SIMULATIONS VS. OBSERVATIONS OF SUPERCOOLED CLOUD LIQUID WATER AT GROUND LEVEL; SENSITIVITY TO MODEL RESOLUTION AND CLOUD MICROPHYSICS PARAMETERIZATIONS

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Abstract: We investigate the potential for predicting episodes of in-cloud icing at ground level, by using a state-of-the-art numerical weather prediction model. For this purpose, we run the Weather Research and Forecasting (WRF) model at different horizontal resolutions, and with different microphysics schemes. Predicted values of supercooled cloud liquid water content SLWC and median volume droplet diameter (MVD) are validated against precise rotating multi cylinder measurements on a hill top in the northern Finland. We obtain the overall best result, with mean absolute error (MAE) of predicted SLWC as low as 0.08 g/m^3 when the highest model resolution is applied together with the Thompson microphysics scheme. The quality of the SLWC predictions decreases dramatically with decreasing model resolution. A systematic difference in predictive skill is also found between the microphysics schemes applied. A comparison between measured and predicted MVD shows that when setting the droplet concentration equal to 250 cm^{-1}, the model predicts MVD ranging from 12 - 20 µm, which corresponds well with the measurements. However, the variation from case to case is not captured by the current microphysics schemes.

1. INTRODUCTION

Even though precise models for the ice accumulation on different structures exist, many practical applications of such ice accretion models (IAM) are limited by the lack of reliable meteorological input data. The greatest uncertainty in the meteorological input data is usually related to the supercooled cloud liquid water content (SLWC) and the size distribution of cloud droplets, usually represented by the median volume droplet size (MVD) in the IAMs.

Until recent years explicit prediction of in-cloud icing with Numerical Weather Prediction (NWP) models has not been attainable because of coarse model resolution and crude parameterizations of sub-grid scale processes. However, the increase of computing power has enabled possibilities to run NWP models at grid spacing of 1 km or even smaller, and made it possible to incorporate more sophisticated and computationally expensive microphysical processes in the parameterization schemes. In this study we test how well the necessary meteorological input data to the AIMs can be predicted by a NWP model, and we focus on the sensitivity to model resolution and cloud microphysics parameterization scheme.

2. RESULTS AND DISCUSSION

As a measure of the predictive skill we compute the mean absolute error (MAE) between predicted and measured SLWC. From Fig. 1 shows that the MAE is decreasing with increasing horizontal resolution, but we also find a systematic difference in predictive skill between the different microphysics schemes. The overall best result with MAE of 0.08 g/m^3 is obtained when we use the highest horizontal resolution in simulations with the Thompson microphysics scheme.

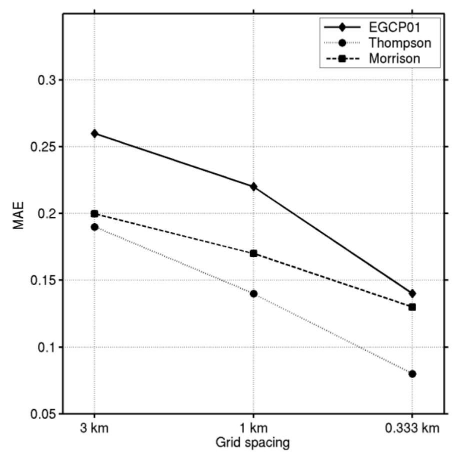

Figure 1: Mean absolute error (MAE) of predicted SLWC for simulations with various combinations of microphysics and horizontal resolutions.

3. CONCLUSION

The study suggest that horizontal resolution is a key element for successful prediction of icing at ground level, because terrain induced vertical motions are the main forcing for the production of cloud water at this site. When the highest horizontal resolution is applied with grid spacing of 0.333 km the model is able to capture all the icing events when the Thompson or Morrison microphysics scheme is used. The study also suggests that explicit prediction of the variation of droplet size from case to case requires a prediction of variation in droplet concentration for cloud water. This is a limitation of all the three microphysics schemes tested here which only predict one moment of cloud liquid water (mass mixing ratio).

