windPRO

EMD-WRF Icing Analysis:

Lat, long: 64.223, 18.358 at 100m agl.

EMD
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Contents

1 Introduction

This report summarizes results from EMD's Icing Model for 100m above ground level (agl) and serves as one of the outputs from the service. The model is driven by EMD-WRF[1] On Demand (OD) mesoscale data from the calculation-node closest to the requested site (mast) location.

EMD's Icing Model is executed based on inputs from the: EMD-WRF OD (for icing) mesoscale modelling data with special emphasis on in-cloud icing. Icing (accretion and ablation) is modelled using industry proven methods and our implementation is aligned with the requirements in the ISO12494:2017 standard (ISO, 2017). Please find more information in the Technical Note including validation information on help.emd.dk [1].

This report contains four main sections as follows:

Section 2 - Site Overview: provides an overview of the site by an elevation map, and a presentation of the temperature and wind speed distribution.
Section 3 - Modelled Icing and Ice Losses: provides an analysis of the monthly and yearly numbers of modelled icing hours and the calculations of the site icing losses.
Section 4 - Icing Distributions: provides an overview of the icing distributions by frequency plots, histograms, sector distributions by wind roses and tables.
Section 5 – Icing Maps: presents icing maps for 100m alg. Based on icing calculations at 15 heights agl. and downscaled to the heights of the elevation map shown in Figure 1.

Next a summary of the modelled icing and IEA classification of the site is given.

1.1 Summary

Table 1 summaries the calculated icing hours and presents the IEA classification of this site at location: 64.223, 18.358 (lat, long) at 100m agl. The IEA classification seen in Table 1 is based on the mean number of modelled meteorological icing hours of the 10 winter seasons covered by: 2009-07-01 to 2019-06-30. Please see the full analysis of the modelled icing and estimated icing losses in Section 3 and Section 4.

Table 1: Site summary for the 10 winters covered by: 2009-07-01 - 2019-06-30 at 100m agl.

ICING:	ICING HOURS	% OF YEAR	IEA CLASS	IEA LOSS
METEO.	668.5	7.59	4.5	15.5

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[1] WRF: Weather Research and Forecasting Model

Terminology

ICING TERMS	DESCRIPTION
In-cloud icing	In-cloud & ice accretion, by a cloud/fog containing super-cooled droplets, which meet an object and freeze upon contact
Icing intensity	Icing rate, deposit of ice per unit time $[dM_{ice}/dt]$
Ice load	Modelled ice mass on standard cylinder $[M_{ice}]$
Ice accretion	The terms used for describing the growth of ice on an object
Ice ablation	The removal of ice by ablation process: sublimation, melting and ice shedding
Meteorological icing	The periods of time with ice growth. Will be referred to as: Meteo. Icing many places in this report Meteorological icing is defined following the ISO 12494 standard [2] and will be identified when the icing intensity (dM/dt) > 10 g/h
Instrumental icing	The periods of time with ice present on instruments/structures Will be referred to as: Instru. icing places in this report Instrumental icing is defined when the ice load (M_{ice}) > 10 g. This is equivalent to the approach used by Hämäläinen et. al. (2017) [3], when defining the Finnish Icing Atlas [4]. The instrumental icing event stops, when the ice load is reduced below the threshold by ice ablation (melting, shedding and sublimation)
Winter season definition	In this report, 10 winter seasons are included. The first season starts: 2009-07-01 and the last ends at: 2019-06-30

2 Site Overview

Icing at 100m agl over the 10 winter seasons covered by (2009-06 to 2019-06) has been modelled and analysed for the site location: EmdWrf_N64.222_E018.358 in Sweden. The WRF point closest to the site location has been used having the coordinates (lat, long): 64.222, 18.358.

Please see the two coordinates on the site elevation plot in Figure 1.

