Wet-snow accumulation

A study of two severe events in complex terrain in Iceland

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Abstract— **On 10 September 2012 and 30 December 2012, two severe northeasterly wet-snow storms caused extreme ice load on many transmission and distribution lines in North Iceland. The wet-snow accretion was combined with strong winds, resulting in broken wooden poles and H-frame towers. The September event was exceptional because of extreme snowfall so early in the autumn. The snowfall was associated with average wind speeds in excess of 20 m/s, causing widespread accumulation of wet snow within a certain altitude interval in North Iceland. In the latter event, heavy snowfall and gale-force winds, as well as extreme wet-snow loading, were more localized, occurring mostly in the lee of the complex orography of Northwest Iceland. The wet snow data are based on: 1) detailed in-situ inspection of accumulated wet snow on conductors of transmission and distribution lines in the affected areas. 2) accurate measurements of accumulation with load cells installed in suspension towers of operating overhead transmission lines and special test span in the areas where the most extreme accumulation occurred. The collected load data are unique in the sense that they describe in detail both the exact timing and magnitude of the wet snow accumulation. Meteorological observations of wind, temperature and precipitation are moreover available from synoptic and automatic weather stations in the areas. The atmospheric flow during the events is analyzed, based on weather observations and simulations at high resolution with an atmospheric model. The simulated data are subsequently used as input for a cylindrical wet-snow accretion model. The measured and simulated wet-snow loading are analyzed and put in relation with the weather during the event, highlighting several key aspects of the flow and icing process that needs further attention.**

I. Introduction

Wet-snow accumulation on overhead structures is of particular interest to both the scientific and engineering communities as such accumulation causes external mechanical load on the structures [1], and is needed for their safe operation and design. In this context, the accretion on overhead power lines has received special attention due to the vulnerability of the system to the accretion and the societal impacts of faults and blackouts. This vulnerability was in particular evident in the wet snow storm of 2005 in Germany, where 82 transmission towers collapsed and 250 000 people were without electricity for days [2]. Severe events have been documented in other high latitude and/or high altitude regions of the world, e.g., in Europe [1] and [3], Japan [4], and Iceland as documented in [5], [6] and [7], as well as reported here for two severe events occurring in the latter half of 2012 in North Iceland.

Wet-snow accretion on overhead conductors is particularly effective due to the strong adhesive forces within the compact snow sleeve which forms on the conductor as it rotates or the accreted mass slides around it [4]. The accretion process itself is critically sensitive to small variations in the wind speed and direction, surface characteristics of the conductor, atmospheric water mass loading as well as the liquid water content of the falling snow, which, among other things, depends on the (wet bulb) temperature in the lowest layers of the atmosphere. Wet-snow loading has traditionally been parameterized based on observational data (e.g., [1], [8] and [9]). Such methods suffer from the lack of accurate estimates of atmospheric parameters that are not routinely observed, but it has been shown that better results can be gained based on output from state-of-the-art mesoscale atmospheric models (e.g., [10]). Accurate and physically sound parameterizations of the wet-snow loading are needed to aid in forecasting wet-snow events and estimating climatological and regional design loads with regard to a given return period. These loads must by necessity be based on output from atmospheric models instead of observational data and are critically dependent on correct representation of the atmospheric flow in complex terrain as well as accurate wet-snow accretion parameterization. Systematic and extensive observations during wet-snow events are however necessary for verifying the accretion methods, as was done in [10], based on simulated and observed climatology of wet-snow events in Southeast Iceland.

This paper presents an analysis of weather and wet-snow accumulation during two severe wet-snow storms occurring in northern Iceland in 2012. Both storms caused extreme wet-snow loading on transmission and distribution lines in the affected regions. The wet-snow accretion was combined with strong winds, resulting in many broken wooden poles in the distribution system and 132 kV H-frame transmission towers, as well as, e.g., significant damage to property and loss of livestock. Unique and detailed data of accumulated wet snow on conductors during the events as well as extensive weather observations, are used to investigate the wet snow accumulation and highlighting, in particular, the differences in the spatial extent of accretion as well as several key aspects requiring special attention.

II. The atmospheric situation

The two events of 10 September and 29 December 2012 share some similarities with each other, as well as with other significant wet-snow events in northern Iceland. Both events occur in relation to a northward moving and deepening extratropical low off the east coast of Iceland, as seen in the atmospheric analysis (Fig. 1) from the European Centre for Medium-range Weather Forecasts (ECMWF). The strong pressure gradients gave rise to the very strong northerly and northwesterly flow over Northeast Iceland in the September event, and the northeasterly flow over Northwest Iceland in the December event, as observed above the Keflavík upper-air station in Southwest Iceland (not shown), as well as at many automatic weather stations (example given in Fig. 2).

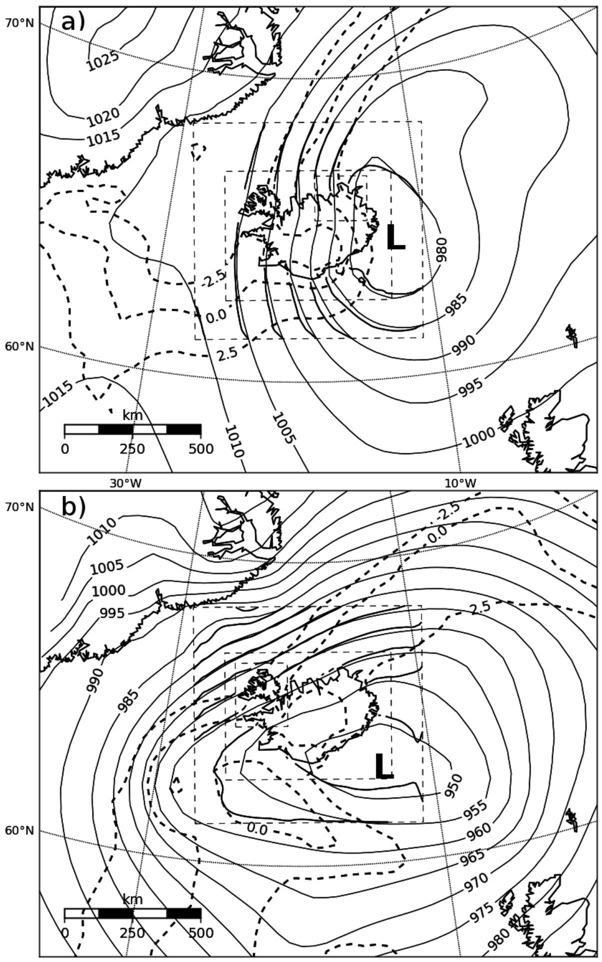

Fig. 1. Mean sea level pressure and 2-meter temperature at 12 UTC on 10 September 2012 (a) and at 6 UTC December 2012 (b) according to the analysis of ECMWF. Also shown is the pressure simulated at 9 km horizontal resolution (thick solid lines), as well as the 9, 3 and 1 km domain bounds (dashed lines) and location of extratropical low (L).