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Abstract— **We investigate the potential for predicting episodes of in-cloud icing at ground level, by using a state-of-the-art numerical weather prediction model. For this purpose, we run the Weather Research and Forecasting (WRF) model, with attention paid to the model's skill to explicitly predict the amount of supercooled cloud liquid water content (SLWC) and the median volume droplet size (MVD) at the ground level, at different horizontal resolutions, and with different microphysics schemes. In total eight cases are validated against precise rotating multi cylinder measurements of SLWC and MVD on a hill top in the northern Finland. We obtain the overall best result, with mean absolute error (MAE) of predicted SLWC as low as 0.08 g/m^3 when the highest model resolution is applied (grid spacing equal to 0.333 km) together with the Thompson microphysics scheme. The quality of the SLWC predictions decreases dramatically with decreasing model resolution. A systematic difference in predictive skill is also found between the microphysics schemes applied. A comparison between measured and predicted MVD shows that when setting the droplet concentration equal to 250 cm^{-1}, the model predicts MVD ranging from 12 - 20 µm, which corresponds well with the measurements. However, the variation from case to case is not captured by the current microphysics schemes.**

Keywords; rotating multi cylinder; wrf model; in-cloud icing; microphysics scheme; droplet concentration.

I. INTRODUCTION

Several studies on how supercooled water droplets accrete on different structures have been published over the last few decades, both from icing tunnel experiments and from theoretical studies of collision and collection efficiency of water droplets. The theoretical basis for modelling ice accretion on cylinders is described in detail in [1] and [2], and has been verified at a high level of accuracy in controlled laboratory experiments [3]. Also numerical models for the formation of ice on wind turbine blades are found in the literature [4], and [5] presented a simulation scheme to model the ice buildup on bundle transmission line conductors. Even though precise models for the ice accumulation on different structures exist, many practical applications of such ice accretion models (IAM) are limited by the lack of reliable meteorological input data. The greatest uncertainty in the meteorological input data is usually related to the supercooled cloud liquid water content (SLWC) and the size distribution of cloud droplets, usually represented by the median volume droplet size (MVD) in the IAMs.

Until recent years explicit prediction of in-cloud icing with Numerical Weather Prediction (NWP) models has not been attainable because of coarse model resolution and crude parameterizations of sub-grid scale processes. However, the increase of computing power has enabled possibilities to run NWP models at grid spacing of 1 km or even smaller, and made it possible to incorporate more sophisticated and computationally expensive microphysical processes in the parameterization schemes, as well as more prognostic variables. [6] showed promising results by running the MM5 model at 1 km grid spacing for an icing episode in coastal mountainous terrain in Norway. Also several conference proceedings based on experimental icing simulations with the WRF model, carried out within the framework of COST 727 [8], have shown promising results ([9]-[10]). However no direct validation of predicted SLWC and MVD at ground level is found in the scientific literature.

In the current study we investigate how well SLWC and MVD measured from the ground can be reproduced in simulations with a state-of-the-art NWP model, namely the Weather Research and Forecasting (WRF) model. We study the effect of different horizontal model resolutions, and investigate the effect of applying different cloud microphysics schemes.

II. EXPERIMENTAL DESIGN

A. Measurements

SLWC and MVD measurements were carried out at the top of Mt. Ylläs (67.6°N, 24.3°E) in northern Finland, having an elevation of 719 m. It is a rounded peak, and is the highest mountain in a large region, with surrounding terrain ranging from 150 m to 300 m elevation. At Mt. Ylläs, accurate in-situ measurements of in-cloud icing have been carried out for several years, using a rotating multicylinder instrument ([10]-[11]). In the current study, eight cases are selected, characterized by a moist planetary boundary layer with cloud base below the mountain top, and temperature below 0 ºC. All measurements are performed in conditions with no precipitation during the exposure time of the rotating multicylinder. Table 1 summarizes the observations. WRF model setup

The mesoscale numerical weather prediction model used in this study is the Weather Research and Forecasting modelling system version 3.1.1 ARW [12]. Simulations are carried out by applying one-way, four domain telescopic nesting. The grid spacing increases stepwise by a factor of three from 9 km in the outermost domain to 0.333 km in the innermost high resolution domain (Fig. 1). The terrain data used as input to WRF are obtained from the U.S. Geological Survey (USGS) global 30-arc seconds elevation (GTOPO30) dataset, and the model is configured with 66 hybrid coordinate vertical levels (η-levels) for all domains, with the model top at 100 hPa.

