Comparison between simulations and measurements of in-cloud icing in test spans

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***Abstract*— In this paper a comparison is made between measured in-cloud ice loading in 80 m long test spans and calculated ice loading. The work is based on numerical data describing the state of the atmosphere at high spatial and temporal resolution. The icing measurements are carried out in test spans which have frequent in-cloud icing. The atmospheric data is created by dynamical downscaling of atmospheric analysis to a horizontal resolution of 9, 3, 1, and 0.33 km. The high horizontal resolution allows the atmospheric model to reproduce accurately the atmospheric flow in complex orography, e.g. in high and steep mountains where overhead transmission lines can be located, not resolved at coarser resolutions. In general, icing calculations based on the atmospheric model identify correctly the observed icing events, but underestimate the load due to too slow ice accretion. This is most obvious when the temperature is slightly below 0°C and observed icing is most intense. The model results improve significantly when additional observations of weather are used for forcing the atmospheric model. However the large variability in the simulated atmospheric variables results in high temporal and spatial variability in the calculated ice accretion. Furthermore, there is high sensitivity of the icing model to the droplet size and the possibility that some of the icing may be due to freezing drizzle or wet snow instead of in-cloud icing of super-cooled droplets. In addition, the icing model (Makkonen) may not be accurate for the highest icing observed.**

I. Introduction

Recent development in numerical weather prediction models (NWP) combined with increased computing power has lead to new opportunities to assess historical and/or make short term forecast of atmospheric icing on structures. Simulated weather from NWP models can be used to evaluating icing in areas with limited observations of weather. The development in NWP models is rapid and future improvements will surely improve the prediction capability, in particular improvements to the parameterization of atmospheric moisture. Studies have been made to compare predicted icing based on results from NWP models to measured icing e.g. [5] and [11] but quantitative measurements of icing are often limited. In this context the extensive datasets of observed atmospheric icing in Iceland are invaluable. Test spans to measure icing have been operated since 1972 in Iceland. Totally there have been erected 86 spans in 56 locations. Many of the locations are in areas with frequent in-cloud icing and more than 1000 icing events have been registered. The maximum load observed is 67 kg/m. The observations of icing collected in the test spans are very suitable for exploring the feasibility of basing prediction of atmospheric icing on results from NWP models.

In this paper a comparison is made between prediction of icing based on NWP simulations and icing measured in a test span at Hallormsstadahals, East-Iceland. Four icing events are used for the comparison and the peak ice load measured in these events ranged between 4 and 36 kg/m. Most of the ice accretion is in-cloud icing but it may partly be mixed with freezing drizzle and wet snow icing.

II. Icing Measurements

The measurements in test span A at Hallormsstadahals started in 1983 and have been continuous since. The measuring site is located 575 m above sea level and in-cloud icing occurs frequently every year. A description of the measuring site is given in [2].

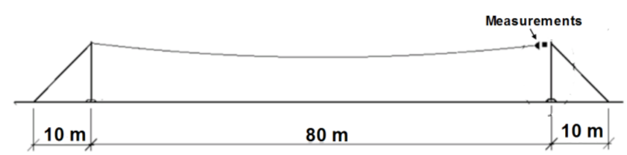

Figure 1. Test span with 80 m measuring span. Conductor tension is measured in attachment to guyed pole 10 m above ground.

Fig. 1 shows the setup of the test span. The spans are 80 m long and the conductor is strung on poles that are 10 m above ground. Description of ice load measurement in test spans is given in [1]. Measurements are made on conductor tension force and temperature. An automatic weather station with unheated anemometer is also operated at Hallormsstadahals. Unit load of icing is derived by assumptions of equally distributed ice load on the measuring span and the guy wires that supports the poles. Figure 2 shows the effects of other distribution of icing. The factor η is defined as the ratio of actual icing on the measuring span compared to predicted icing with the assumption of equal distributed load. It is believed that actual ice load is most often well predicted with the assumption of equally distributed load.

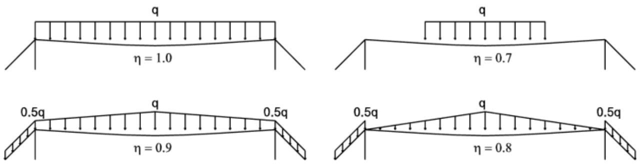

Figure 2. Influence of load distribution on assumed icing.