10-minute mean winds at 10 meters exceeded 20 m/s at many locations in North Iceland during the period of most active wet-snow accretion on 10 September, and were as great as 25 m/s at several stations, which can also be considered to be the large-scale wind aloft in the boundary layer and away from complex orography. Weaker winds were observed at several more sheltered locations in Northeast Iceland as well as away from the most affected region, while at the same time there was a severe northerly windstorm in Southeast Iceland. The winds were slowly turning anticlockwise from the northeast as the low approached and winds increased. The large-scale wind direction was close to north at the start of the wet-snow event and close to northwesterly at its end and immediately after the event.

The December event in Northwest Iceland occurred in far more complex orography than the event in September. This is reflected by the strongest winds, being associated with downslope windstorms in the lee of mountains; these winds (10-minute) were as great as 40 m/s and exceeded 30 m/s at many locations, with far stronger gusts (3-second). Mountain top winds were on average close to 30 m/s and not as gusty, while far weaker winds were in general observed close to the upstream side of the mountains. The wind direction varied somewhat between the stations as can be expected in complex orography, but the large-scale wind direction was close to being northeasterly during the event, but gradually turned more towards north. It should be noted that wind observations may in general be expected to be severely affected by wet-snow accretion slowing, or even stopping, the anemometers, but to a lesser extent during wet-snow accretion than in-cloud icing.

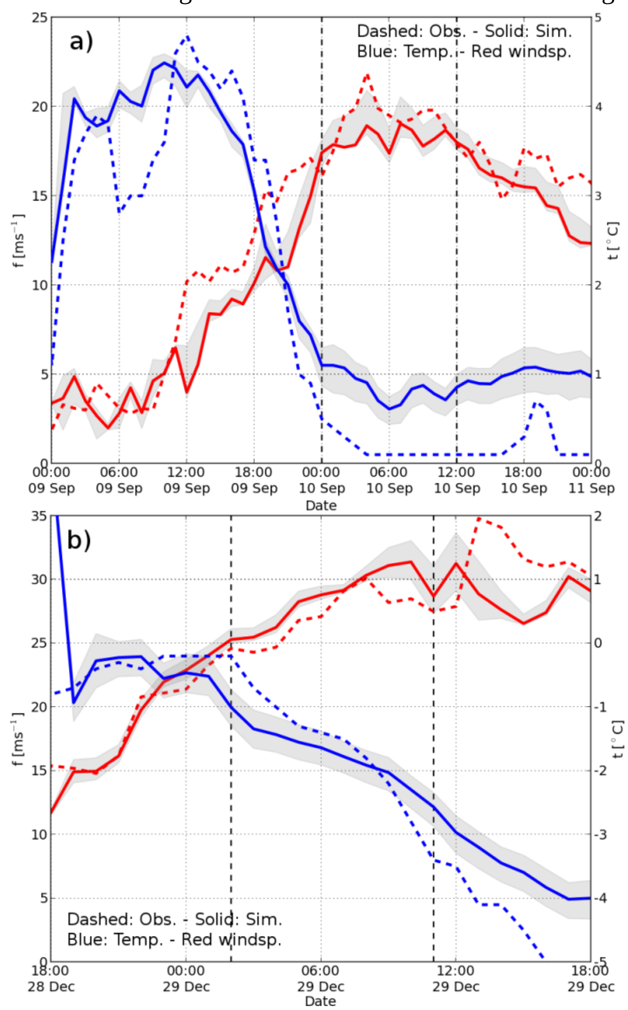

Fig. 2. Observed (dashed) and simulated (solid) 10-meter mean wind speed (red), as well as 2-meter temperature (blue) at Þeistareykir in Northeast Iceland (a) and at Þröskuldar in Northwest Iceland (b). Also shown with dashed vertical lines is the approximate timing of active wet-snow accretion.

A backward trajectory analysis reveals the southern origin of the relatively warm and moist air mass immediately to the east of Iceland, while to the north of Iceland the air was cold and of arctic origin (not shown). This contributed to the deepening of the lows and the extreme amounts of precipitation that fell during the events. The September event was in fact associated with unprecedented snowfall for the time of year and widespread wet-snow accretion in a certain altitude interval, while in the latter event, the most extreme accretion was confined to locations on the immediate leeside of the complex orography in Northwest Iceland. The unprecedented snowfall in September further disrupted traffic, and caused the loss of thousands of sheep still grazing in the highlands when the storm hit, which were consequently buried under thick layer of snow. Fences for livestock fell or were greatly damaged throughout the region, and in the relatively small and few forested areas, there was great damage to tree growth in an elevation interval associated with the wettest and heaviest snow. Precipitation observations during the events were very unreliable due to undercatch of snow during such strong winds. During the December event synoptic observations of the snowfall were nevertheless 40-50 mm (water-equivalent) in 12-15 hours in the accelerated flow in the lee of the mountains and were generally far smaller in weaker winds on the upstream side. Precipitation was more intense and widespread during the September event, with up to 40 mm of rain in 24 hours observed at sea level. In the most affected region the observed precipitation was approximately 50-130 mm (water-equivalent) in 24 hours of what was described as very wet and heavy snow.

