Wet snow icing - Comparing simulated accretion with observational experience

Árni Jón Elíasson [1], Sigurjón Páll Ísaksson[2], Hálfdán Ágústsson [3], Egill Þorsteins[2]
[1] Landsnet, [2] EFLA Consulting Engineers, [3] Belgingur
arnije@landsnet.is, sigurjon.pall.isaksson@efla.is, halfdana@gmail.com, egill.thorsteins@efla.is

***Abstract*: Coupled icing and mesoscale atmospheric models are a valuable tool for assessing ice loading for overhead power lines. This paper presents an analysis of how well icing model captures wet snow accumulation in areas that are historically known to be exposed to wet snow icing in Iceland. Wet snow icing maps were prepared using a snow accretion model with 21 years of data. The weather parameters used in the accretion model, i.e., wind speed, temperature, precipitation rate and snowflake liquid water fraction, were derived by simulating the state of the atmosphere with WRF model at a horizontal resolution of 3 km. The icing maps were compared to data from an icing database that contains long term historical information on icing events on the overhead power lines in Iceland.**

Keywords: wet snow accretion, modelling, icing observations

I. INTRODUCTION

Wet snow accretion on overhead power lines can cause mechanical overloading and can lead to a failure of the supporting structures. Historically, wet snow accumulation has led to many severe failures of power lines in the distribution grid in Iceland. Especially before adequate knowledge and experience had been obtained regarding the most severe icing areas and the main icing directions. An important step in the quantification of the risk was taken in 1977 when a systematic registration of known icing events on all overhead power lines in the country was initiated.

In recent years a huge step has been taken in further understanding of the wet snow accretion risk with use of icing models. The improved icing accretion models combined with weather parameters that are derived by simulating the state of the atmosphere, for example with the WRF model, are very powerful tools to gain further understanding and quantification of the wet snow accretion risk. Especially in complex orography and in areas where no prior operational experience of power lines exists. An increased use of icing models to assess the risk of wet snow accretion is foreseen in coming years.

The paper presents an analysis of icing model performance based on a comparison with observed wet snow icing. Icing maps containing maximum predicted accretion mass in the period 1994-2014 were prepared for the analysis. The main focus of the study is on how well the predicted wet snow accumulation reflects areas prone to icing as well as how icing in complex terrain is reproduced.

II. HISTORICAL OBSERVATIONS OF WET SNOW ACCRETION

In a global context, wet snow accretion is a frequent occurrence on overhead power lines in Iceland. It may occur in all regions but some parts are more exposed than others and the frequency and the amount has varied greatly between locations. Experience from the overhead network reveals a dependence of accretion on predominant icing directions. Power lines oriented favourably with regard to the predominant icing directions often experienced far less and minimal accretion compared to nearby lines with a more unfavourable orientation.

A systematic collection of data and registration of all icing events on power lines was started in 1977 due to the impact of the icing on the operational reliability of the power lines. The registration has been continuous from the start and an effort has also been made to find information on events prior to 1977. A reasonable good overview is now reaching back to 1930, with the database containing data from power lines of all voltages as well as on some older telephone lines. The largest part of the records is related to wet snow accretion on the 11-33 kV distribution net. Records of individual icing events are done for all affected line sections and contain estimates, and in some cases actual measurements, of typical and maximum ice diameters on the section, type of accretion, information on wind and eventual failures. Figure 1 shows the number of broken poles from 1960 that have been registered in the database in relation to icing, with most failures due to wet snow icing. The reduction in failures rate from 1995 is related to a program where distribution lines exposed to severe wet snow icing were put underground. The data is collected, organized and hosted by Landsnet, the transmission system operator in Iceland, and has previously been described in [1].

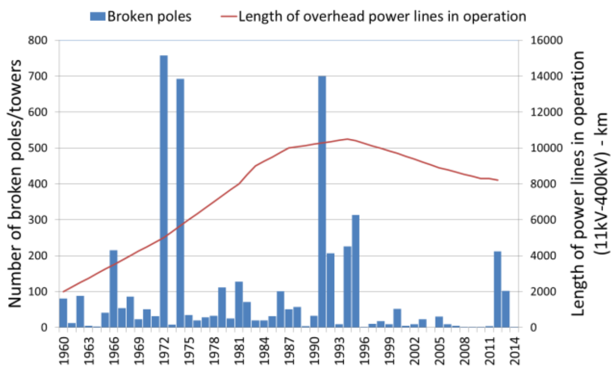

Figure 1: Number of broken poles registered in the database since 1960. Most failures are due to wet snow icing on 11-33 kV lines.