Initial fields and lateral boundary conditions are retrieved from the global ECMWF re-analysis data ERA-INTERIM, at 38 pressure levels with a temporal resolution of 6 hours. All simulations are cold started between 6 and 12 hours in advance of the measurement time. In order to keep the model numerically stable throughout the simulations, a time step as low as 0.45 s was required in the innermost domain.

TABLE 1 WEATHER DATA COLLECTED FROM THE YLLÄS TEST SITE.

Date	Time (UTC)	Wind dir	Wind speed (m s^{-1})	T (ºC)	LWC (g m^{-3})	MVD (μm)
08/2/1990	09	NW	6	-3	0.43	15.8
14/2/1990	06	SSE	4	-5	0.27	19.9
17/12/1990	12	SW	14	-4	0.25	15.3
08/12/1994	08	SSE	14	-5	0.40	14.3
12/12/1994	11	W	4	-6	0.09	13.7
19/12/1994	11	SSW	22	-3	0.30	12.1
09/1/1996	11	SW	13	-5	0.30	12.2
10/1/1996	11	SW	20	-5	0.43	13.6

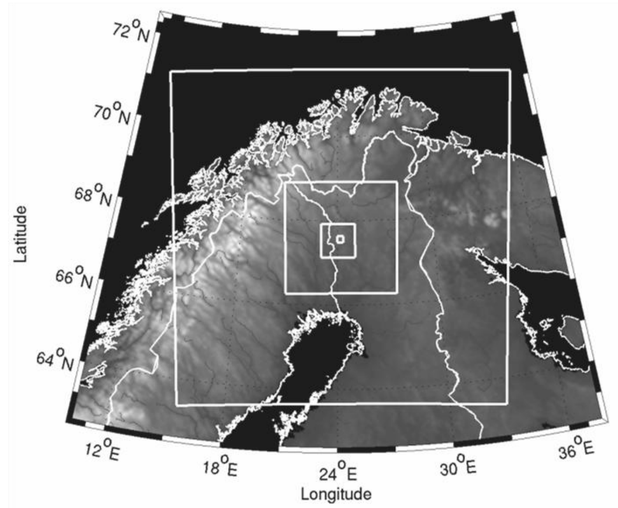

Figure 1. Configuration of nested domains used in the WRF simulations. The four nested domains are indicated with white squares, with grid spacing decreasing from 9 km in the outermost domain to 0.333 km in the innermost domain.

Special attention is paid to the sensitivity to how the model parameterizes the cloud microphysical processes. Therefore we have performed all the simulations with three different microphysics schemes: Morrison two-moment scheme [13], the Thompson scheme ([14]-[15]) and the Eta Grid-scale Cloud and Precipitation scheme (EGCP01) [16], also known as the Ferrier – ETA scheme. Among the three schemes, the EGCP01 is the most efficient one, and it represents an example of a typical scheme employed in many operational forecasting models, such as the North American Modeling System [17]. The Thompson scheme was originally developed in order to improve explicit prediction of aviation icing, and from there it applies rather sophisticated formulations of mixed phase processes compared to other bulk microphysics schemes [15]. The Morrison two-moment scheme is the most advanced and computationally expensive of the three schemes as it predicts both the mass concentration and number concentration of the cloud and precipitation species.

III. RESULTS AND DISCUSSION

A. Validation of predicted SLWL

Instantaneous values of measured SLWC are compared to the corresponding predicted values at 719 m.a.s.l. In the innermost domain this height corresponds to the lowest model level, while in the coarser domains it corresponds to levels located higher above the ground because the height of the hill is reduced due to smoothing effects. In these coarser domains the predicted SLWC is linearly interpolated between the vertical levels, to match the height of the real mountain.

In general the results suggest that the predicted SLWC increase with increasing model resolution as exemplified in Fig. 2a, where many cases are underestimated at 3 km and 1 km grid spacing, and the best match with observations is obtained when using the highest resolution (0.333 km grid spacing). The reason for the large dependency on horizontal resolution is to a large extent related to condensation of cloud droplets (production of SLWC) by orographic lifting of air over the hill top. At grid spacing of 3 km the modeled hill is only 367 m.a.s.l. which is a significant difference from the real height of 719 m. In the highest resolution domain the hill is correctly represented with 719 meters height, and not surprisingly this provides the best predictions of SLWL at the top of the hill.