III. ICING MODELING

The calculation of atmospheric icing is made in two steps: (i) High-resolution simulations with an atmospheric model (WRF) are used to reproduce the necessary meteorological data, i.e. temperature, wind speed and cloud/precipitation particles. (ii) Modeling of ice accretion using results of the atmospheric simulation as input to an ice accretion model.

A. Simulated atmospheric data, WRF-modeling

The atmospheric datasets employed in this study are created by dynamically downscaling the ECMWF-analysis with the non-hydrostatic mesoscale Advanced Research WRF-model (versions 3.2.1 and 3.0.1) [10], which is a state of the art numerical atmospheric model, used worldwide for operational simulation of weather and in atmospheric research, e.g. of atmospheric icing. With the dynamical downscaling to high horizontal resolution the orography is represented more correctly than at coarser resolutions, e.g. as is typical in the ECMWF-analysis, and hence weather in complex terrain is better reproduced. The relevant microphysics parameterization scheme used is the Thompson bulk scheme ([12] and [13]) which explicitly predicts cloud and precipitation variables used by the icing model. Namely, the mass of cloud water and ice, as well as rain, snow and graupel. As direct measurements are not available, the scheme is using a well-tested and fixed droplet number of 100 droplets/cm^3 which is applicable for a maritime climate.

The largest dataset is based on 15 years (1994-2009) of downscaled weather in Iceland at a horizontal resolution of 9 and 3 km, with 55 layers in the vertical. This dataset is a part of the RÁV-project [9], and is the most detailed high-resolution dataset available to date, describing the weather and climate in the complex terrain of Iceland. This setup is nearly identical to that used in operational numerical simulations by Reiknistofa í veðurfræði (RV) which are used for forecasting of weather at Veðurstofa Íslands ("http://belgingur.is"). In order to better assess the effect of increased horizontal resolution on how well weather is reproduced in the steep mountains of East-Iceland, observed intense icing events during Dec. 2000 and Nov.-Dec. 2006 were downscaled to a resolution of 1 km and 0.3 km. Furthermore, as a limited number of surface observations are used to correct the atmospheric analysis forcing the dynamical downscaling, another dataset at 1 km was created where the WRF-model was forced with hourly observations of wind, temperature, pressure and humidity at Egilsstadir. This forcing is strongest at Egilsstadir and at the time of each observation, while the forcing decreases quite fast both spatially and temporally with increasing distance and time from the observations. The additional forcing improves the model results for a region near Egilsstadir, which extends to Hallormsstadahals in the downwind direction. The model could in theory be forced with observations from other automatic weather stations but here we choose to limit us to only observations from Egilsstadir. The quality of the simulations and representation of the orography improves significantly as the resolution improves from 9 km to 3 km to 1 km. The orography near the observation site at Hallormsstadahals is reasonably well reproduced at 1 km and the model altitude is approx. 550 m while the true altitude is 575 m. The error is slightly smaller at 0.3 km model resolution but far worse at 9 and 3 km.

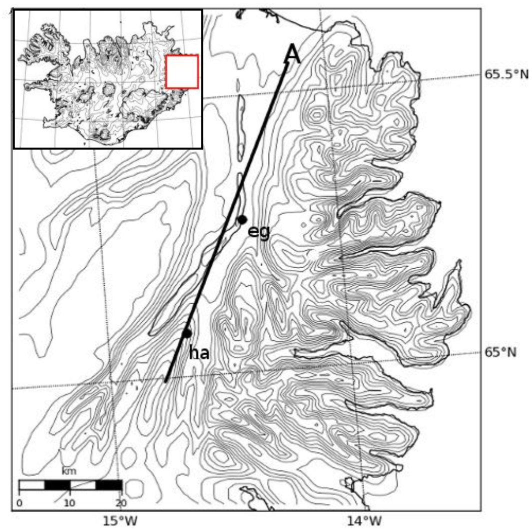

Figure 3. Grid model space. Model orography at a resolution of 1 km with a 100 m interval. Also shown is the true coastline, locations of Egilsstadir (eg) and Hallormsstadahals (ha), as well as the location of vertical section A. The inset shows the 3 km model orography at a 200 m interval.

Four different WRF-simulations (WRF_{1km}, $WRF_{1km\text{-}F}$, WRF_{3km} and $WRF_{0.3km}$) are made and they are used to produce six different input series for the icing model. Two of the models ($WRF_{1km\text{-}A}$ or $WRF_{1km\text{-}F\text{-}A}$) adjust the simulated values in order to evaluate the sensitivity of the icing model. The modification consist of: (i) using temperature measurement from the site instead of temperature in the WRF-simulation, (ii) adding 3 m/s to the wind speed in the WRF-simulation. The models are given in Table 1.

