Validation of Modelled In-cloud Ice Accretion on Overhead Power Lines at Exposed High Altitude Sites in Norway

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Abstract— **This paper presents results from a validation study of a state-of-the-art in-cloud ice accretion model (IAM). The IAM was forced with ERA5 data that was downscaled using the Weather Research and Forecasting (WRF) model. Modelled ice loads were validated against three years of load cell measurements from multiple exposed high-altitude sites in Norway. The validation study emphasises assessments of the model's ability to skilfully predict the timing of individual icing events as well as ice accretion rates for different line diameters. Two different approaches were made with respect to the representation of droplet sizes in order to optimize the calculated collision efficiency: 1) the standard median volume diameter (MVD) approach and 2) using a full droplet size distribution. The results show that the IAM is capable of predicting icing events with a true positive rate of 0.87 and a false positive rate of 0.13, yielding an AUC score of 0.93 at the most exposed site. The model does a good job also in reproducing measured icing intensities, in particular for small to intermediate line diameters. For line diameters > ~10 cm, however, the IAM had a tendency to underestimate the measured ice accretion rates using the standard MVD approach. Replacing the MVD with a full droplet size distribution showed promising results, in particular for larger line diameters.**

Keywords— ***WRF, ice accretion modelling, icing measurements, validation***

I. Introduction

The vast abundance of moisture, strong winds and prolonged periods with sub-zero temperatures combine to create extremely harsh icing conditions across large areas in Norway, particularly at high altitudes in the southwest. The density of exposed mountain regions makes planning of power line routes difficult with respect to mitigation of ice accumulation. In many cases, power grid operators have no other choice but to build power lines across high mountain tops, ridges etc. – potentially resulting in component failures and even tower collapses [1]. Furthermore, the remoteness of many of these regions makes monitoring of icing conditions as well as maintenance of the power lines difficult. Accurate numerical models are therefore crucial both for monitoring (forecasts) and design load purposes.

In 2014, this issue motivated the initiation of the FRonTLINES research project ("Frost and rime icing impact on overhead transmission lines"), whose main goals were to obtain real-time measurements of ice loads at selected locations and to develop a state-of-the-art numerical ice accretion model. Measurement stations including test spans equipped with load cells and met masts were installed at two different sites close to the western coast of southern Norway (both located above 1000 m.a.s.l.). In addition to measurement data from a third site at Hardingnuten further to the east, the results from the aforementioned measurement campaigns have been used to validate the ice accretion model, and the results are presented in this paper. The validation study emphasises on assessments of the model's ability to skilfully predict the timing and duration of individual icing events as well ice accretion rates for different line diameters.

II. Methodology

A. Icing Measurements

This validation study is based on load cell measurements from three different high-altitude sites in southern Norway. The site locations are marked in Fig. 1. Although the elevations of the different test sites would generally suggest otherwise, the site at Ålvikfjellet is significantly more exposed to icing than the remaining two. This is due to a near complete lack of shielding during southwesterly winds.

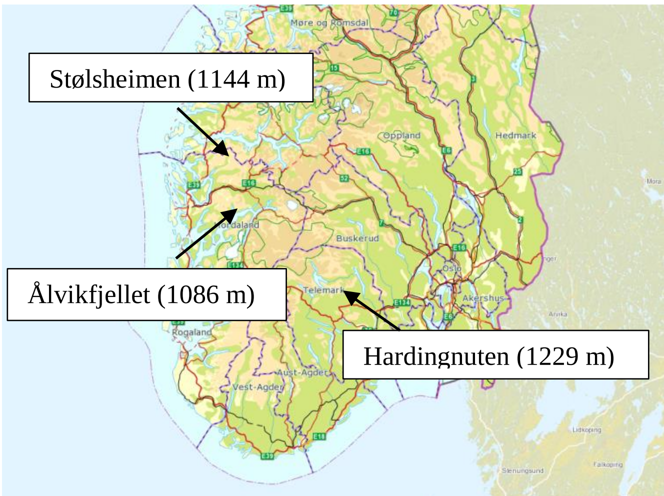

Fig. 1 Locations of the three test sites in southern Norway (background map from norgeskart.no).