As a measure of the predictive skill we compute the mean absolute error (MAE) between predicted and measured SLWL. From Fig. 2b we see that the MAE is decreasing with increasing horizontal resolution, in accordance with the argumentation above, but we also find a systematic difference in predictive skill between the different microphysics schemes. The overall best result with MAE of 0.08 g/m^3 is obtained when we use the highest horizontal resolution in simulations with the Thompson microphysics scheme.

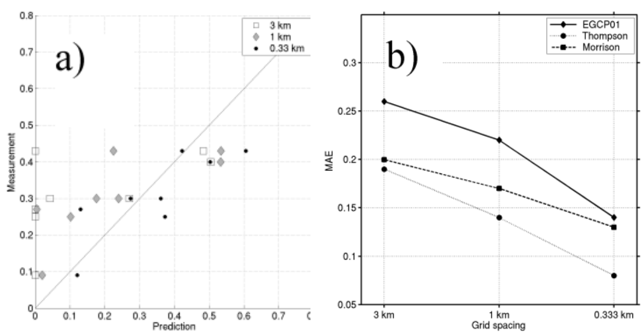

Figure 2 a) Measured vs. predicted SLWC at three different horizontal resolutions. All simulations are carried out with the Thompson microphysics scheme. b) Mean absolute error (MAE) of predicted SLWC for simulations with various combinations of microphysics and horizontal resolutions.

B. Validation of predicted MVD

The current versions of the three cloud microphysics schemes predict only the mass mixing ratio of the cloud water, and apply a fixed number concentration for cloud droplets (N_c) throughout the simulations. A droplet size distribution is employed to describe how droplet mass is distributed with respect to size. Based on the droplet concentration and the assumed size distribution, characteristic droplet sizes can be diagnosed, such as the MVD, which is required for further post-processing in IAMs. A description on how to diagnose the MVD from the model output can be found in [18]. Following this procedure we have calculated the predicted MVD for the simulations with the highest horizontal resolution and the Thompson microphysics. The default value for droplet concentration in the Thompson scheme is 100 droplets per cubic centimeter, and the corresponding MVD predictions are compared with measurements in Fig. 3a. Based on N_c = 100 cm^{-3} the model overestimates the droplet size in seven out of eight cases, indicating that in average, the true droplet concentration has a higher value. In Fig. 3b we have repeated the calculation, but now with a droplet concentration equal to 250 cm^{-3}, which is a more typical value for continental air masses [19]. In this case the systematic over prediction of droplet size is strongly reduced, and when using N_c equal to 300 cm^{-3} the bias is totally eliminated from the results.

From Fig. 3 we can also see that even though we are able to predict the average MVD by setting the proper droplet concentration, the model does not seem to capture any of the variation in MVD from case to case. To explore this issue further we start by the definition of SLWC

$$SLWC = \frac{\pi\rho_w}{6}\int D^3 N(D)dD \qquad (1)$$

If we let the droplet diameter be represented by the MVD in (1) we obtain the following equation for SLWC.

$$SLWC = \frac{\pi}{6}(MVD)^3 \rho_w N_c \qquad (2)$$

From (2) we find that for a given droplet concentration we have a MVD = LWC1/3 relation. By plotting measured MVD against measured LWC (Fig. 5) we find the measurements randomly distributed on the scatter plot, and we do not see any sign of relation between the two variables, such as suggested in (2). By comparing the measurements with theoretical curves for different values of N_c (Fig. 5), we find large variation in the true droplet concentration, with two measurements corresponding to N_c smaller than 100 cm^{-3} and four measurements corresponding to N_c larger than 500 cm^{-3}. The result implies that a one moment prediction of cloud water is not adequate for predicting the variation in droplet size for the cases considered here. This is most likely related to different wind directions and advection of air masses with different concentrations of cloud condensation nuclei. It should be mentioned that this might be totally different for icing at a costal site, where in-cloud icing only occurs with winds from a certain sector with marine air masses. At such sites the droplet concentration would be expected to vary less between icing events, hence a more pronounced correlation between droplet size and LWC than found here would be expected [19].