In the presence of enough precipitation, but away from complex orography, the largescale (wet bulb) temperature field (Fig. 1) is decisive for the possibility of wet-snow accretion. The temperature must be in the approximate range of 0 to 1.5°C in some elevation intervals in the region, as was the case in large areas in North Iceland in September 2012. Temperatures dropped sharply from 4-8°C in approximately 8 hours preceding the event and were in general below approximately 0.5°C when the most intense precipitation and wet-snow accretion started. Temperature observations from automatic weather stations are unreliable at most of the wet snow locations, as shortly after the onset of wet-snow accretion the strong winds drove the intense precipitation into the thermometer shelter, after which the sensors showed 0°C while covered in melting snow for at least 24 hours before temperatures dropped sharply again. In complex orography, as in Northwest Iceland, the response of the atmospheric flow to the orography is an additional factor which can cause localized enhancement of wet-snow accretion in spite of, for example, the larger scale temperature and/or precipitation fields not being optimal for accretion on a larger scale. Observations from the December event reveal this with lowland temperatures slowly decreasing from 2-3°C at the start of the event and being at or below 0°C at its end. In this temperature range, widespread wet-snow accretion could be expected, but in fact only occurred in the lee of the mountains where the precipitation was concentrated.

In addition to the example data presented in Fig. 2, data from a large number of automatic and synoptic weather stations spread throughout Iceland have been used in analyzing the two events and validating atmospheric simulations of the events. The data from all the stations is stored and checked for systematic errors at the Icelandic Meteorological Office.

III. Numerical simulations of the atmospheric flow

Both events are simulated with the non-hydrostatic mesoscale Advanced Research WRF-model (ARW-V3.4.1, [11]). The model is initialized and forced at its boundaries with the ECMWF analysis. The simulations are done at a resolution of 9, 3 and 1 km with, respectively, 95x90, 205x157 and 190x175 grid points in the 2-way nested domains (locations in Fig. 1) The model top is at 50 hPa and the simulations use 50 layers in the vertical, with higher resolution in the lower parts of the troposphere compared to further aloft. The model is run for the whole accretion period as indicated by the wet snow observations, with a delay of approximately 12 hours before starting the nested domains at 3 and 1 km, which allows for at least 24 hours of total spin-up time before the time of interest.

Two most relevant parameterizations employed are those for boundary layer processes and atmosphere moisture physics. The boundary-layer parameterization uses the Mellor-Yamada-Janjic scheme (ETA, [12]), which is centered on the prognostic equation for the turbulence kinetic energy and is frequently used for both operational and research simulations. The structure and magnitude of the atmospheric water content is particularly dependent on the parameterization of atmospheric water and precipitation physics. This is done with the Thompson scheme [13], which predicts mass mixing ratios of cloud water, cloud ice, graupel (QGRAUP), snow (QSNOW) and rain (QRAIN), as well as number concentrations of ice and rain. The graupel, snow and rain phases are relevant for studies of wet snow and have been converted to mass content. The Thompson scheme has previously been reported to give good results in studies of atmospheric icing as in [14].

Considerable work was dedicated to optimizing and improving the simulations based on several different sensitivity tests. The main points that needed addressing, in addition to careful considerations regarding the simulation setup described above, include:

- Improved land-use classification for the whole of Iceland, based on the Corine-dataset from 2007 and a one-to-one projection to the prescribed land use characteristics of the original 30" dataset from the United States Geological Survey.
- An additional correction to the land-use classification, based on the best representation of the outlines of the Icelandic glaciers. A significant error in this is present in the USGS-dataset, as well as in all the global atmospheric datasets available for Iceland, including those from the ECMWF.
- Correction of errors related to skin temperatures and land-sea mask in the ECMWF-analysis in some coastal regions of Iceland. The error is presumably related to post-processing and interpolation of skin temperatures in the ECMWF-data.
- A better representation of skin temperatures of inland water bodies which have previously often been initialized with skin temperatures of the closest ocean-grid point, which can be very wrong for inland bodies in complex orography.

These modifications lead to improvements in, but are not limited to: 1) A more correct representation of surface roughness and hence better reproduced surface winds. 2) A better representation of moisture fluxes from the surface and hence better reproduced surface temperature and energy budget. 3) More accurate surface temperatures and significant modifications to low-level atmospheric stability. The modifications affect the surface and low-level flow throughout Iceland.

In addition, after careful verification of the general validity of the simulation of each event, simulated data at relevant locations were post-processed by comparison with available observations. This was done in order to correct (mostly small) errors in the simulated datasets and make them more accurate and suitable for input into the wet-snow accretion models. In light of the previously mentioned sensitivity of wet-snow accretion to small variations in atmospheric water content and temperature, a single atmospheric simulation cannot be expected to correctly capture all the relevant atmospheric variables with sufficient accuracy. Even in the presence of perfect input data, inaccurate model parameterizations and surface characteristics are only a few of the important sources of model errors.

Overall, the large-scale fields are well represented by the atmospheric simulations, as is for example seen for the surface pressure field, where errors are on average well below 1 hPa (Fig. 1). The errors are greatest in the lee of mountains, as can be expected since the relatively coarse resolution of the ECMWF-data is not sufficient to correctly represent the large-scale orography. Simulated surface winds and temperatures have been validated for the relevant regions in northern Iceland, using observations from a large set of automatic weather stations. The biggest errors, both in temperature and wind, are found in locations of complex orography, for example, in the December event in several locations in the lee of large mountains. Errors are generally smaller for the simulated September events, presumably a result of better representation of the topography by the model. Surface winds at 10 m are in general very well captured away from complex orography with mean errors of less than 2 m/s, and peak winds are well represented (Fig. 3). Errors are somewhat greater at locations downstream from high and complex orography: however, the observations are well represented if the high spatial variability in the simulated winds is taken into account (e.g., Fig. 2). Observed temperatures are slightly overestimated (less than 1°C) at several stations but generally accurately captured at others. This error appears to be related to errors in the forcing data or the vertical heat flux from the surface, and is greatest over the ocean or near water bodies.