At the Ålvikfjellet and Stølsheimen sites, load cells have been installed on single conductor test spans having average heights of 10 m AGL. From the third test site at Hardingnuten we have used data from load cells installed in a suspension tower of a 420 kV transmission line with twin bundle phase conductors with an average height of 15 m AGL. A total of 7 winter seasons worth of measurement data spread across the three different sites were used in the analysis. More detailed descriptions of the different test sites and data availability can be found in [2].

Fig. 2 shows an image of the test span at Ålvikfjellet. The load cell measurements read 42 kg/m at the time that the picture was taken (February 2nd, 2018).

Fig. 2 Picture of the test site at Ålvikfjellet. The load cell equipped on the test span (in front) measured 42 kg/m at the time that the picture was taken (February 2nd, 2018). Photo: Kjeller Vindteknikk AS.

B. WRF setup

The ice accretion calculations presented in this paper were largely based on input data from the Weather Research and Forecasting (WRF) model. The model was setup with a horizontal resolution of 3 km x 3 km covering all of Norway and Sweden. The ERA5 [3] reanalysis data set from the ECMWF was used as input to the WRF model. Cloud microphysics was handled by the Thompson scheme [4] and the Mellor-Yamada-Janjic [5] scheme was used for planetary boundary layer physics.

C. Ice Accretion Model (IAM)

The IAM that was used in this study is based on the model described in [6] which yields ice accretion rate on a reference collector. However, results from the FRonTLINES project have shown that simplifying the representation of the droplet size distribution by using a single parameter (e.g. the MVD) typically leads to underestimations of the collision efficiency. This is found to be particularly true for small values of the droplet inertia parameter, *K*. Typical situations that yield small values of *K* are calm wind conditions and/or large cylinder diameters. The latter becomes particularly relevant at the exposed sites considered in the present study, where prolonged icing events may allow continuous ice growth over several months. Consequently, two different approaches were made with respect to the representation of droplet sizes in order to optimize the calculated collision efficiencies: 1) The "standard" median volume diameter (MVD) approach, and 2) using a full droplet size distribution. Following the recommendations from [7], the Langmuir D distribution was used in 2).

With respect to ice ablation, the IAM includes both melting and sublimation processes. Additionally, partial shedding during ice ablation periods has been accounted for by adding "shedding factors" derived from comparisons of modelled melting and sublimation rates to measurements.

Due to the complexity of the terrain surrounding all three sites, the relatively coarse WRF data fails to capture crucial impacts of topography on the wind fields. Consequently, the measured wind speeds and wind directions (available at all three sites) were long-term corrected and subsequently used as input to the IAM. The long-term correction was performed using the model data and the methodology described in [8].

III. Results and discussion

Fig. 2 compares modelled average icing intensities for different cylinder diameters to measurements from all three test sites. The results indicate that the implementation of the Langmuir D droplet size distribution increases the average modelled icing intensities. The figure suggests that for cylinder diameters larger than approximately 5 cm, the use of the Langmuir D droplet size distribution gives better results compared to the standard MVD approach. For smaller cylinder diameters however, the use of the Langmuir D droplet size distribution seemingly leads to an overestimation of the actual icing intensities.