Table 1: Data from WRF-simulations used in icing models.

Model	**Grid spacing [km]**	**Comment**
WRF_{1km}	1	
$WRF_{1km\text{-}F}$	1	Forced through observation at Egilsstadir
WRF_{3km}	3	
$WRF_{0.3km}$	0.33	
$WRF_{1km\text{-}F\text{-}A}$	1	Same as $WRF_{1km\text{-}F}$, but measured temperature used and 3m/s added to simulated wind
$WRF_{1km\text{-}A}$	1	Same as WRF_{1km}, but measured temperature used and 3m/s added to simulated wind

B. Modeling ice accretion

The time dependent cylindrical ice accretion model described in ISO 12494-2000 [3] is used to predict icing (Makkonen model). It describes how particles that can be either liquid (usually super-cooled), solid, or a mixture of water, accumulate on objects. The icing rate is described by

$$\frac{dM}{dt} = \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot w \cdot V \cdot A \qquad (1)$$

where V is particle velocity (m/s), A is the cross-sectional area (m^2) perpendicular to object, w is water content (kg/m^3), α_1 is the collision efficiency, α_2 is the sticking efficiency and α_3 is the accretion efficiency.

The test spans have a conductor with a specific direction and some restriction to rotation at the ends. It is assumed that the accretion shape is cylindrical and it is taken into account that the measuring span has specific horizontal direction and does not collect icing as in the vertical cylinder approach that is often used. The option of ice shedding is not used in this version of the icing model.

The water phase in the WRF-model is classified into: cloud water (Q_c), cloud ice (Q_i), rain (Q_r), snow (Q_s) and graupel (Q_g). Three of the phases can lead to icing accumulation but particles in form of ice and graupel are assumed to give no ice accumulation since they should not stick to the object.

Cloud water is the source of in-cloud icing: V is taken as the wind velocity, water content w is it taken as the liquid cloud water (Q_c). α_1, α_3 as well as density of in-cloud icing are calculated by formulas in [4]. A fixed droplet number N_d = 50 droplets/cm^3 is used, here a lower value is used than in the WRF-simulation (N_d=100) in order to increase the collision efficiency and accretion rate. Medium volume droplet is derived using formulas in [11].

Rain is treated as freezing drizzle/rain when the temperature is below zero. The horizontal velocity of the particles is taken as wind velocity at 10 m height in the WRF-model and the vertical velocity is assumed as 3 m/s. Water content w is taken as Q_r, $\alpha_1 = 0.9$, $\alpha_2 = 1.0$ and α_3 is for simplicity assumed as 1.0 but should be calculated similar as for in-cloud icing.

The snow leads to accretion as wet snow icing when the temperature is between 0 and 2°. The horizontal particle velocity is taken as simulated wind velocity and vertical velocity is taken as 1 m/s. The water content w is taken as Q_s, $\alpha_1 = \alpha_3 = 1.0$, α_2 is taken as 1/V if temperature is in range of 0°C to 2°C, otherwise it is taken as 0. Density of wet snow is assumed to be 700 kg/m^3.

IV. THE OBSERVED AND PARAMETERIZED ICING

The period studied here includes four observed icing events, in particular the event of 4-6 December 2000 with the highest ice load measured during 28 years of systematic measurements in test span A at Hallormsstadahals. Three smaller but significant icing events were observed during November and December 2006. All the icing events are associated with persistent north- and northeasterly winds, related to extratropical lows or troughs located to the south and east of Iceland. The events can be divided into two categories depending on the observed temperature, which was slightly below 0°C in events in the beginning of December 2000 and 2006 but well below freezing during the events in November and middle of December 2006. The low level winds levels are in general orographically channeled along the N-S oriented Herad lowlands in Northeast-Iceland. When impinging on the Hallormsstadahals ridge, a part of the low level flow is in general blocked and partly deflected around the ridge while the flow a short distance further aloft experiences orographic lifting above the ridge. Super-cooled cloud droplets are created during the lifting in a large region near and upslope from the observation site, but the site itself is frequently only marginally inside the orographic cloud. All of the icing events experience periods of significant snowfall (or rain) from clouds further aloft, through the orographic cloud. This snowfall appears to collect the orographic cloud condensate, effectively reducing the super-cooled water-content available for in-cloud icing.