The flow aloft is revealed to be strongly affected by the complex orography. Gravity wave activity is particularly strong in the December event, as revealed by the isentropes (isentropes can considered to be equivalent to streamlines) in a section across the Snæfellsnes Peninsula in West Iceland (Fig. 4). A dramatic gravity wave resembling a hydraulic jump is set up above the peninsula when the flow impinges on the mountain barrier. Large amounts of super-cooled cloud and/or rain water form when the low level upstream flow is lifted over the mountains, and are subsequently carried down the lee slopes of the mountains in the fast plunging flow below the wave. Due to the strong descending flow, there is very small simulated evaporation and scavenging by snowflakes, allowing significant amounts of this dynamically created atmospheric water to reach the lowlands in the lee. This appears to introduce a new method to enhance the amount of atmospheric water and its liquid water fraction in the lee of mountains. Previously, it was only the melting of the larger scale snowfall below the 0°C isotherm which was considered to introduce the necessary liquid water content of the snow, as is presumably the case in general during the September event, and as can be deduced from the section in Fig. 4. The gravity wave mechanism of enhancing the atmospheric water flux on the leeside needs more investigation and observations to be verified; however, it is supported by observations of leeside precipitation maxima during orographic precipitation events.

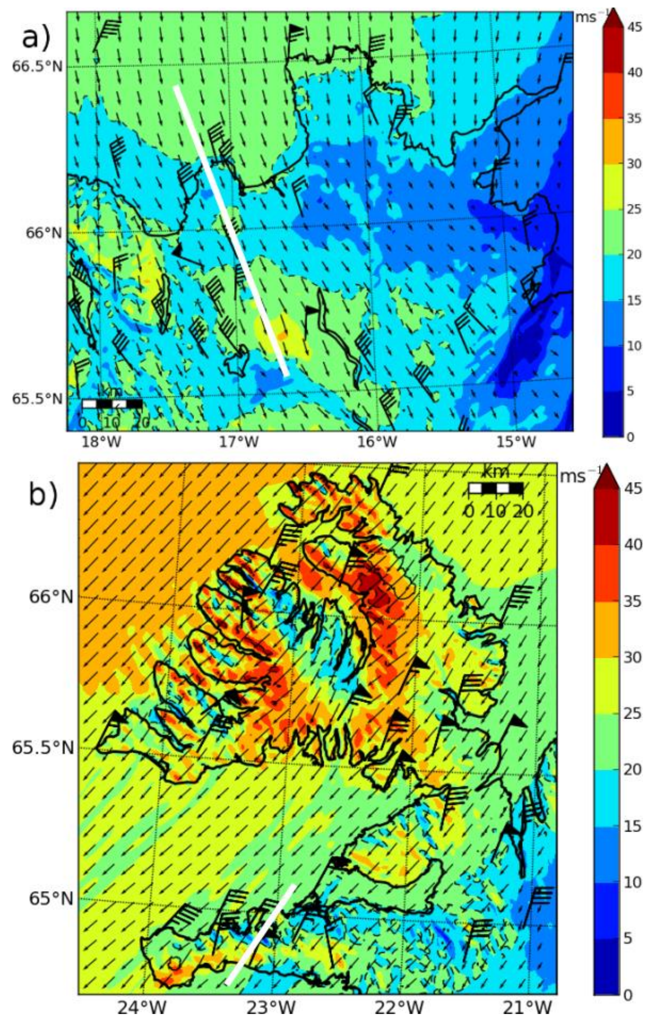

Fig. 3. Simulated 10-meter mean wind speed [m/s] and wind vectors at a horizontal resolution of 1 km, as well as observed winds at automatic weather stations (5 m/s each half barb, 25 m/s each flag) at 0600 UTC on 10 September in North Iceland (a) and on 29 December in Northwest Iceland (b). Contours of 20 and 40 m/s are indicated by dashed lines, coastline and location of sections in bold.

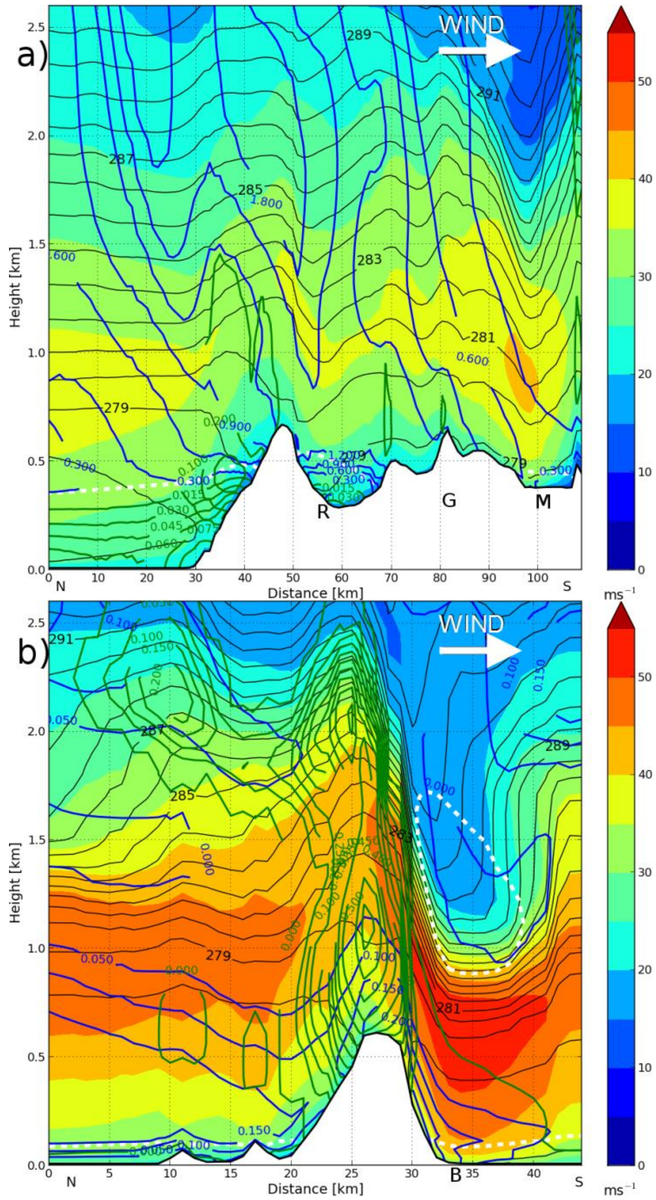

Fig. 4. Wind speed contours [m/s] in color, isentropes [K] (thin, black) as well as isolines of atmospheric water [kg/m3] (blue=snow, green=rain and cloud) content in sections at 0600 UTC on 10 September 2012 (a) and on 29 December 2012 (b). White dashed lines are the 0°C isotherm. Wind is from the left and follows the isentropes. Locations of sections are shown in Fig. 3. Approximate projections of locations of wet snow sites on to the section are indicted in bold: Reykjaheiði (R), Gæsafjöll (G), Mývatn (M) and Bláfeldarhraun (B).

