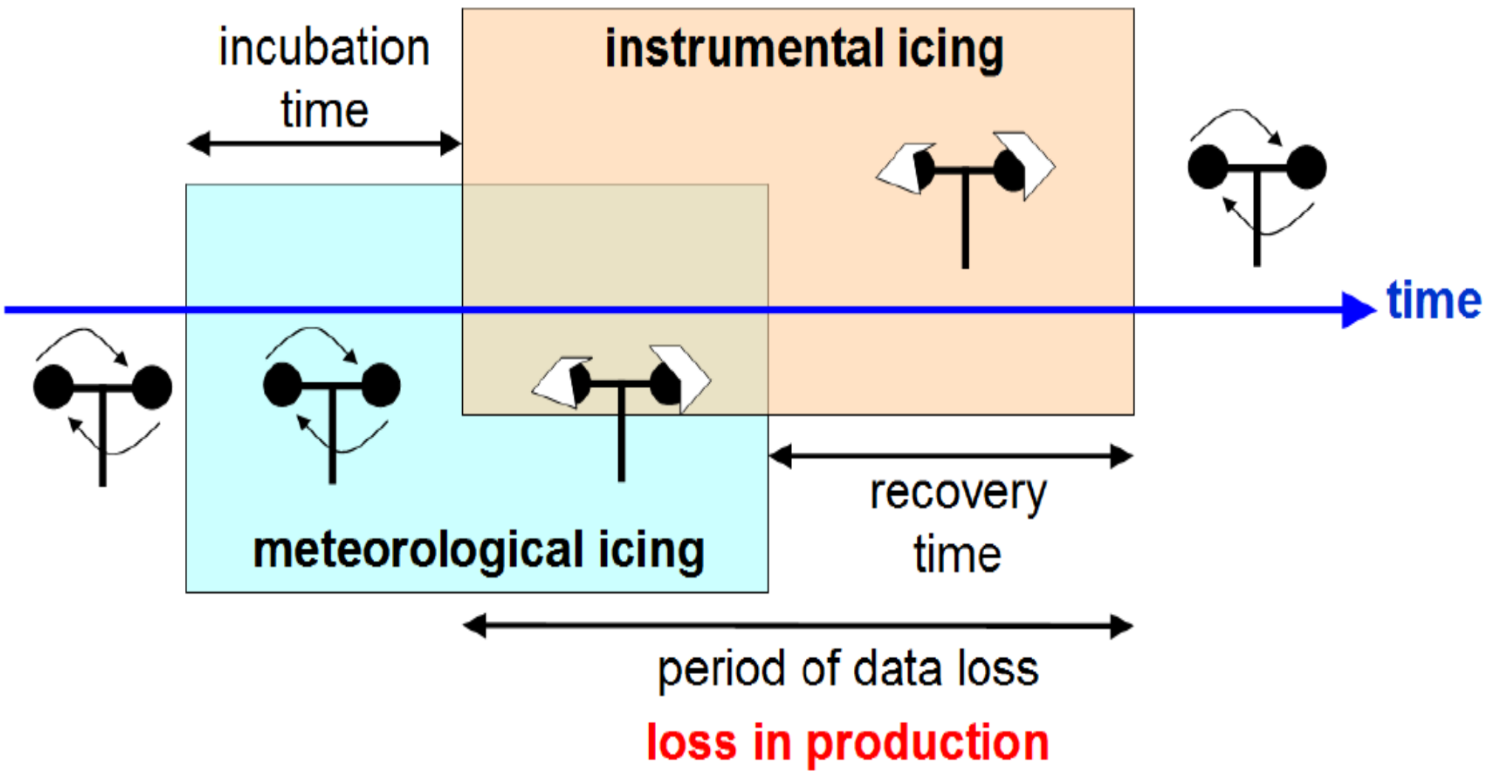
1. To develop wind energy production forecast system by considering icing impacts.
   - Obtain empirical relationship from statistical analysis of historical icing events (from a database of model icing simulations)
   - Apply this to wind energy forecast

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
instrumental icing
time
meteorological icing
recovery
time
period of data loss
loss in production