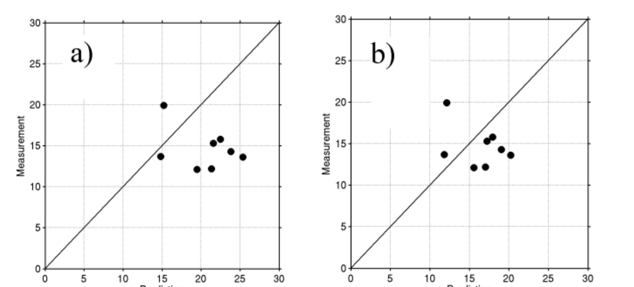

Figure 3. Measured vs. predicted values of MVD (µm) using the Thompson microphysics scheme at grid spacing of 0.333 km. a): MVD calculated with Nc=100 cm^{-3} and b): MVD calculated with Nc=250 cm^{-3}.

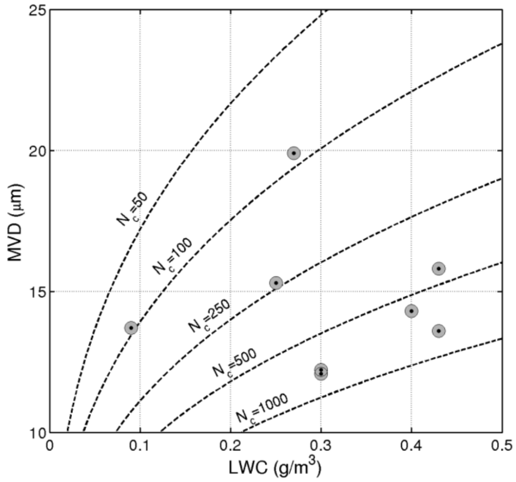

Figure 5. Measured MVD plotted against measured SLWC. The black lines indicate theoretical curves for various droplet concentrations based on the assumed droplet size distribution.

IV. CONCLUSIONS

The main objective of the study has been to examine how well episodes of in-cloud icing at ground level can be simulated by a state-of-the-art NWP model. In total eight cases have been simulated with the WRF model and instantaneous values of SLWC and MVD were validated against measurements at Mt. Ylläs, located in the northern Finland.

The overall results suggest that horizontal resolution is a key element for successful prediction of icing at ground level, because terrain induced vertical motions are the main forcing for the production of cloud water at this site. When the highest horizontal resolution is applied with grid spacing of 0.333 km the model is able to capture all the icing events when the Thompson or Morrison microphysics scheme is used. We obtain the best match between measured and predicted SLWC when the highest resolution is applied in combination with the Thompson microphysics scheme, resulting in a mean absolute error of only 0.08 g m^{-3}. There are at least two reasons why such good results can be obtained for this particular site. First, the main forcing for the production of SLWC is the orographic lifting of moist air on the upstream slope of the hill. This forcing is rather strong and a successful simulation is to a large extent a matter of good representation of the local terrain (horizontal resolution). Second, many of the icing events are related to pure liquid low level stratus and/or orographic clouds without interaction with ice particles. More mixed phase conditions would have increased the number of interaction terms in the prognostic calculation of cloud water, and hence reduced the predictability of SLWC.

By using the droplet size distribution and droplet concentration that is assumed in the microphysics schemes together with the predicted SLWC we are able to predict the droplet size in terms of median volume droplet diameter. The results suggest that a droplet concentration of 100 cm^{-3} results in an overestimation of the MVD compared to observations. By changing the droplet concentration to 250 cm^{-3} or higher, which is more typical for continental sites, the overall MVD corresponds much better with the measurements. The study also suggests that explicit prediction of the variation of MVD from case to case requires a prediction of variation in droplet concentration for cloud water. This is a limitation of all the three microphysics schemes tested here which only predict one moment of cloud liquid water (mass mixing ratio). For practical application of the model, this will introduce an uncertainty in the predicted icing intensity for single icing events. However, since there is no bias in MVD when using the proper droplet concentration, a fixed number concentration may be adequate for climatological studies of in-cloud icing. It is a subject for future experiments to test whether full two-moment schemes are able to explicitly predict the variation in droplet concentration, for improvement of explicit prediction of icing intensity.

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