IV. Wet snow accumulation

Observations of the wet snow accumulation during the two events reveal large spatial differences in the extent of the affected regions during the events. The event of 10 September was associated with widespread wet-snow accretion on overhead conductors in a certain elevation interval in North Iceland (cf. Fig. 5). However, during the December event, the greatest accumulation was observed at locations in the lee, and close to mountains of significant height and in very complex topography (cf. Fig. 9). Furthermore, there were indications of small-scale topography enhancing the accretion process, e.g., through drifting snow associated with locally accelerated surface flow, or when it was lifted by small scale topographic features in the immediate vicinity of the power lines.

The event of 10 September 2012

The wet-snow event in September 2012 was most severe in the eastern part of North Iceland (Fig. 5). Active wet-snow accretion started at approximately 0100 UTC during the night of 10 September, as is seen from operational observations with a suspended load cell in a 132 kV KS1 transmission line on Reykjaheiði, approximately 20 km south of the coast. The line at this site is approximately perpendicular to the prevailing northerly and northwesterly winds, at an elevation of approximately 275 m above sea level, and a relatively short distance downstream from an approximately 700 m high mountain ridge. The topography at the site is flat up to 2 km from the measuring tower. Based on observations and simulated data, mean winds are expected to have peaked at the site early in the night at 27 m/s, with gusts exceeding 40 m/s. At approximately 1145 UTC the total measured load was 2600 kg with 150 m weight span, and the towers on both sides of the tower with suspended load cell broke. The load measurements indicate that wet-snow accretion continued until at least 1445 UTC and possibly longer, but the actual load cannot be calculated after the failure (Fig. 7). At the time of the failure the equivalent ice load is estimated to be 14.5 kg/m, which, with a mean density of 750 kg/m3, is characteristic for similar events in Iceland, gives an equivalent mean diameter of 16.2 cm. A total of 23 wooden H-frame towers broke or fell at this site during the event, with the damage in general limited to the upper parts of the towers, i.e., cross-arms and X-braces (sample photos in Fig. 6b). Slightly farther the south and west in the same region, eight similar towers broke in a 132 kV transmission line. Most of the wet snow fell off the conductors in the afternoon of 11 September.

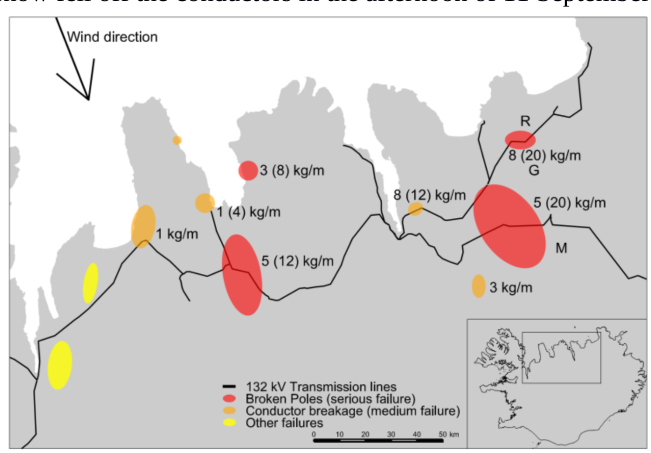

Fig. 5. Overview of measured/estimated wet-snow loading as well as main regions of failures during the event on 10 September 2012 in North Iceland. Values shows median (max) loading. Also shown are approximate locations of the measuring sites on Reykjaheiði (R), Gæsafjöll (G) as well as that of Lake Mývatn (M).

Fig. 6. Photos from the wet-snow event on 10 September in North Iceland. a) Loaded conductors and leaning poles of the distribution system north of Lake Mývatn. b) Accumulated wet snow and broken transmission towers in 132 kV KS1 at Reykjaheiði. c) Wet snow sample on a faulted transmission line conductor on Reykjaheiði, measuring 21 cm mid-span which is however not an average value for the area.

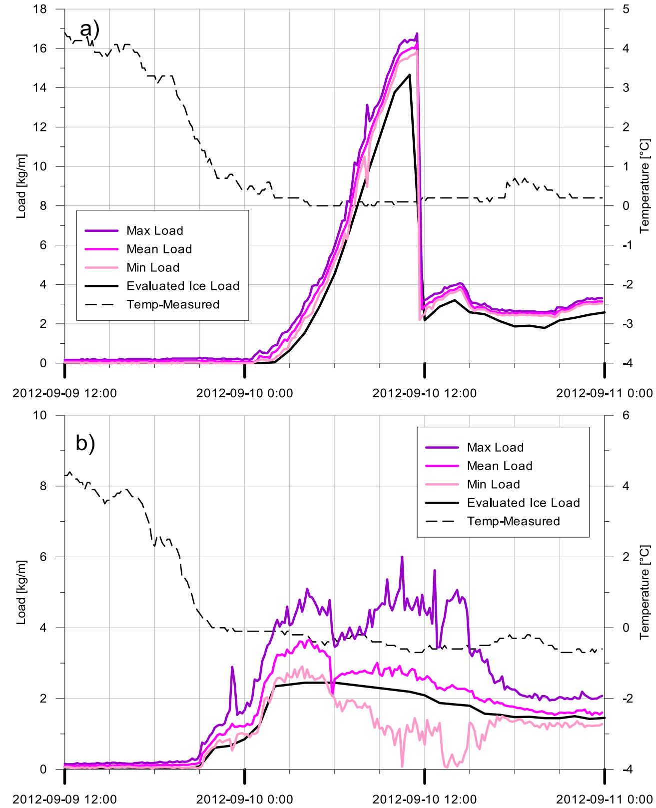

Fig. 7. Measured and evaluated ice load a) in 132 kV KS1 and b) in test span in Gæsafjöll.

