Evaluation of icing simulations for the "COST727 icing test sites" in Europe

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Abstract— Earlier studies have clearly demonstrated that there is a potential for using numerical weather prediction (NWP) models to predict in-cloud icing events at ground level. However, due to the lack of reliable iceload measurements, these studies have mainly focused on single icing events for one station, or a very limited area. During the winter season 2007/2008 six test stations around Europe were equipped with the IceMonitor (Saab Security) instrument, collecting ice load measurements throughout the whole season. In this paper we present results from icing simulations for selected icing events from the test stations, by applying a state-of-the-art numerical weather prediction model, in combination with a cylindrical rime ice accretion model. We emphasize the differences between in-cloud icing at continental and maritime sites, and how these differences are handled by the numerical model. We also discuss topics such as local terrain effects, terrain blending in numerical models, and how we extract and interpret information on the cloud liquid water and the cloud droplet size from the NWP model.

I. Introduction

THE use of numerical weather prediction (NWP) models to predict in-cloud icing events is an ambitious and challenging task, because of the chaotic nature of the atmosphere, and due to the fact that supercooled liquid water in the atmosphere is often a result of several complex and poorly understood small scale processes in the atmosphere. On the other hand the increase in available computing power allows current NWP models to be run at much higher spatial resolution than before, and the complex microphysical processes can be parameterized in a much more sophisticated way than only few years ago. State-of-the-art NWP models handle the microphysical processes in a much more physical way than older models, in which oversimplified relations had to be applied in order to keep the computing time as low as possible. This huge improvement during the last decade is clearly demonstrated in [1]. Quantitative precipitation forecasts (QPF) are produced operationally at centers worldwide by using high resolution NWP models with such sophisticated microphysical parameterization schemes. Based on the arguments mentioned above, one would expect that the microphysical schemes used to produce the QPF, could also output the supercooled cloud water leading to in-cloud icing. This potential has already been studied for instance in [1] and [2] with promising results. However, these studies were limited by the lack of reliable ice load measurements, and they only focused on single case studies for one specific site.

In this paper we seek to further explore the ability and shortcomings of high resolution NWP models to explicitly predict in-clod icing by running simulations for nine recorded icing events from the winter season 2007/2008 at different exposed sites in Europe.

II. Icing measurements

Icing measurements are carried out at six test sites in different European countries: Luosto (Finland), Sveg (Sweeden), Deadwater Fell (UK), Zinnwald (Germany), Studnice (Chech Republic) and Guetsch (Switzerland). In addition, one icing event from the site Schwyberg in the Swiss pre-Alps is included. All test sites are equipped with the Saab Security (former Combitech) IceMonitor, which measures the accumulated iceload on a 0.5 meter tall vertically oriented cylinder, according to the guidelines in [3]. All test stations are located on exposed hills or mountain tops, which as prone to in-cloud icing. In addition to icing instruments, all test stations are equipped with heated anemometer and temperature sensors. A detailed description of the test sites is presented in [4].

In this study we use data from the winter season 2007/2008 to verify the icing simulations. The most essential variables used in the verification are: ice load (kg/m), temperature (°C) and wind speed (m/s). The data is split into single icing events, or time periods, which are subject to icing simulations with the numerical model. For some of the stations additional information like wind direction, humidity, visibility and precipitation amount is available for the icing events.

During the 2007/2008 winter season all test stations were subject to in-cloud icing. Unfortunately the only icing event recorded at the Sveg station was extremely light (<50g) and smaller than the range of uncertainty of the IceMonitor instrument. Therefore the icing event at Sveg was not used in this study. The lack of icing events at Sveg during this winter season was really unfortunate, because Sveg is the only test station that measures the vertical profile of icing, by using four IceMonitors at four different heights in a 300 meter tall tower. In that sense, the Sveg site is unique, and data from next winter seasons is considered very valuable for future verification studies. From the other five test stations nine icing events are selected for simulation studies. Some of the events only have an accretion phase, and some also contain the melting/shedding phase.