Figure 2 shows the location of overhead power lines in Iceland. Most of the power lines, and especially those in the distribution grid, are located in coastal regions. Some of the 132 kV and 220/400 kV lines are located inland and on the boundary of the central highlands. No overhead power lines have so far been built in the central part of the country, but several test spans have been installed. All power lines can be expected to get wet snow accretion but the amount and frequency varies greatly. Line sections of where the highest and most extreme wet snow loads have been observed are marked in Figure 2. Wet snow accretion has been observed on many line sections not marked, but to a lesser extent.

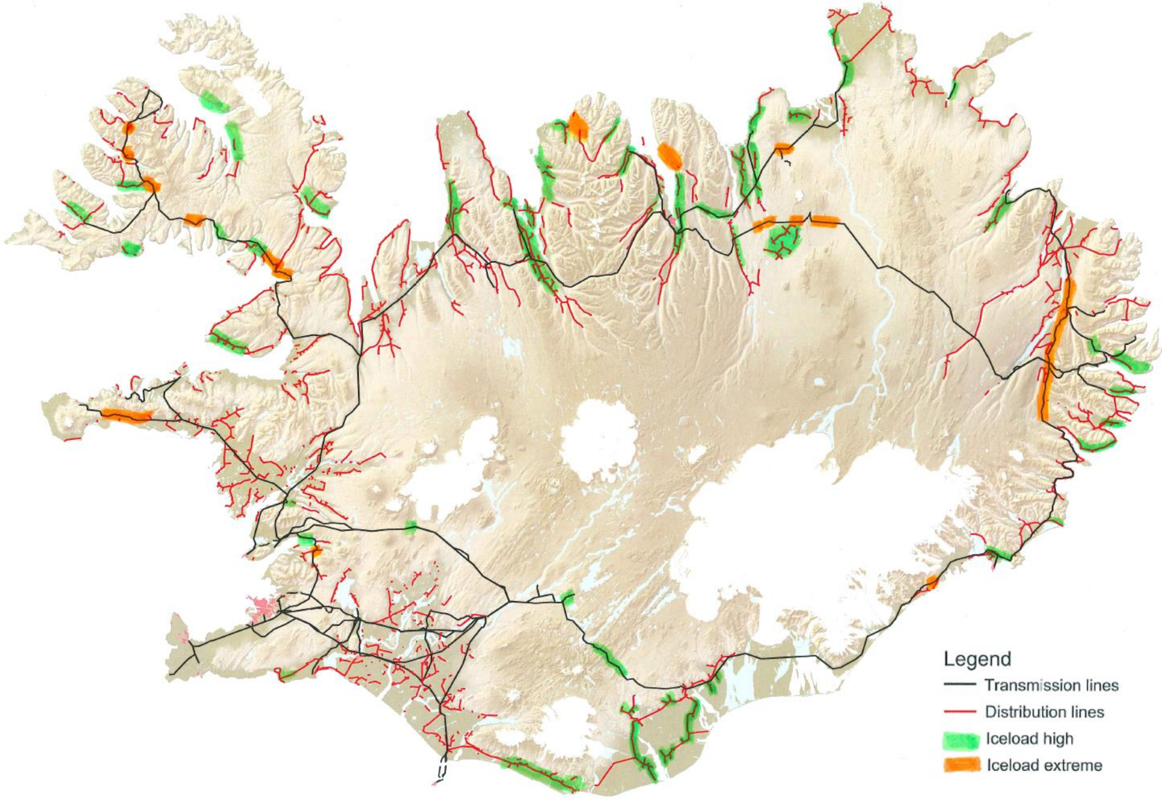

Figure 2: Power lines where high and extreme wet snow accretion has been observed.

III. ICING MODEL

The atmospheric parameters needed as input for the wet snow accretion models are obtained from the RÁV-project [2]. In the project, weather in Iceland during 1994-2014 was dynamically downscaled using version 3.0 of the non-hydrostatic mesoscale Advanced Research WRF-model (ARW, [3]). This state of the art numerical atmospheric model is used extensively both in research and in operational weather forecasting throughout the world, including Iceland. The atmospheric modelling is done at high resolution, 9 km (1957-2014) and 3 km (1994-2014) in the horizontal and 55 levels in the vertical, with the 3 km dataset employed in this study. The model is forced by atmospheric analysis from the European Centre for Medium-Range Weather Forecasts (ECMWF). The model takes full account of atmospheric physics and dynamics, and the relevant parameterization scheme for this study is the moisture scheme of [4], with other details of the setup of the model found in [5]. One of the key aspects of the dataset is its high spatial resolution, but as resolution is increased, the atmospheric flow and its interaction with the complex orography are in general better reproduced. In short, the readily available RÁV-dataset is currently the most accurate and detailed dataset describing the state of the atmosphere above Iceland, at high temporal and spatial resolutions in 4 dimensions. The dataset has previously been used in a number of studies of weather and climate in Iceland, including studies of orographic winds and precipitation, as well as the climatology of wet snow accretion in Southeast-Iceland [6].