The 11 kV distribution system was severely damaged in several areas farther inland, and after the event most of the overhead conductors in the affected areas were replaced with 11 kV underground cables. The most serious failure occurred at Lake Mývatn (300 m a.s.l., sample photo in Fig. 6a), where approximately 100 distribution poles fell or broke, causing widespread blackout lasting for four days. The measured snow sleeve was up to 13-14 cm in diameter at some locations, but was on average close to 10 cm on conductors oriented perpendicularly to the prevailing winds.

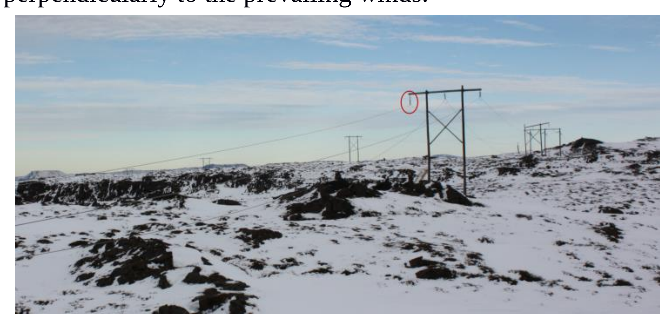

Fig. 8. Suspension tower in 132 kV KS1 with measuring equipment in left phase at Reykjaheiði site.

THE EVENT OF 29 DECEMBER 2012

A severe northeasterly windstorm occurred in Iceland during the night of 29 December 2012. The storm was associated with significant wet-snow loading on many distribution and transmission lines in Northwest Iceland. All the major icing occurred in the lee of mountains of significant height, i.e., on the southern and western side of the complex orography of the region (Fig. 9). Temperatures were on average coldest in the northern part of the region where the least accumulation occurred, but temperatures were slightly higher towards the south where the greatest accumulation and the most failures occurred.

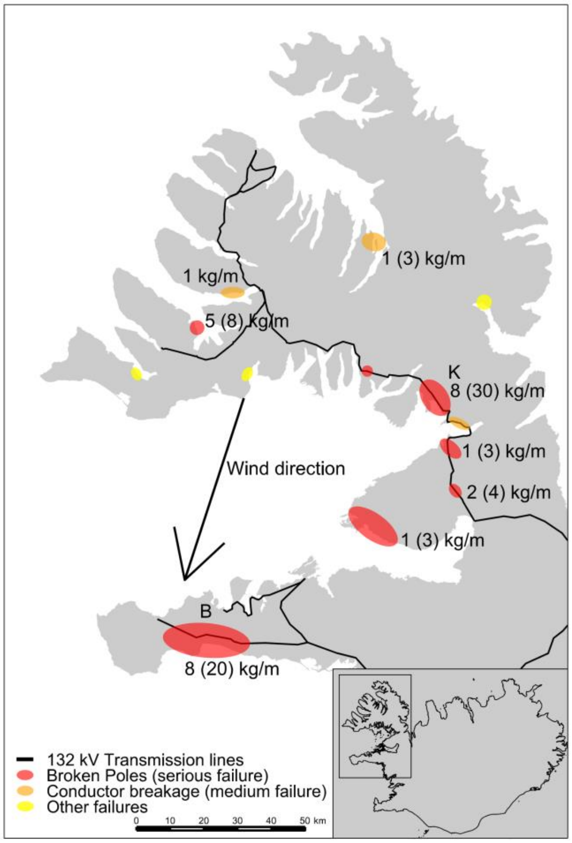

Fig. 9. Overview of measured/estimated wet-snow loading as well as main regions of failures during the 29 December event in Northwest Iceland. Values shows median (max) loading. Also shown is the approximate location of Kambur (K) and Bláfeldarhraun (B).

The accumulation started around 0300 UTC and continued for approximately nine hours, as is seen from operational measurements from a load cell (Fig. 10) suspended in a 132 kV MJ1 transmission line at Kambur, in the lee of very complex topography (Fig. 11 and Fig. 12). The maximum load measured was 3220 kg with 124 m weight span, but at that time the conductor was so loaded that it lay on the snow layer below. The largest diameter was measured to be up to 40 cm, with an equivalent mean diameter of 22-25 cm. The most intense loading occurred on a very short interval between three transmission towers and was presumably strongly affected by the upstream topography enhancing the atmospheric water flux through drifting snow caused by channeling or lifting of the surface flow to the elevation of the conductors. This may be deduced from Fig. 12, which shows the topography on a section through the site at Kambur, along the main wind direction. The density of the accreted wet snow was found to be 700-740 kg/m^3, based on four samples. Measurements of the orientation of snow keels on the poles indicate that the prevailing wind during the accretion period was slightly east of north.

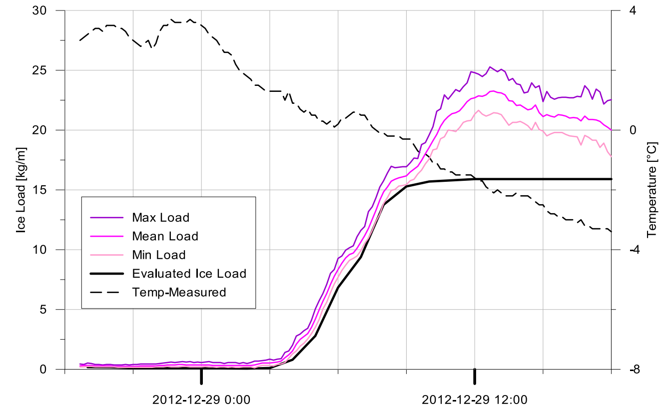

Fig. 10. Measured and evaluated ice-load at Kambur in 132 kV MJ1.

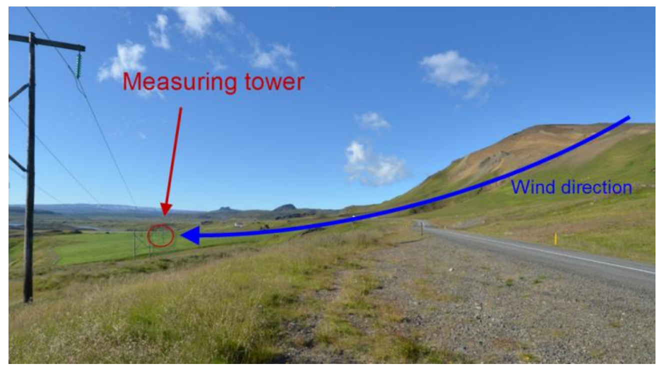

Fig. 11. Suspension tower at Kambur in 132 kV MJ1 with measuring equipment.