III. ICING MODELING

The icing simulations are carried out in a two step manner. First we run the numerical weather prediction model for a time window covering the recorded icing event. The output from the NWP simulations is four dimensional fields of atmospheric data, including all necessary variables to predict atmospheric icing. In the second step, we use the gridded output from the NWP model to drive a time dependent cylindrical accretion model for in-cloud icing.

A. *The WRF model*

The NWP model used in this study is the Weather Research and Forecasting model (WRF) version 2.2.1 (ARW). WRF is a mesoscale non-hydrostatic modeling system developed to serve research purposes as well as operational weather forecasting. A detailed model description is found in [5]. There are several reasons why WRF is applied in the current study. The modelling system is very flexible and easy to set up for different regions and different configurations, it is coded to run efficiently on multi processor systems, however the main argument is the option in WRF to select among many different schemes for parameterization of cloud microphyscs, including the more expensive schemes with two moment (mass and number concentration) prediction of some or all the moisture species. The latter is considered as a key point when the goal is to explicitly predict the amount of supercooled water in the atmosphere. In this study we apply the Thompson scheme for microphysics parameterization [6]. Other sub grid processes are parameterized with the following schemes: YSU for the planetary boundary layer, The Monin-Obukov scheme for the surface layer, the Noah scheme for the land surface processes, the RRTM longwave radiation scheme and the Dudhia shortwave radiation scheme. Convection is assumed to be explicitly resolved in the model grid so no cumulus scheme is applied. Initial fields and the lateral boundaries are retrieved from the archived operational analyses of the ECMWF global model (http://www.ecmwf.int/services/archive/). The terrain data used to create the digital terrain in WRF is the USGS 30 arc-second global data set GTOPO30.

For all the simulations the WRF model is set up with a triple one-way nested domain with grid spacings equal to 12.8 km, 3.2 km and 0.8 km, respectively, from the outermost to the innermost domain, illustrated in Fig. 1 with an example from the Zinnwald station. The grid spacing of the input data from the ECMWF is 25 km. In the vertical direction the WRF model is set up with 51 model levels, with a model top at 100 hPa. This corresponds to approximately 15 levels in the lowest kilometer of the atmosphere.

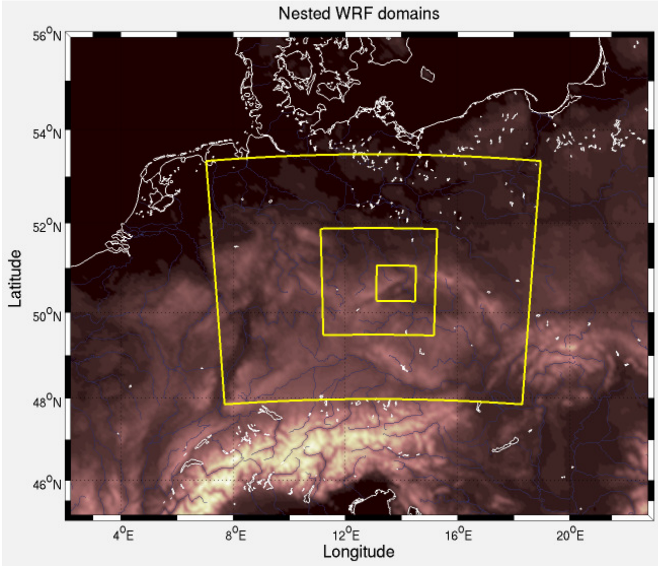

Fig. 1 Nested WRF domains for the Zinnwald test station in Germany. The three domains are indicated by the yellow squares. The grid spacing from outer to inner domain is 12.8 km, 3.2 km and 0.8 km, respectively.