The WRF-model captures reasonably well the observed weather at Egilsstadaflugvollur airport and at Hallormsstadahals during the icing events. The biggest discrepancy is in general found in a slight underestimate in the observed 10-meter wind speed on the order of a few m/s which may be a result of to high surface friction or sub-grid orography not accounted for in the model. There is furthermore at times a small error in the observed temperature but this presumably has the largest impact on the icing model when temperature is slightly below 0°C. The model performance is in general improved significantly with increasing resolution and with the additional forcing by observations from Egilsstadaflugvollur airport.

A. Hallormsstadahals A, 4-6 Dec. 2000

The most intense icing observed occurred during 4-6 December 2000. During the period, the cloud ceiling was low and temperatures were relatively mild with 2-4°C observed at the lowlands and with the freezing level located below mountain tops. The simulated 0°C isotherm was on average at 500-700 m above the low-lands and fluctuated in height near the site of the test span on Hallormsstadahals (Fig. 4). There was at times an extensive cloud layer in the region but the model results indicate that a localized and persistent cloud with super-cooled droplets was created by orographic uplift at Hallormsstadahals (Fig 5). Considerable precipitation fell during the period, both as rain and snow near the test span. The lowering of the isotherms near Hallormsstadahals may at times be associated with significant evaporative cooling but it is also a result of the upstream blocking of the low-level flow. The variations in the locations of the 0°C isotherm and the amount of cloud condensate near the site of the test span have a strong impact on the parameterized icing. Considerably greater icing may be parameterized for a location slightly further upslope from the test-span than at the site itself, as is evident from the section in Fig. 5.

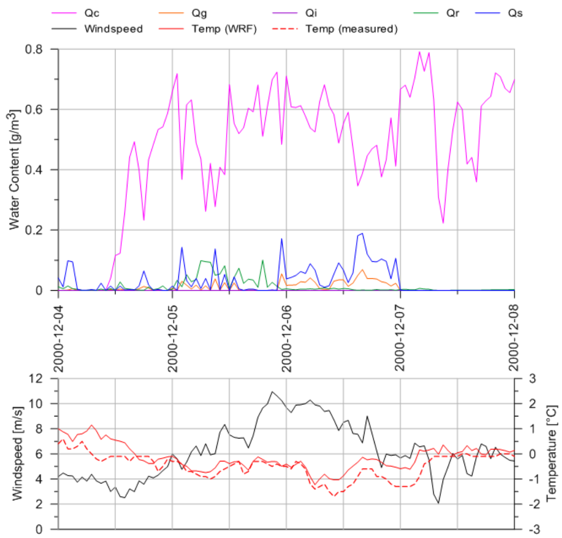

Figure 4. $WRF_{1km\text{-}Forced}$ simulation with 1 km grid and forced simulation. Upper part shows water content of each water phase. Lower parth shows wind speed and temperature.

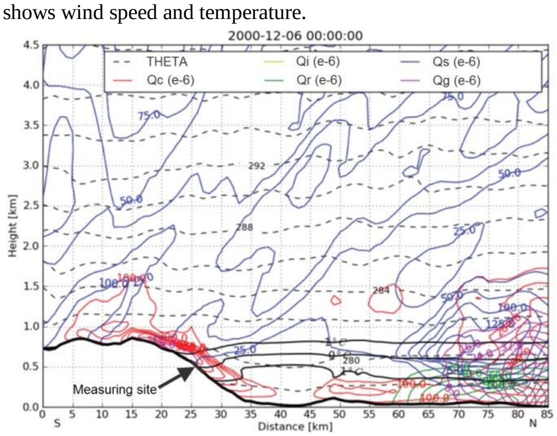

Figure 5. $WRF_{1km\text{-}F}$. South-north oriented section above the measuring site on Hallormsstadahals through the 1 km model domain. The main wind directions is from north to south. Shown are the topography, the -1, 0 and 1°C isothermes, isentropes with a 2 K interval as well as concentrations of cloud hydrometeors and precipitation variables.