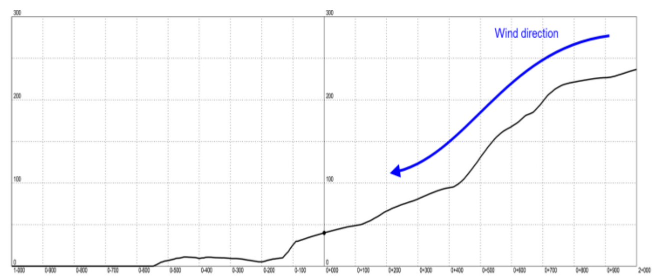

Fig. 12. Topography on a section through the site at Kambur, along the main wind direction.

At the same time severe accretion occurred at many locations in the region, but most significantly on a 66 kV OL1 transmission line at Bláfeldarhraun on the southern (downstream) side of the Snæfellsnes Peninsula (Fig. 9). The line was out of operation for seven and half days. The diameter of accreted wet snow was estimated to be 8-18 cm, with serious failures, including 42 broken H-frame wooden towers, 55 cross-arms, and torn conductors (sample photos are given in Fig. 13).

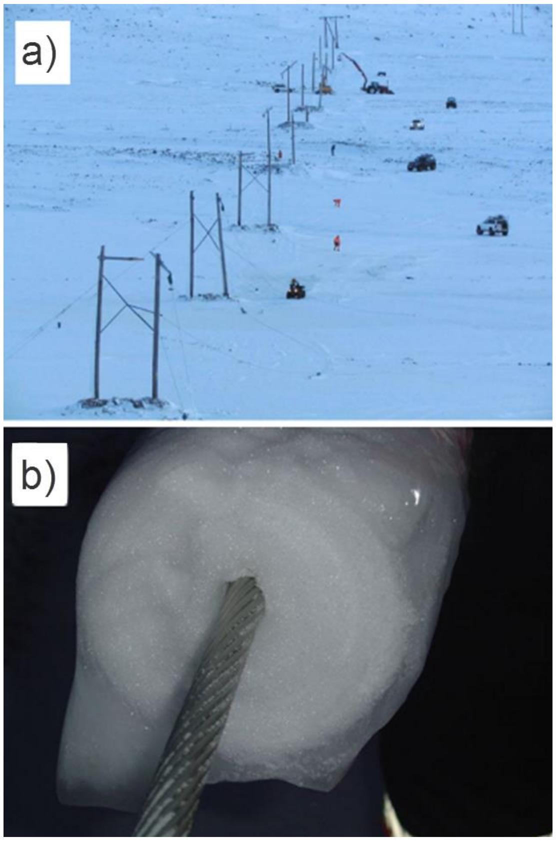

Fig. 13. Photos from the wet-snow event of 29 December in Northwest Iceland. a) Reparation work on faulted 66 kV OL1 at Bláfeldarhraun. b) Wet snow sample east of Bláfeldarhraun, measuring 14 cm in diameter.

V. SIMULATED WET-SNOW ACCUMULATION

The direct model output data from the atmospheric simulations are used as input data for the wet-snow accretion model presented in [10] and subsequently used to prepare maps of the spatial structure of the simulated accumulation (Fig. 14). The direct model output was furthermore post-processed in an attempt to correct for errors present in the data at several locations where wet snow load measurements are available from test spans. The post-processed data was then used as input to the same icing model to prepare time-series of simulated accumulation to be compared with the observed loading at the measurement sites (Fig. 15). It should be noted that the simulated loads are here done on a vertical, rotating, cylinder and are thus independent of the wind direction and greater than simulated loads taking wind direction into account, as in [15]. The overall spatial structure of the simulated wet-snow accumulation compares well with locations of reported failures and other damage observed during the events. Large accumulated wet-snow masses are simulated at the location of a measuring site at 132 kV KS1 and around Lake Mývatn, where the greatest damage occurred to the overhead distribution and transmission system in September 2012 (Fig. 5). Icing is on average underestimated during the December 2012 event, but the pattern of largest wet snow sleeve diameters is correctly located in the lee of the mountains, in areas where the greatest damage was observed in on the overhead system at Bláfeldarhraun and near the measuring site at Kambur (Fig. 9). Gravity wave activity above the Snæfellsnes Peninsula may have affected the accumulation in Bláfeldarhraun, as previously mentioned. A comparison of the measured and simulated wet-snow loading at the measuring site at Reykjaheiði and test span in Gæsafjöll in the September event, and at Kambur in the December event, shows that extreme wet-snow accumulation is underestimated at Reykjaheiði and Kambur, while the less severe accumulation at the test span in Gæsafjöll is well reproduced. A comparison with the spatial structure of the simulated accretion at Reykjaheiði reveals that only a small shift in the extent of the extreme icing region is needed to reproduce the measured accumulation at the site. This appears not to be the case at Kambur in Northwest Iceland, but there are indeed indications that local small-scale topography may have locally increased the atmospheric water flux, possibly due to drifting snow or channeling of the flow. Such phenomena may be partly reproduced at far higher resolutions, but not at the current resolution of the atmospheric model. A more detailed discussion of the icing models themselves and their performance is given in [15], for both the current cases and several other severe events.