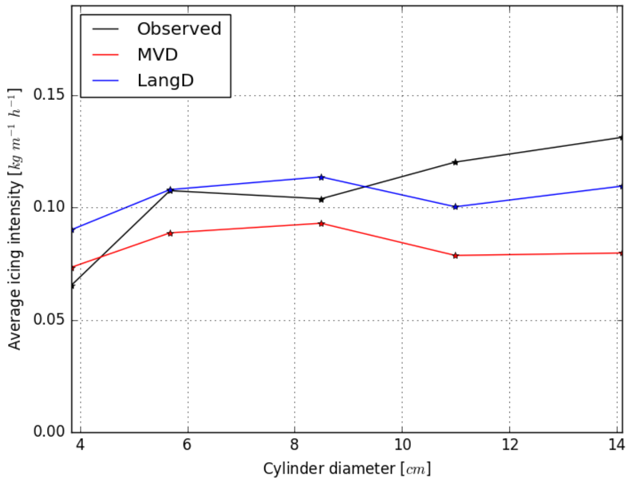

Fig. 3 Average icing intensities for different cylinder diameters as obtained from the measurements (black line) and from the model using the standard MVD approach (red line) and the Langmuir D droplet size distribution (blue line). The results are based on data from all three test sites. The modelled icing intensities are based on cylinder diameters derived from measured ice loads.

The model's ability to skilfully predict the timing of individual icing events is also crucial, particularly if the model is to be applied in forecasting. In Fig. 4, the *true positive rate* (TPR) of the model is plotted against the model's *false positive rate* (FPR) at Ålvikfjellet and Stølsheimen (there was not enough data from Hardingnuten to make a similar plot). The TPR indicates the rate at which the model is able to correctly predict that there is ice at the site, while the FPR indicates the rate at which the model expects ice at the site, but no ice is found in the observations. Given that a perfect model would predict 100 % of all real icing events (TPR = 1) while giving no false alarms (FPR = 0), it would be represented by a single dot in the upper left corner of Fig. 4. Due to sensitivities to input parameters and other uncertainties connected to the model it can be useful to plot TPRs against FPRs assuming different ice load thresholds in the modelled time series. The continuous curves in Fig. 4, called *receiver operating characteristic* (ROC) curves, are obtained by plotting the TPR against the FPR for all possible thresholds. By doing so, one can measure the model's skill in predicting icing events by calculating the area under the curve (AUC). For a perfect model, the AUC would be equal to 1, while a model with no skill at all would yield an AUC of 0.5 (ROC curve along the diagonal). The ROC curves for Ålvikfjellet and Stølsheimen yields AUCs of 0.93 and 0.90, respectively, indicating that the model does a good job in predicting the timing and duration of actual icing events.

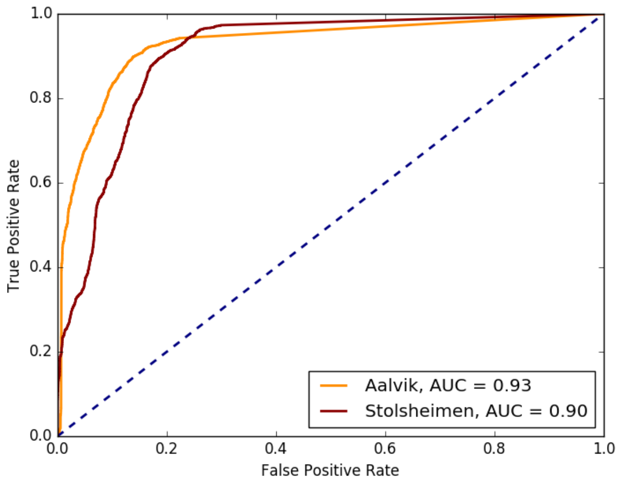

Fig. 4 ROC curves for Ålvikfjellet (orange line) and Stølsheimen (red line).

Fig. 5 compares time series of modelled ice loads [kg/m] to load cell measurements from the test span at Ålvikfjellet (2016-17 winter season). Similar to what was shown in Fig. 3; the results show that the implementation of the Langmuir D droplet size distribution (blue line) generally amplifies the icing rates when compared to the MVD approach (red line). Even so, there are still several events where model underestimates the measured ice loads. This could be largely due to uncertainties connected to the input data or the roughness of the iced surface (the IAM assumes a smooth, cylindrical shape). The difference between the two modelled time series is evidently most pronounced during the most extreme icing events.