B. *Modeling ice accretion*

To be able to compare measured iceloads with the output from the WRF model it is necessary to process the WRF results through a cylindrical rime ice accretion model. For this purpose we use the theory presented in [7], often referred to as "the Makkonen model". The main input data needed to drive the accretion model are temperature, wind speed, supercooled liquid water content in the atmosphere, and median volume droplet size (MVD). The latter is used to compute the collision efficiency between the droplets and the cylinder according to [8], and is a crucial variable in the icing modeling. Since the microphysical schemes in NWP models usually are one-moment schemes (only predict the LWC) the cloud MVD is not predicted explicitly. In this study we derive the MVD for cloud droplets by using the generalized gamma distribution for cloud droplets applied in the Thompson microphysics:

$$N(D) = \frac{N_t}{\Gamma(\mu+1)} \lambda^{\mu+1} D^{\mu} e^{-\lambda D} \qquad (1)$$

where N_t is the total number of cloud droplets, D is the droplet diameter, λ is the slope of the size distribution, and μ is the shape parameter. The shape parameter is determined by the preset CCN concentration N_c (number of droplets that get activated upon condensation) used in the WRF simulations according to:

$$\mu_c = \min\left(15, \frac{10^9}{N_c} + 2\right) \qquad (2)$$

Typical values for N_c are $100 \cdot 10^6$ m^{-3} for maritime air masses and > $250 \cdot 10^6$ m^{-3} for continental air masses. From (1) the MVD of cloud droplets can be derived:

$$MVD = \frac{3.672+\mu}{\lambda} \qquad (3)$$

Time series of temperature, wind speed, LWC and MVD are extracted from the WRF simulations, at one hour intervals, and used as input to the accretion model. The final result is a time series of accumulated ice load, which can be compared with the measurements.

IV. RESULTS

Extracting data from a discrete grid to use for comparison with real measurements is not a straightforward task, especially not in complex terrain because the terrain in the NWP model will always be smoothed to some extent in order to keep the model dynamically stable. This implies that the height of single mountain peaks and deep valleys can differ significantly between the model and the reality, which is the case for all the test sites considered here. To limit the terrain blending as much as possible we have used a very high resolution in the model, with grid boxes of 0.8 x 0.8 km. But still we see significant differences in elevation between the model and reality. We find the largest discrepancy for the Luosto site, which is located on the very top of a narrow ridge (~ 1.5 km wide). The real height is 515 m, and the model height is 370 m. On the other hand, the Zinnwald site is located on a more plateau-shaped area where the real height is 877m and the model height is 843 m. The height differences raise the question; from which vertical level in the model is it most proper to extract data when comparing simulated and measured values, the lowest model layer or the layer that corresponds to the real height of the hill? To explore this question we set up an experiment where we use data from both levels to compute accumulated loads, and since wind speed and temperature are measured at all stations, we also compute accumulated ice loads based on modeled LWC and measured wind and temperature. This leads to five different combinations of input data for the accretion model. The different combinations are illustrated in table I. In the horizontal direction the nearest neighboring grid point to the real location of the station is used. Alternatively one could have used an average or a weighted average of the closest grid points.

TABLE I
OVERVIEW OVER THE DIFFERENT COMBINATIONS OF TIME SERIES INPUT DATA FOR THE RIME ICE ACCRETION MODEL. "T" IS TEMPERATURE, "V" IS HORIZONTAL WIND SPEED AND "LWC" IS THE LIQUID WATER CONTENT IN THE ATMOSPHERE.

	WRF lowest level	WRF real height	Measured
Combination 1	V, T, LWC		
Combination 2		V, T, LWC	
Combination 3	V	T, LWC	
Combination 4	LWC		V, T
Combination 5		LWC	V, T

The results from the nine icing events are compiled in table II, in terms of maximum measured and simulated iceload during the event. In order to try to give a quantitative evaluation of the different combinations of input data, the mean error and the mean absolute error is displayed in the lower part of the table.

TABLE II
COMPARISON OF MEASURED ICE LOADS WITH MODEL RESULTS USING THE FIVE DIFFERENT COMBINATIONS OF INPUT DATA. THE MEASUREMENTS ARE DISPLAYED IN THE GRAY SHADED COLUMN.