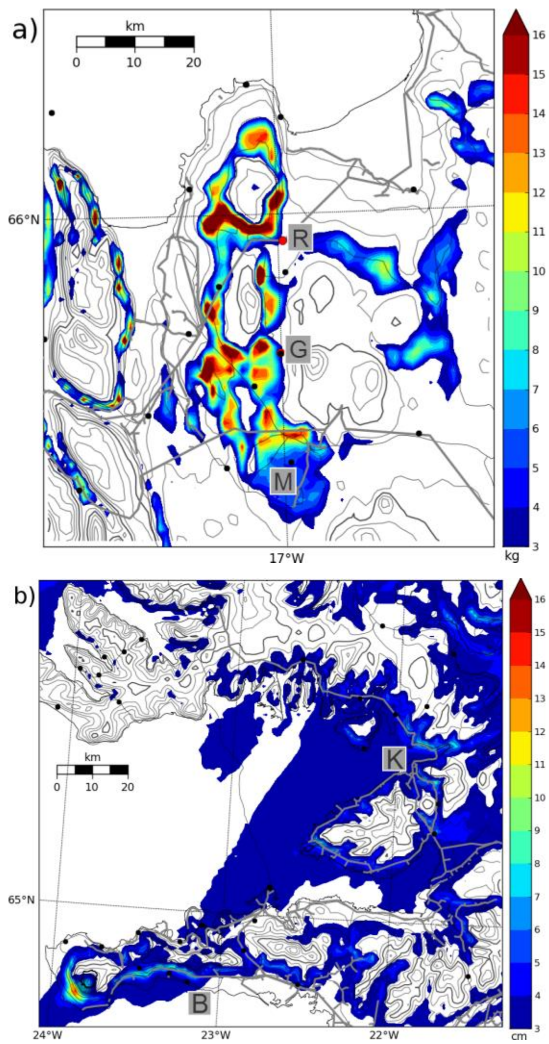

Fig. 14. Simulated wet snow mass [kg/m] in North Iceland (a) and accreted wet snow diameter [cm] in Northwest Iceland (b). Also shown are locations in Reykjaheiði (R), Gæsafjöll (G), Mývatn (M), Kambur (K) and Bláfeldarhraun (B).

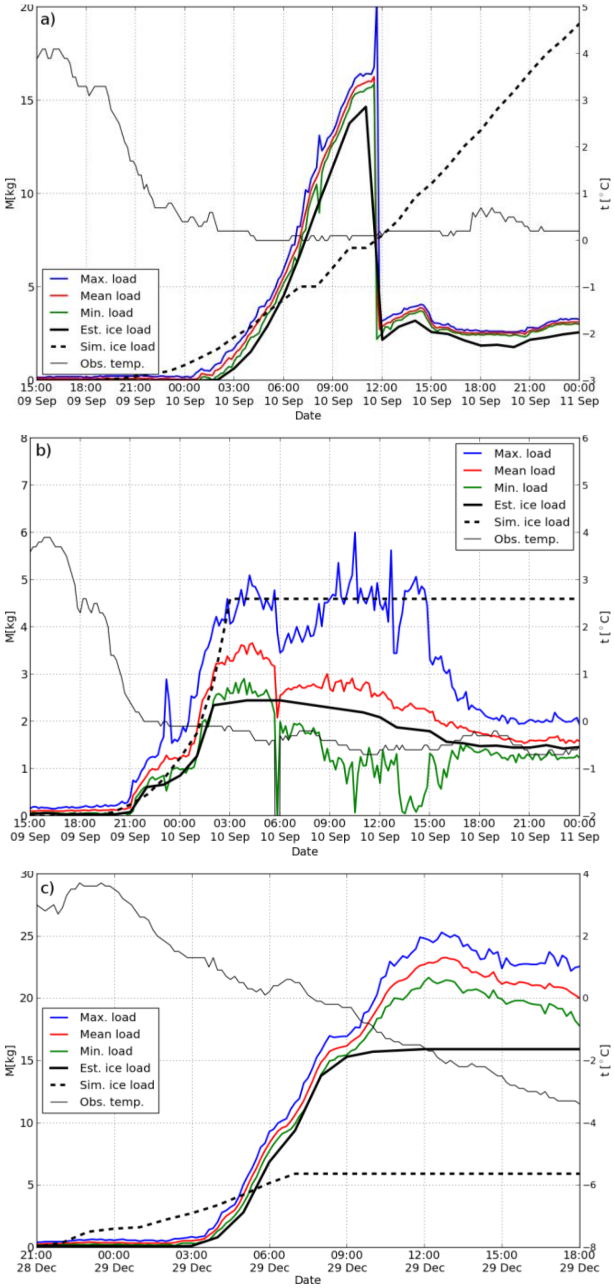

Fig. 15. Measured loading, estimated and simulated ice load, as well as temperature at Reykjaheiði (a) and in Gæsafjöll (b) in Northeast Iceland and Kambur in Northwest Iceland (c).

VI. Concluding Remarks

Here, two severe wet-snow events in northern Iceland have been described and analyzed using systematic observations and reports of wet-snow loading, observations from a dense network of automatic weather stations as well as high resolution atmospheric simulations. The observed wet-snow accumulation varied greatly within the cases. It was more widespread in a certain elevation interval in the September event in North Iceland, while accretion was more localized and occurred mainly in the lee of mountains in the December event in Northwest Iceland. Both events were associated with very strong winds and high amounts of precipitation, in particular the September event where the snowfall amounts were exceptionally great so early in the season.

The observed wet-snow loading was close to 15 kg/m in the cases, with equivalent diameters greater than 20 cm and exceeding 40 cm in some places. Both the transmission and distribution systems were damaged during the events, with a total of more than 200 fallen or broken poles and H-frames for the two events. Blackout was widespread and lasted for few days at some of the locations, making these events some of the most severe documented in Iceland.

The first attempt was made to simulate observed wet snow accumulation, based on the wet-snow model presented in [10], which uses a physically based parameterization of the sticking efficiency. The model is forced, using input data from the atmospheric simulations, which includes parameters which are not routinely observed, such as the atmospheric water flux and liquid water fraction, which is critically dependent on the wet bulb temperature but has previously been based on in-situ observations of the temperature. A successful simulation of wet snow accumulation is critically dependent on: 1) a detailed and accurate icing model and 2) detailed and correct atmospheric input data. Here, the overall performance of the icing model is better for the September event, which occurred in less complex orography than the December event. This was somewhat as expected since atmospheric simulations are in general less accurate, and harder to perform, in complex orography than less complex orography. The strong dependence of the accretion process on a relatively narrow interval in both temperature and liquid water fraction of the falling snow, as well as the actual snow amounts, should be noted [16]. In fact, a large part of the error in simulated wet snow accumulation may be explained if the spatial variability in the simulated fields is accounted for. Often only a slight vertical or horizontal shift within the simulated dataset is needed to reach far more favorable conditions for efficient accretion of wet snow on conductors. A more thorough discussion of the comparison of observed and simulated wet snow accumulation for the current events, as well as for other events, is given in [15].

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