Figure 6 shows measured icing and predicted accretion for different weather parameters. The calculated ice accretion from WRF-models identifies the icing event. All models predict much lower ice accretion than measured. Very small accretion is predicted by the WRF_{3km}, WRF_{1km}, and $WRF_{0.3km}$ models, while the forced model, $WRF_{1km\text{-}F}$, is somewhat better. The adjusted model $WRF_{1km\text{-}F\text{-}A}$ gives better results although accretion rate is only about 1/3 of the measured. The water content in $WRF_{1km\text{-}F\text{-}A}$ is primarily cloud water but the small amount of freezing drizzle that exists, leads to 20% of the ice mass due to the high collision efficiency of drizzle. Fig. 6 also shows two hypothetical cases with constant weather parameters for the event. The parameters were selected to see how much modification is needed to give results close to the observed icing. Wind speed was taken as V=14 m/s, which may be close to the peak wind in the event but is definitely higher than the average wind. Only cloud water particles were included with an assumed liquid water content given by w = 0.6 g/cm^3, which is slightly above the average value predicted by the $WRF_{1km\text{-}F}$. Droplet number was taken as before as N_d = 50 droplets/cm^3, which results in a droplet size as 31 µm. Temperature is the only difference between the hypothetical cases, it was taken as -1°C in $Hypothetical_1$ and -2°C in $Hypothetical_2$. The icing predicted using the Hypothetical assumptions shows the strong influence of temperature when it is close to zero. Then the accretion efficiency (α_3) is reduced from one since the heat balance at the icing surface will not allow all particles to freeze. The assumptions in $Hypothetical_2$ leads to icing close to the observed icing, it is though based on higher wind speed and lower temperature than occurred during the event.

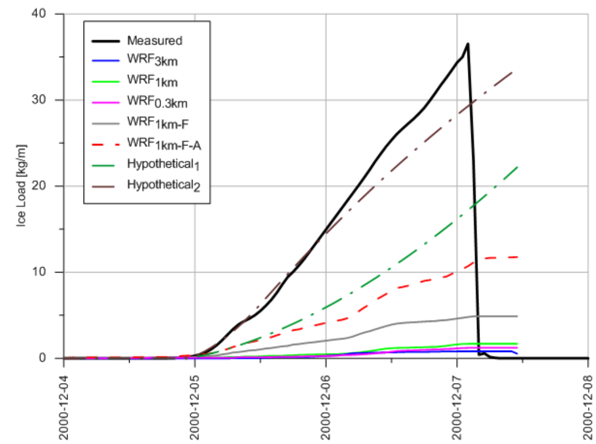

Figure 6. Measured and simulated/calculated accretion. Five different results of WRF-simulations are given. Two calculations are based on assumptions of constant weather parameters.

Fig. 4 shows the weather parameters in the $WRF_{1km\text{-}F}$ simulation. The model captures the high water content that is needed for the accumulation and the simulated temperature is close to the measured temperature on site. Simulated wind speed may be slightly underestimated based on nearby lowland observations, (2 to 3 m/s). The reason for the big discrepancy between the observed and calculated icing is unclear but it can be related to some of the following:

- Droplet size has a big impact on the accumulation. It will lead to increased accumulation if droplets are fewer than 50 droplets/cm^3 or if larger part of the water content is classified as freezing droplets instead of cloud water.
- Temperature in this icing event was close to zero and the accretion efficiency (α_3) reduces calculated icing, assuming that the heat balance at the icing surface will not allow all particles to freeze. This influence may be overestimated in the case of a rough surface.
- The icing model (Eq. 1) is not calibrated for the high icing observed in this event; the accuracy above 15 kg/m is unclear. Large ice diameters often have a rough surface and that may lead to incorrect formulas for α_1, α_3 and the

ice density.

- The WRF-simulations use 100 droplets/cm^3 but the icing model assumes 50 droplets/cm^3. Reducing droplet number in the WRF-simulation leads to a somewhat different water particle distribution, as the cloud droplets will contain less liquid cloud water before they start to convert to drizzle size droplets.
- Wind speed has a large effect on the icing rate and unresolved terrain features may lead to locally enhanced winds not captured in the model.
- Overestimation of observed icing. Value of observed icing may be slightly too high, see paragraph 2 and Fig.2.

B. Hallormsstadahals A, 13-30 Nov. 2006

The icing event during 12-30 November 2006 can be split into three sub-periods of intense icing. Temperatures are well below zero during the period and there is significant orographic uplift above Hallormsstadahals with the creation of large amounts of super-cooled cloud-condensate near and above the observation site. As for the other events there is during the first and third sub-period of intense icing, large scale snowfall through the orographic cloud. The second sub-period is characterized by high amounts of condensate above and near the test span, while the site itself is at times just outside the region.

Figure 9 shows measured icing and how different weather simulations predict the accretion. The WRF$_{1km}$ model underestimates the icing by factor of 3.3. The underestimation is at least partly because the WRF$_{1km}$ model predicts a very high mass of snow particles and low mass of super-cooled cloud droplets, see Fig.7. An adjusted model (WRF$_{1km\text{-}A}$) with wind speed increased by 3 m/s and temperature from the observation site results in somewhat higher icing. The third accretion curve is the WRF$_{3km}$ model, it predicts mainly freezing drizzle and wet snow icing and in-cloud icing is only around 40% of the ice mass.