Site	Date	Obs (kg/m)	C1 (kg/m)	C2 (kg/m)	C3 (kg/m)	C4 (kg/m)	C5 (kg/m)
Luosto	22 Dec 08	8.8	0.8	5	2.2	2.5	7.1
Luosto	02 Jan 08	7.9	0.1	2.2	0.7	0.1	2.8
Zinnwald	11 Jan 08	6.6	8.0	9.5	8.1	10.7	10.4
Zinnwald	18 Feb08	0.9	2.6	3.4	3.0	1.3	1.4
Studnice	10 Jan08	3.8	5.0	4.0	3.4	3.0	2.0
Studnice	28 Dec 07	2.7	3.4	1.9	1.7	2.3	1.2
Deadwater	03 Jan08	0.8	0.3	0.8	0.5	0.9	1.2
Guetsch	22 Nov07	1.8	2.1	2.9	2.2	2.3	2.2
Schwyberg	30 Oct07	2.0	-	5.2	-	-	1.9
Mean Error			-1.38	-0.04	-1.44	-1.28	-0.57
Mean Absolute Error			2.70	2.24	2.44	2.55	1.70

A. *General performance of the modeling system*

The table shows that in general terms, the numerical model predicts icing conditions in all the nine cases considered, while the maximum predicted load in some cases deviates significantly from the measured load. The model seems to perform least skilfully for the two icing events at the Luosto test site, which is probably due to the fact that the hill is poorly represented in the digital terrain in the model. The height of the hill is reduced by 145 m in the model, suppressing the orographically induced vertical motions in the model, probably leading to an underestimation of LWC.

Unfortunately all the icing events except the case from Deadwater Fell in the UK occurred during weather situations with strong temperature inversions in the lower atmosphere. Such situations are usually not very well predicted dynamically by NWP models, and if the dynamics are predicted incorrectly the icing prediction will also be bad. In such conditions the large scale forcing of the relative humidity in the lower troposphere is relatively weak, and the predicted LWC will be very sensitive to small errors in the RH field. An example of the opposite is the icing event at Deadwater Fell, for which the model preformed relatively well. In this event the icing occurs in relation to a frontal system with a strong large scale forcing of the moisture in the lower atmosphere.

B. *Sensitivity to selection of grid point*

The C1 and C4 have the highest mean absolute error, indicating that LWC should be extracted from the real height in the model rather than the lowest model layer. This is most evident in the simulations for Luosto, where the height difference is greatest. We obtain the best result by applying measured values of temperature and wind speed in combination with LWC from the real height of the hill (Combination 5). This is not surprising because we eliminate two sources of errors by using the measured values for wind and temperature; however comparison between C4 and C5 underlines the improvement gained by using LWC from the level that corresponds to the real height of the hill, instead of LWC from lowest model level.

C. Duration of ice accretion

In many applications it is not necessarily the maximum accumulated ice load which is the most important information, but rather the duration of icing, or the number of icing hours. To get an idea how the model performs in terms of icing duration, we have estimated the duration simply by summarizing the number of hours where more than 20 g is accumulated. The results are displayed in table III.

TABLE III
COMPARISON OF MEASURED ICE LOADS WITH MODEL RESULTS USING THE FIVE DIFFERENT COMBINATIONS OF INPUT DATA. THE MEASUREMENTS ARE DISPLAYED IN THE GRAY SHADED COLUMN.

Site	Date	Obs hr	C1 hr	C2 hr	C3 hr	C4 Hr	C5 hr
Luosto	22 Dec 07	69	14	32	28	22	42
Luosto	02 Jan 08	66	0	39	23	0	41
Zinnwald	11 Jan 08	65	63	58	57	55	51
Zinnwald	18 Feb08	24	22	21	21	19	20
Studnice	10 Jan08	35	38	35	33	35	26
Studnice	28 Dec 07	58	37	30	28	36	24
Deadwater	03 Jan08	19	8	11	11	12	13
Guetsch	22 Nov07	20	18	18	18	18	18
Schwyberg	30 Oct07	22	-	25	-	-	18
Mean Error			**-19.5**	**-12.1**	**-17.1**	**-19.9**	**-13.9**