Wet snow icing accretion is calculated based on the cylindrical accretion model approach ([7], [8]) where sticking efficiency is calculated with the equation from Nygaard et. al. [6]. Two different icing model setups are employed in this study: (i) vertical cylinder approach, (ii) horizontal cylinder approach. In the vertical cylinder approach the particle impact speed is always perpendicular to the object and hence the accretion is independent of wind direction. In the horizontal cylinder approach, eight different span directions are considered, with a 22,5° interval. Hence, accretion is reduced proportionally when the snow flux is not perpendicular to the spans. Ice shedding is assessed to take place as soon as the air temperature exceeds 3°C or when no accretion has occurred for 24 hours.

IV. WET SNOW ICING MAPS BASED ON ICING MODEL

Wet snow icing maps were made using the icing model and 21 years of simulated atmospheric data. The results from the vertical cylinder icing model are shown in Figure 3 where the maximum modelled icing in the period is presented in kg/m.

Wet snow icing in Iceland is usually combined with strong winds which enhance the accretion intensity and density. Extreme wet snow accretion has in few cases been measured or observed in range of 15-20 kg/m in Iceland.

Figure 4 shows a box-plot (histogram) of wet snow icing events classified based on elevation above sea level, total area of land for each class is also presented. Figure 5 shows the median values of wet snow icing in different regions of the country (SW, NW, NE and SE), also based on elevation.

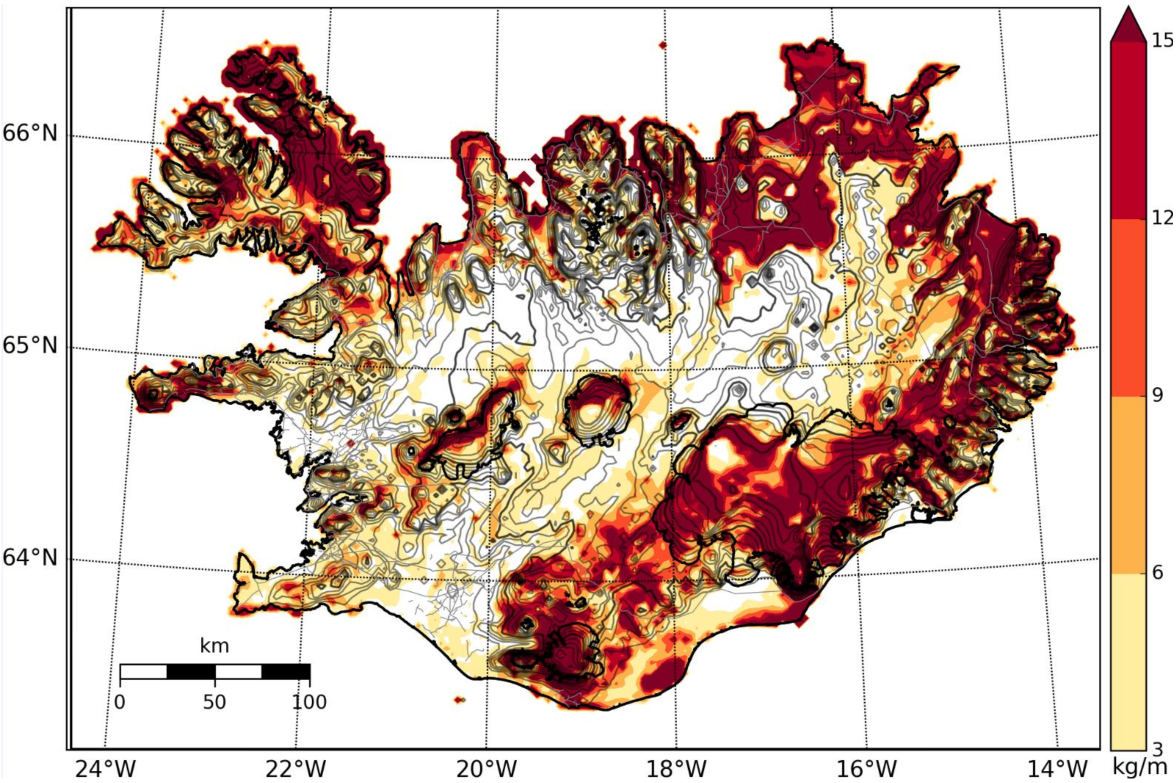

Figure 3: Estimated maximum wet snow load in the period 1994-2014, based on the vertical cylinder model approach.