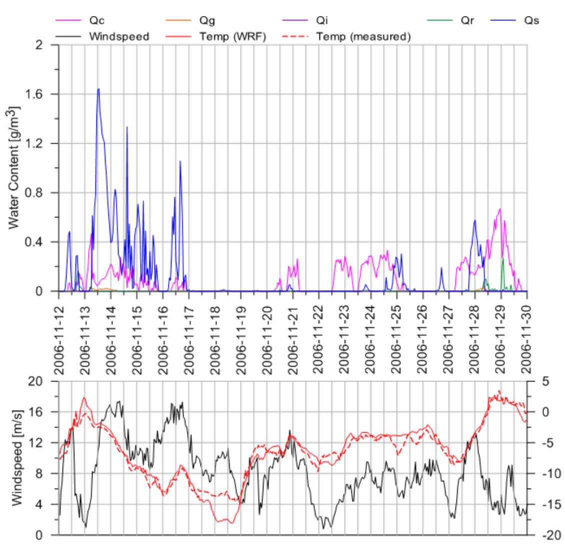

Figure 7. WRF$_{1km}$ simulation with 1 km grid. Upper part shows water content of each water phase. Lower parth shows wind speed and temperature.

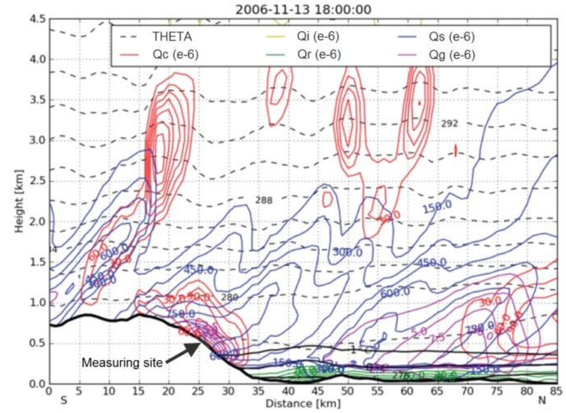

Figure 8. WRF$_{1km}$. Weather cross section taken through measuring site in main icing direction to sea (NNA direction). UTC 2006-11-13 18:00. Shown are the topography, the -1, 0 and 1°C isothermes, isentropes with a 2 K interval as well as concentrations of cloud hydrometeors and precipitation variables.

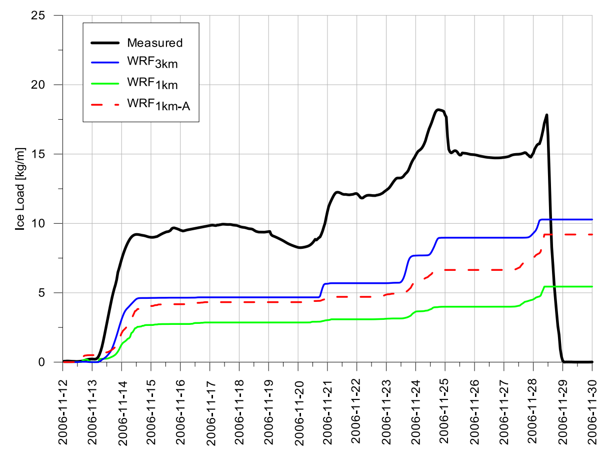

Figure 9. Measured and simulated/calculated accretion.

C. Hallormsstadahals, 4-12 Dec. 2006

The atmospheric simulations during the icing period of 3-11 December 2006 are characterized by significant rainfall and higher temperatures at the beginning than at the end of the period when there is some snowfall. The large scale and orographic clouds in the region contain mostly super-cooled cloud condensate, and it appears that the rainfall can be associated with freezing rain at higher altitudes. This, however, remains to be investigated more closely.

Figure 11 shows measured icing and how three different WRF-models predict the accretion. The measured icing is influenced by ice shedding which needs to be taken into account in the comparison. The WRF$_{3km}$ model highly underestimates the icing accretion. The WRF$_{1km}$ model performs reasonably but underestimates the observed icing by a factor of 1.7 when the ice shedding is taken into account. Part of the explanation may be the relative high amount of snow particles in the period 7-9 Dec. 2006 (Fig.10). The WRF$_{1km\text{-}A}$ model gives increased accretion and it fits measurements quite well in the period of 3-6

Dec. 2006. The accumulation on the 7 Dec. 2006 is underestimated although it may partly be explained with accumulation on different ice diameter due to the ice shedding in the measuring span.