The analysis indicates a consistent underestimation of number of icing hours by the model. This is most evident if we use the LWC from the lowest model layer (C1, C3 and C4). The reason for the underestimation is, at least for some of the events, closely related to the underestimation of the whole icing event, most evident for the Luosto cases. However, there is also a small underestimation of icing duration for the other events where the maximum load was close to the measured. This is an indication that the model predicts intense icing in a shorter time period instead of a lower intensity over a longer time period. This is related to the discussion about droplet size and droplet concentration discussed in the next section.

It should be emphasized that the IceMonitor instrument is designed to measure accumulated load rather than the instantaneous icing intensity. So, the reader should keep in mind that the observed icing hours in table III are just a rough estimate and not a direct measurement, and might explain some of the inconsistencies with the model results.

D. Sensitivity to the droplet concentration

The collision efficiency of the droplets with the cylinder is very sensitive to the droplet size, causing a large uncertainty in the icing modeling. In the current study we derive the MVD of the droplets from the assumed size distribution used in the Thompson microphysics. Equations (2) and (3) show how the MVD is related to the volume number concentration of cloud droplets N_c. The N_c is a prescribed number of droplets that get activated upon condensation, and represent the CCN concentration in the WRF simulation. In the current version of Thompson microphysics, the N_c is prescribed and kept constant throughout the simulation. In future versions of the scheme, the N_c can vary based on information about aerosol type and concentration.

The most important effect on the icing simulation by changing the N_c is the impact on the droplet size. If the N_c is increased in a situation with constant LWC the droplets will be smaller, causing the collision efficiency to decrease and icing intensity will decrease. A second effect is that a higher N_c allows a higher liquid water content in the clouds before it starts to convert to drizzle size droplets. This is also important for icing simulations because freezing drizzle has a very high collision efficiency (typically 90% with a cylinder of 3cm diameter) compared to cloud droplets (typically 15% with a cylinder of 3cm diameter). Whether the supercooled water in the atmosphere is present as cloud water or drizzle size droplets makes a huge difference for the icing calculation. However in the cases considered here freezing drizzle is only present in very small amounts, so this second effect is not very important.

The default value for N_c is 100 cm^{-3}, which is used in the nine simulations presented here. This value is rather low and represents maritime or relatively clean air, which is not necessarily correct for the sites considered here. Fig. 2 shows one example of time series from the January 2008 event recorded at the Zinnwald station based on WRF simulation with N_c =100 cm^{-3}. This case indicates that icing is too intense and duration is slightly underestimated. Combination 4 and combination 5 show that even though we use measured values of wind and temperature, the icing intensity is overestimated. In this case the overestimation is due to too high LWC or too large cloud droplets.

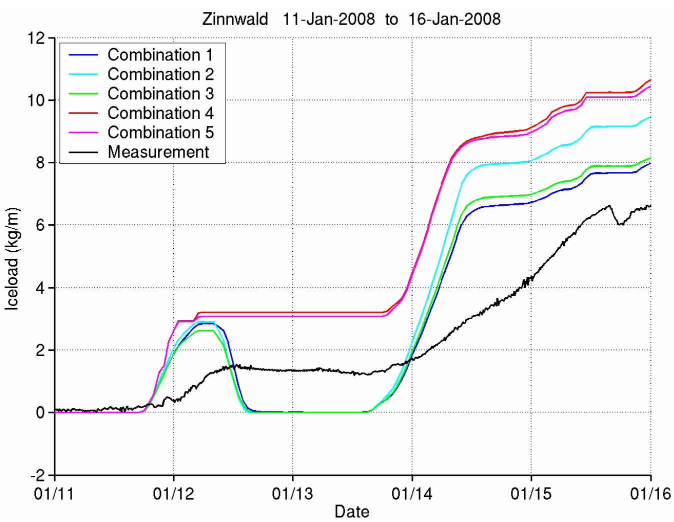

Fig. 2 Measured and simulated ice load for the Zinnwald test site. The WRF simulation is performed with a droplet concentration equal to 100

cm^{-3}. The different colored lines correspond to the modeled ice load according to the combinations specified in table I.