The following remarks can be made on the estimated maximum wet snow load in the period 1994-2014 presented in Figure 3. In this context it should be noted that the figure presents icing based on the vertical cylinder approach and does not necessarily resemble to what would accrete on a horizontal span.

- The expected wet snow accretion is very site dependent.
- The most severe icing is usually relatively close to the coast.
- The wet snow ice load can be quite high, in most severe cases it can be well above 15 kg/m
- The central highlands experience low loads in the icing model, especially in the precipitation shadow north of the glaciers.
- High wet snow icing loads inland are often associated with a relatively gentle upwards slope of the land, or where there is an upstream mountain barrier.
- Extreme wet snow maxima are found at the foot of high mountains and massifs in parts of the country.
- High accumulation occurs on the glaciers. Most of the severe accretion in higher altitude occurs on glaciers.
- Southwest-Iceland has relatively little wet snow accretion except in localized areas.

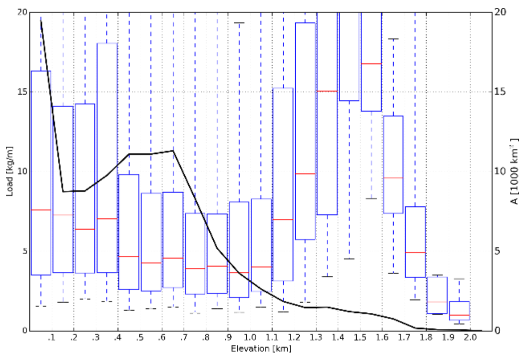

Figure 4: Box-plot of wet snow icing classified on elevation above sea level. Total land area is given on Y2 axis.

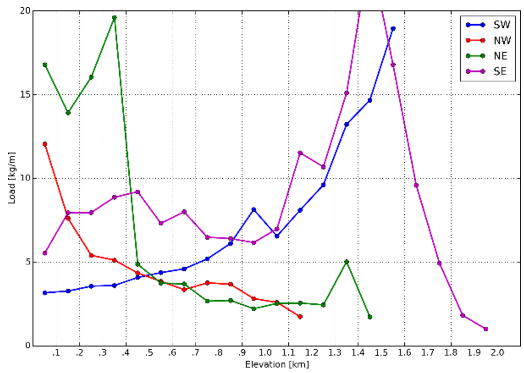

Figure 5: Median values of wet snow icing in different regions.

The complex spatial structure of the simulated ice loading depends strongly on regional differences in atmospheric and topographic factors. Those include, the complexity and shape of the orography, prevalent precipitation directions, average air temperature and its typical evolution during precipitation events.

Accretion downstream in complex orography, especially in the mountains in N and E

The interaction of atmospheric flow with complex orography may create favourable conditions for wet snow accretion on the lee slopes, and immediately downstream, of large mountains, such as in the mountains in north- and east-Iceland, see [9], [10] and [11]. Three key factors are relevant here.

- Heavy precipitation may occur as a result of the orographic uplift experienced by the air mass as it passes above the mountain. The precipitation is partly carried downstream with the flow and to the lowlands in the lee of the mountains.
- In a stable stratified air mass gravity (mountain) waves may be excited in the flow above the mountain. As a result, the wind accelerates in the descending part of the wave and a local wind speed maximum is created over the lee slopes of the mountain. Furthermore, previous studies [11] and [12]

indicate that enhanced cloud water amounts created in the ascending part of the wave may strongly influence the total atmospheric water content in the lee.

- The plunging airflow on the lee side warms slightly due to adiabatic heating in the descending air. When the adiabatic heating is sufficient to bring sub-zero temperatures up to 1-2°C, partial melting of snowflakes will occur, while orographically enhanced precipitation and downslope accelerated winds guarantee an abundant in-flux of wet snow.

Gently sloping terrain in N and NE

When it comes to wet snow accretion, several locations in gently sloping terrain in North- and Northeast-Iceland seem to be favoured over similar locations in other parts of Iceland. A possible explanation is as follows: When the temperature at sea level is only several degrees over freezing, the 0°C isotherm will inevitably intersect the topography at some level, say few hundred metres above sea level. Hence, in gently sloping terrain there will always be a large region somewhere inland, where temperatures are favourable for wet snow formation, i.e. in the range 0.5-2°C. The adiabatic cooling associated with the forced uplift of the impinging air mass is also of relevance here and may contribute towards heavy precipitation by destabilizing the layers aloft. Such conditions are more likely to occur in the north than in South-Iceland as precipitation during winter in north- and northeast-Iceland generally falls in colder weather than during precipitation events in the south. This is mostly associated with different origins of the air masses and their mixing with cold air advection from the north, but colder sea surfaces are also relevant.