The results from Fig. 4, indicating that the model has a high TPR and a low FPR, are also evident from Fig. 5.

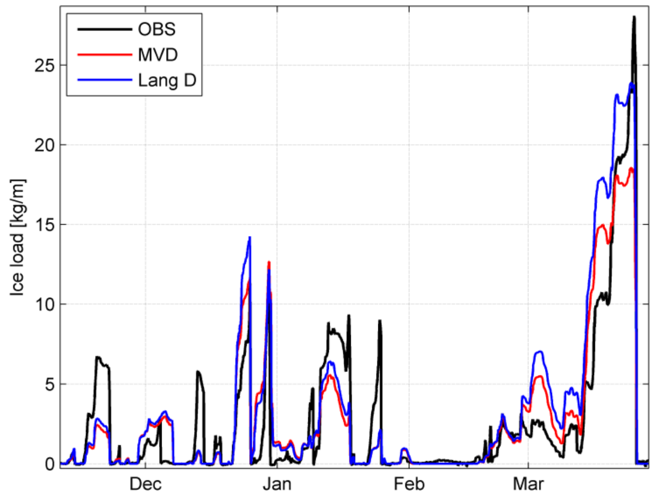

Fig. 5 Time series comparison of modelled ice loads (red and blue lines) vs. measurements (black line) from the test span at Ålvikfjellet (2016-17 winter season).

IV. Conclusions

The results presented in this paper show that the IAM is capable of predicting the timing and duration of icing events with good skill. Replacing the single parameter representation of droplet sizes with the full Langmuir D distribution also helped to improve the modelled icing intensities for large cylinder diameters. For cylinder diameters smaller than approximately 5 cm, however, the standard MVD approach seemed to give the better results. Considering that the growth rate is a function of the cylinder diameter, accurate predictions of the initial ice growth are crucial. This is particularly true in harsh icing climates where any prediction error in the initial phase of an icing event spanning over several weeks, or even months, may escalate with time. Combining the two approaches could therefore be a viable solution; however, a similar analysis should be performed when more data is available. The work will continue in the on-going ICEBOX research project funded by Statnett SF (the Norwegian transmission system operator).

Considering the results shown in Fig. 3 and Fig. 5, the implementation of the Langmuir D distribution may also have significant impacts on calculations of extreme values. As an example, extreme value analyses (not shown) of the annual maximum values using the Generalised Extreme Value distribution indicate 50-year ice loads of 90 kg/m (MVD) and 116 kg/m (Langmuir D) at the most exposed site (Ålvikfjellet).

Acknowledgment

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References

[1] B.E. Nygaard, H. Ágústsson, L.A. Moen, Ø. Welgaard, Á.J. Elíasson, *Monitoring and forecasting ice loads on a 420 kV transmission line in extreme climatic conditions*, Proc. CIGRE, 2016

[2] B. E. Nygaard, Ø. Byrkjedal, E. Iversen, M. Fredbo and H. Ágústsson, *Development of a reliable modelling system for the calculation of rime ice loads on overhead transmission lines*, Proc. IWAIS, 2017.

[3] Hersbach, Hans. "The ERA5 Atmospheric Reanalysis." *AGU Fall Meeting Abstracts*. 2016.

[4] Thompson, Gregory, et al. "Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization." *Monthly Weather Review* 136.12 (2008): 5095-5115.

[5] Janić, Zaviša I. "Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP Meso model." (2001).

[6] Makkonen, Lasse. "Models for the growth of rime, glaze, icicles and wet snow on structures." *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 358.1776 (2000): 2913-2939.

[7] Sokolov, Pavlo, and Muhammad S. Virk. "Droplet distribution spectrum effects on dry ice growth on cylinders." *Cold Regions Science and Technology* 160 (2019): 80-88.

[8] Liléo, Sónia, et al. "Long-term correction of wind measurements. State-of-the-art, guidelines and future work." *Elforsk report* 13 (2013): 18.