Fig. 3 displays results from the same icing event, but now the WRF model is run with N_c =300 cm^{-3}, which is more realistic for a continental site. We see that the increased number of droplets in the simulation causes more droplets of smaller size and the icing intensity is reduced because of reduced collision efficiency. In this single case the change in the N_c in the WRF model improved the simulation result in terms of maximum ice load, but the icing duration is more or less unaffected.

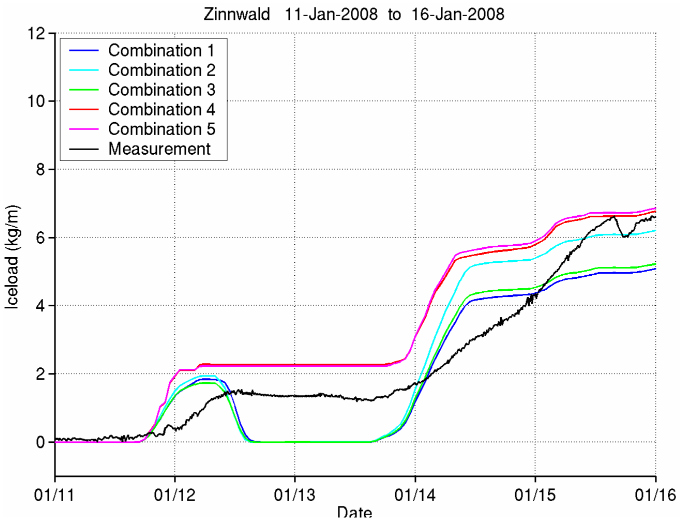

Fig. 3 Measured and simulated iceload for the Zinnwald test site. WRF simulation is performed with a droplet concentration equal to 300 cm^{-3}. The different colored lines correspond to the modeled ice load according to the combinations specified in table I.

V. Summary and Conclusions

Simulations of nine recorded icing events have been performed with the WRF model, and post-processed through a cylindrical time dependent rime ice accretion model. The study shows that all the icing events are recognized in the numerical model, producing supercooled cloud water in the lowest level of the model. The maximum accumulated ice load produced by the model is in most cases comparable with the measured value, however underestimation seems to be evident for sites where the height of the terrain differs much from the real height, like the Luosto site in Finland. In cases with such height differences, the simulated ice load is very sensitive to the choice of a vertical level to use in comparison with the measurements. The sensitivity tests suggest that the best results are obtained by using data from the model level that corresponds to the real height of the hill.

A second sensitivity test emphasizes the importance of the volume number concentration used in the WRF simulations. This is important for the icing simulations because the droplet size used in the post-processing step is diagnosed based on the droplet size distribution used in the Thompson microphysics in the WRF model. The MVD is closely related to the number concentration of cloud droplets, and simulations with different droplet concentrations show that increasing the N_c from 100 cm^{-3} to 300 cm^{-3}, reduces the simulated ice load by approximately 40 %.

In general, using results from a high resolution NWP model to drive an accretion model for in-cloud icing is a powerful tool because of its flexibility and its huge potential in mapping and forecasting applications. However there are still challenges that need to be handled before such a modeling system can be used with its full potential. One of the biggest problems is the blending of the terrain in the NWP models. Case studies with very high horizontal resolution (grid spacing ~ 100 – 500 m) could be performed in order to remove the effect of the height differences between modeled and real terrain.

A compilation of nine icing events is still too few to obtain any statistically significant results, but the study is meant to gives some ideas on how the modeling system performs under different conditions at different sites. This study only focuses on the registered icing events. A continuous forecast archive or re-analysis should be used to explore how often icing is predicted when it is not occurring (the "false alarm" rate).

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