Accretion upstream of mountains in SE

Previous observational and modelling studies of wet snow in southeast-Iceland ([13], [14]) revealed that catastrophic events are related to eastward moving extratropical cyclones of the south coast of Iceland, which is presumably also the case for other significant icing events [6]. These synoptic systems are often associated with slowly moving precipitating fronts at or off the coast and temperatures of 0-2°C ahead of the fronts. The role of the topography (Vatnajökull glacier, Mýrdalsjökull ice cap and surrounding highlands) in creating favourable icing conditions is at least twofold; it blocks the impinging flow and channels a cold northeasterly flow ahead of the front, along the low-lands and perpendicular to many distribution lines in the region. The flow accelerates when it is forced to turn further to the south as it approaches Mýrdalsjökull glacier. The precipitation is furthermore increased as the warmer impinging flow is cooled in a forced ascent above the colder northeasterly flow, which furthermore destabilizes the layers aloft and may cause heavy precipitation. The stability and speed of the cold low level flow is enhanced, which with the heavy precipitation creates ideal conditions for rapid accretion of wet snow icing of high density compared to reports from many other countries.

V. Example of Directional Influence of Accretion

Experience shows that in most areas the risk of wet snow accretion is related to specific icing- and wind directions. There are numerous cases where repeated failures of distribution lines due to wet snow accretion were solved by changing the orientation of the lines to being as much as possible parallel to the predominant accretion direction. The southeast coast between Mýrdalsjökull and Vatnajökull ice caps is an example of a region with great difference in wet snow accretion on power lines depending on the line direction. Icing events in this area have previously been described and studied in [13], [14] and [6].

Figure 6: Observing and measuring a diameter of wet snow accretion in southeast-Iceland.

Figure 7 shows that the maximum observed icing on power lines in the area varies greatly with the line direction. Figure 8 shows the maximum simulated accretion in the period 1994-2014 using the vertical cylinder approach, i.e. assuming accretion from all directions, while Figures 9 to 16 shows accretion on differently oriented horizontal spans, stepwise with a 22,5° interval, during the same period. There is a clear dependence of ice loading on the span direction. The span direction 67,5°/247,5° is most favourable while span directions: 0°/180°, 22,5°/202,5°, 135°/315° and 157,5°/337,5° accrete a far greater load.

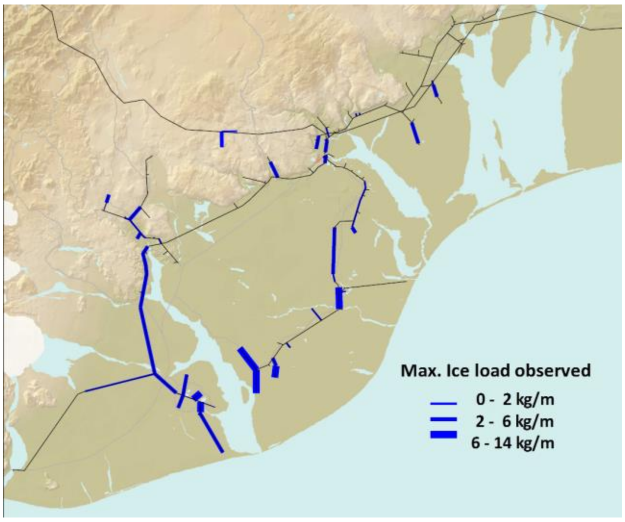

Figure 7: Observed icing in part of southeast-Iceland.

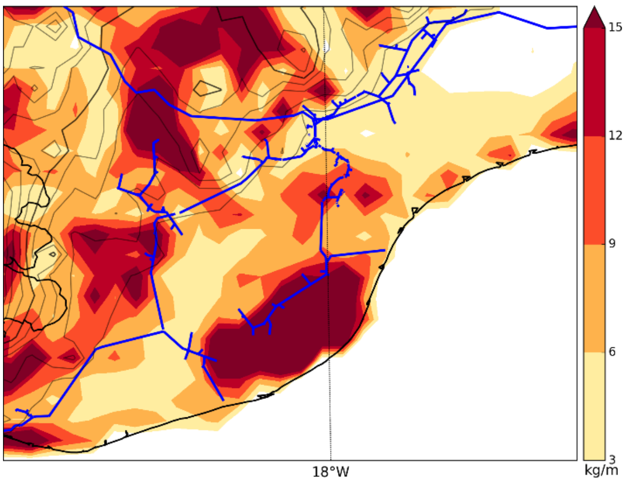

Figure 8: Wet snow accretion, vertical cylinder.