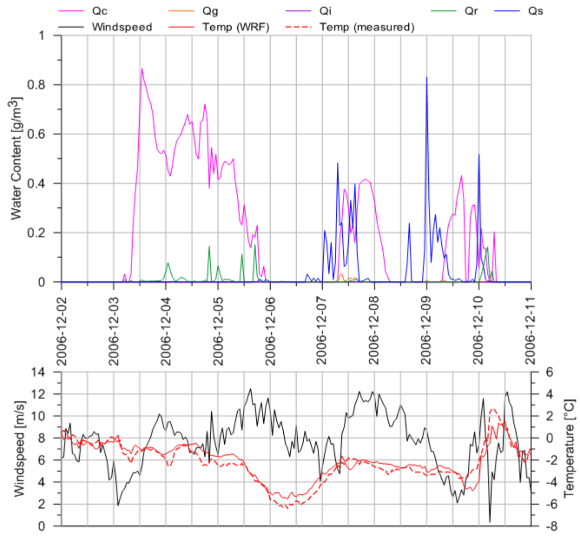

Figure 10. WRF_{1km} simulation. Upper part shows water content of each water phase. Lower parth shows wind speed and temperature.

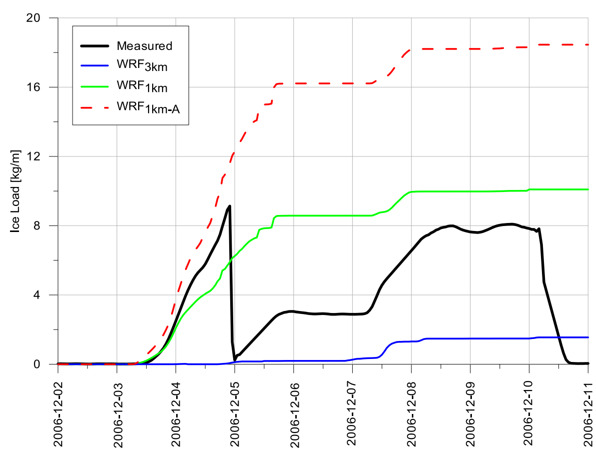

Figure 11. Measured and simulated/calculated accretion.

D. *Hallormsstadahals A, 14-21 Dec. 2006*

During 12-19 December 2006 temperatures are well below zero and the low level flow is mostly blocked and deflected around Hallormsstadahals. However, the flow above experiences orographic uplift above Hallormsstadahals with significant and variable amounts of super-cooled cloud condensate near and above the location of the test span, with the maximum amount on average located a short distance upslope from the observation site. There is some simulated snowfall during the event.

Figure 13 shows measured icing and how three different WRF-models predict the ice accretion. All of the models fail to quantify the accretion. The $WRF_{1km\text{-}A}$ model leads to the best results although ice accumulation is underestimated by factor of 3.5 if the ice shedding is taken into account. The underestimation of the models is partly explained by the large part of the water content that is classified as snow in the WRF-simulations, see Fig. 12. The icing model does not consider it as a source of icing at this temperature range.

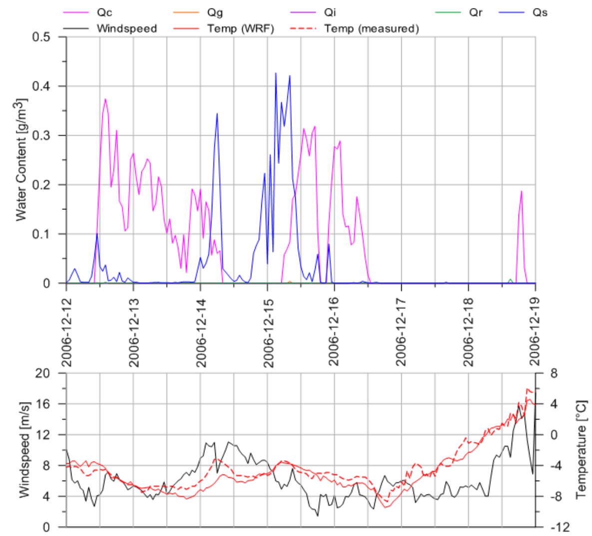

Figure 12. WRF_{1km} simulation. Upper part shows water content of each water phase. Lower parth shows wind speed and temperature.