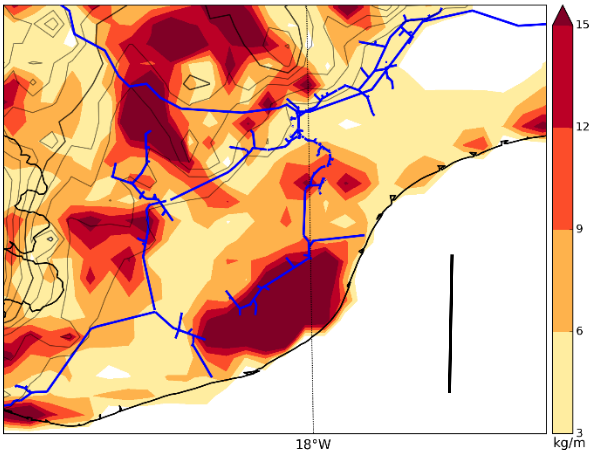

Figure 9: Span direction 0°/180°.

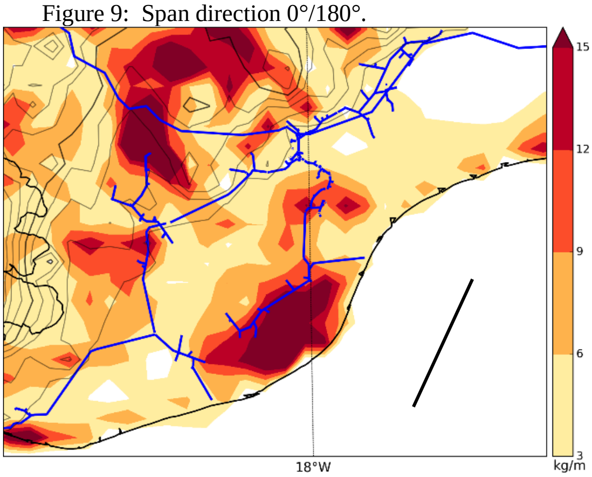

Figure 10: Span direction 22,5°/202,5°.

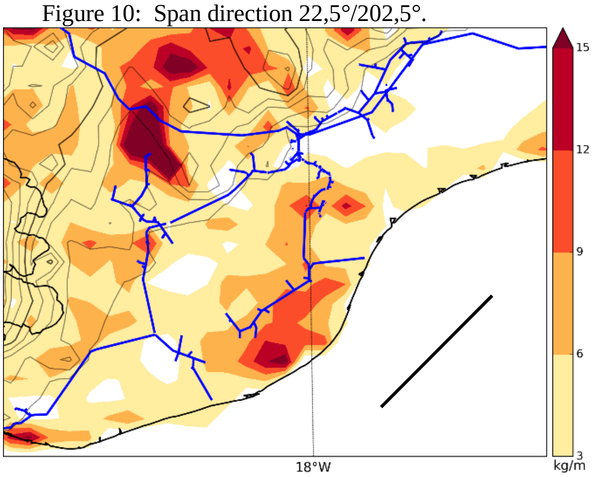

Figure 11: horizontal span direction 45°/225°

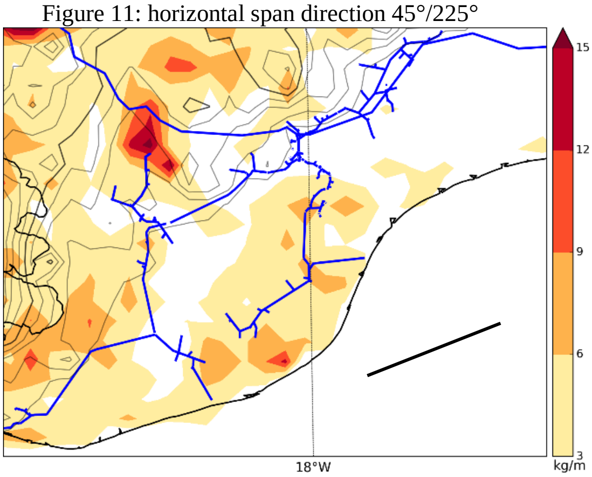

Figure 12: horizontal span direction 67,5°/247,5°

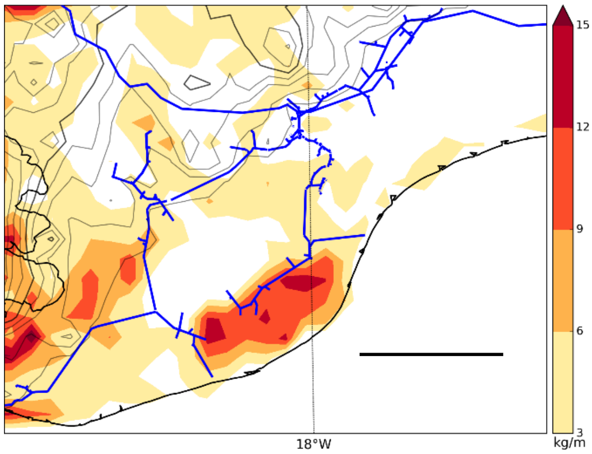

Figure 13: Span direction 90°/270°

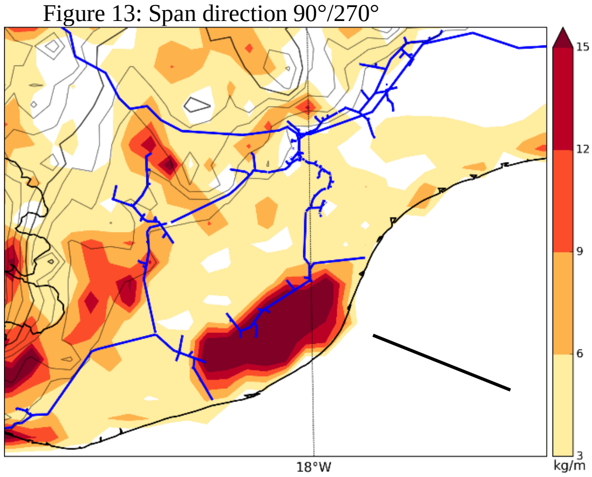

Figure 14: Span direction 112,5°/292,5°

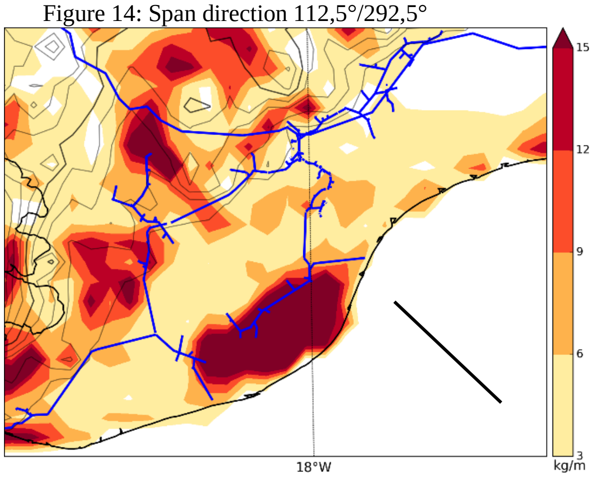

Figure 15: Span direction 135°/315°

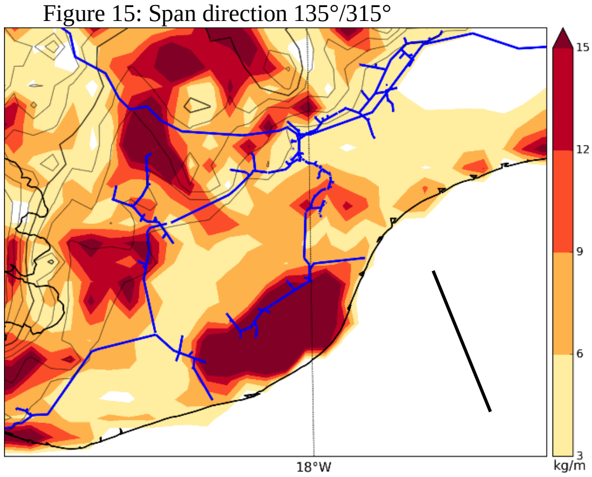

Figure 16: Span direction 157,5°/337,5°

VI. Comparison of Observed Accretion with Icing Map

It can be concluded that, qualitatively, there is in general a good correlation between areas with observed accretion and areas with modelled icing. High ice load is simulated in areas where the most severe accretion has been observed. In some cases high loads are simulated where high loads have not been observed. These cases can most often be explained by the strong dependence on the actual line direction compared to main icing direction. In fact, the icing model needs to be analysed with the actual direction of the power line instead of the vertical cylinder model, as is exemplified in paragraph V. There are no power lines operated in the central parts of the country but there is, however, data available from many test spans located there. Those test sites have generally observed little wet snow accretion, fitting well with the low values in the model.

There are indications that the icing model may be predicting too high loading in the higher end of the loading. Extreme wet snow accretion has in few cases been measured or observed in the range of 15-20 kg/m in Iceland but larger values may be possible. The icing model predicts considerably higher values at some locations. It is believed that there is a considerable uncertainty in those cases since the icing model has not been calibrated or verified for so high values.