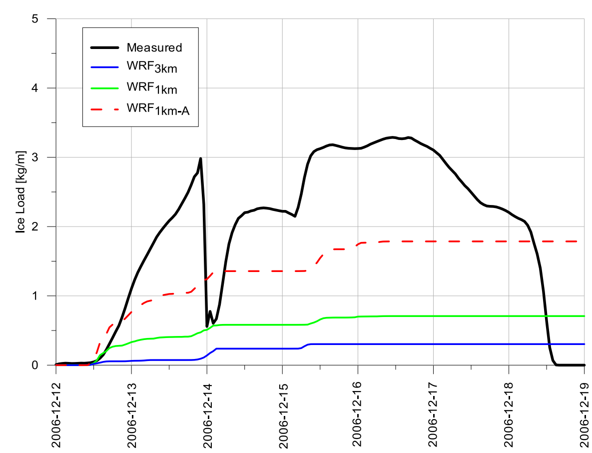

Figure 13. Measured and simulated/calculated accretion.

V. CONCLUSION

The test site at Hallormsstadahals experiences frequent in-cloud icing. Here four icing events were selected, the weather condition were simulated using the WRF atmospheric model and icing accumulation evaluated with an icing model. One of the events contains by far the most intense icing observed in 28 years of systematic observation at Hallormsstadahals.

It is found that the WRF-simulations in general predict considerable water content at the measuring site during the icing events and that the temperature is most often well predicted. Wind speed is believed to be slightly underestimated (2 to 3 m/s). The calculated ice accretion rate was in general underestimated compared to the measurements. A large variability exists in the magnitude of the simulated atmospheric variables and in the location of their maximum, which results in high temporal and spatial variability in the calculated ice accretion. In particular, far greater icing would be calculated for a location a short distance upslope from the observation site, where conditions are in general characterized by significantly higher amounts of cloud water, stronger winds and the temperature is normally well below 0°C. The classification of the simulated hydrometeor species into cloud water, rain and snow is also sensitive and has a great influence on the predicted icing but no direct observations are available to verify the model. Direct observations of the droplet size would also be beneficial. The study shows that the results from the atmospheric model improve considerably when in addition to the atmospheric analysis; the model is forced through nearby surface based observations of weather. This is especially important when the temperature is close to 0°C as a small error in simulated temperature will strongly influence whether icing is taking place or not. The model performance increases as the resolution is increased, especially when going from 3 km to 1 km, but moderately when going from 1 km to 0.3 km.

In the extreme icing event 5-7 December 2000 the measured ice accumulation was 36 kg/m in 50 hours and the temperature was mostly between 0°C and -1 °C. The WRF-models identified the event and predicted reasonable amounts of cloud water. The icing model however predicts much lower ice accretion than measured. By using hypothetical weather parameters it was demonstrated that the current icing model has difficulties to explain the accumulation based on most likely weather parameters. Assumption on cloud droplet size (or droplet number) and classification of the water in the WRF-model into freezing drizzle has large effects on the predicted icing. These effects need to be studied further, ideally with observations of e.g. droplet size and hydrometer species to help verify the model performance. Furthermore, the icing model may not be accurate for the highest icing observed here. It is known from other test spans in Iceland that extreme icing sometimes occurs similar to the event 5-7 Dec. 2000, i.e. with temperature slightly below 0°C and severe ice accretion during 2 to 3 days. Further studies are needed to better understand such icing events. One aspect of it relates to the evaluation of the accretion efficiency (α_3) which may give to low values in cases with high icing.

The ice accretion is often underestimated at the same time as there is simulated snowfall from a lower or middle tropospheric cloud through the orographically generated cloud above Hallormsstadahals. The snowfall through the orographic cloud is effective in collecting the cloud condensate and hence reduces the available super-cooled water content available for in-cloud icing. The orographic cloud is continually created due to uplift and will presumably retain the droplet size distribution of a cloud not affected by snowfall. This may affect the calculation of droplet size in the icing model which is generally based on the amount of the actual liquid water content. The icing model furthermore assumes that there is no accretion due to snow when the temperature is below zero as the snow particles will not stick to the icing surface. This assumption may not be valid for snowfall through near-surface clouds with high water content and temperatures slightly below 0°C. It is not obvious that the snow will still be dry when leaving the cloud and if not, whether it can become sufficiently wet to partly stick to the icing surface. The processes on the icing surface may furthermore be more complicated than assumed when the surface is simultaneously hit by super-cooled cloud droplets and snow particles.

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