Wet snow accretion depends on a critical combination of strong winds and large precipitation amounts in a narrow temperature interval, and small deviations in temperature can have a large effect on the overall accreted load. The simulated ice accretion based on the atmospheric RÁV data does not capture all events correctly. It does sometimes underestimate and in other cases overestimate the load. The deviation can often be explained by small errors in the temperature rather than due to errors in wind speed or precipitation amounts. Better atmospheric input data can be prepared, given adequate computational resources, based on a more recent version of the atmospheric model, higher horizontal resolution (1 km) as well as improved descriptions of necessary input and forcing data. Simulated icing based on improved atmospheric data for chosen events gave better and more realistic results and highlights the high sensitivity of ice accretion to small deviations in the atmospheric parameters.

A closer inspection of accretion events at sites with high loading, revealed that in some cases only one or two events gave extreme loading while other events were much smaller. This raises the question if the 21 years long data series is long enough and how to take model errors into account. Sensitivity analysis may be performed, e.g. based on shifting the temperature and the liquid water content of the snow in the icing model slightly compared to the dataset and evaluate icing assuming unchanged precipitation and wind speed.

Overall the performance of the wet snow icing model has been found to give relatively reliable results compared to observations, i.e. it correctly identifies main icing directions and locations of high observed loads as well as locations with no or little ice loading. If correctly used and interpreted then it can be of great use for identifying areas prone to wet snow accretion and assessing main icing directions in the areas.

References

[1] S. P. Ísaksson, Á. J. Elíasson and E. Thorsteins, "Icing Database—Acquisition and registration of data," in *Proc. Eighth Int. Workshop on Atmospheric Icing of Structures (IWAIS)*, Reykjavik, 1998.

[2] Ó. Rögnvaldsson, H. Ágústsson and H. Ólafsson, "Stöðuskýrsla vegna þriðja árs RÁVandar verkefnisins," 2009.

[3] W. C. K. J. Skamarock, J. Dudhia, G. D. O., D. M. Barker, M. G. Duda, X. Y. Huang, W. Wang and J. G. Powers, A description of the advanced research WRF version 3, NCAR: Boulder, 2008.

[4] G. Thompson, R. Rasmussen and K. Manning, "Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis," *Mon. Wea. Rev.,* vol. 132, pp. 519-542, 2004.

[5] Ó. Rögnvaldsson, J. W. Bao, H. Ágústsson and H. Ólafsson, "Downslope windstorm in Iceland – WRF/MM5 model comparison," *Atmos. Chem. Phys.,* no. 11, pp. 103-120, 2011.

[6] B. E. K. Nygaard, H. Ágústsson and K. Somfalvi-Tóth, "Modeling wet snow accretion on power lines: Improvements to previous methods using 50 years of observations," *Journal of Applied Meteorology and Climatology,* vol. 52, no. 10, pp. 2189-2203, 2013.

[7] ISO 12494, "Atmospheric icing of structures," Geneva, 2001.

[8] L. Makkonen, "Models for the growth of rime, glaze, icicles and wet snow on structures," *Phil. Trans. R. Soc. London,* vol. 358, pp. 2913-2939, 2000.

[9] Á. J. Elíasson and E. Thorsteins, "Field measurements of wet snow icing accumulation," in *IWAIS 2000*, Chester, UK, 2000.

[10] H. Ólafsson, Á. J. Elíasson and E. Thorsteins, "Orographic influence on wet snow icing - Part II: Downstream of mountains," in *IWAIS 2002*, 2002.

[11] H. Ágústsson, Á. J. Elíasson, G. M. Hannesson and E. Thorsteins, "Modeling wet-snow accretion -- Comparison of cylindrical model to field measurements," in *Proc. 15th International Workshop on*, Canada, 2013.

[12] Á. J. Elíasson, H. Ágústsson and G. M. Hannesson, "Wet snow accumulation - A study of two severe events in complex terrain in Iceland," in *IWAIS 2013*, St. John's, 2013.

[13] Á. J. Elíasson, E. Thorsteins and H. Ólafsson, "Study of wet snow events on the south coast of Iceland," in *IWAIS 2000*, Chester, UK, 2000.

[14] H. Ólafsson, Á. J. Elíasson and E. Thorsteins, "Orographic creation of wet snow icing conditions, Part I: Upstream of mountains.," in *IWAIS 2002*, 2002.

[15] G. Thompson, P. Field, R. Rasmussen and W. Hal, "Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization," *Mon. Wea. Rev.,* vol. 136, pp. 5095-5115, 2008.

[16] G. Thompson, N. B. E., L. Makkonen and S. Dierer, "Using the Weather Reserach and Forecasting (WRF) Model to Predict Ground/Structural Icing," in *13th IWAIS*, Andermatt, 2009.