EMD-WRF ICING name: EmdWrf_N64.222_E018.358, Sweden
Site Location   Lat, long: 64.223, 18.358
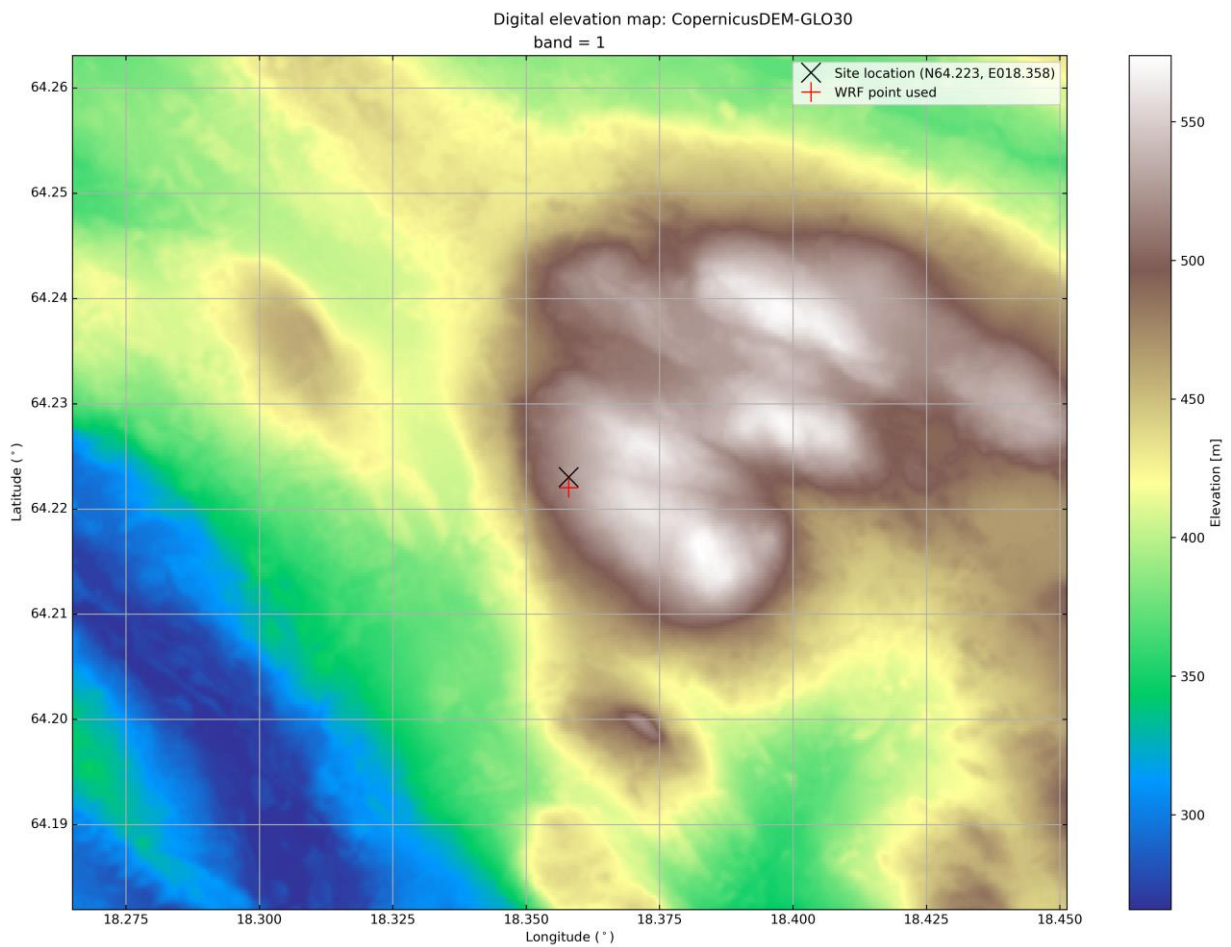
Figure 1: 9 km by 9 km digital elevation map of site. The site location and the WRF point location are shown. The colorbar to the left shows the elevation above sea level in meters (m).

2.1 Temperature and Wind Speed Characteristics

An overview of the monthly temperature and wind speed distributions over the 10 years covered are shown in the box-and-whiskers figures next. The green triangle is the mean value, the green line the median, while the box reflects the 25% and 75% percentiles. The whiskers reflect the minimum and maximum values. Figure 2 shows the monthly temperature distribution over the year and Figure 3 shows the monthly wind speed distribution over the year.

Figure 2: Temperature (temp.100) distribution on different months at 100m agl.

Figure 3: Wind speed (wSpeed.100) distribution on different months at 100m agl.

In the next section the monthly modelled icing is presented followed by the seasonal results.

3 Modelled Icing and Icing Losses

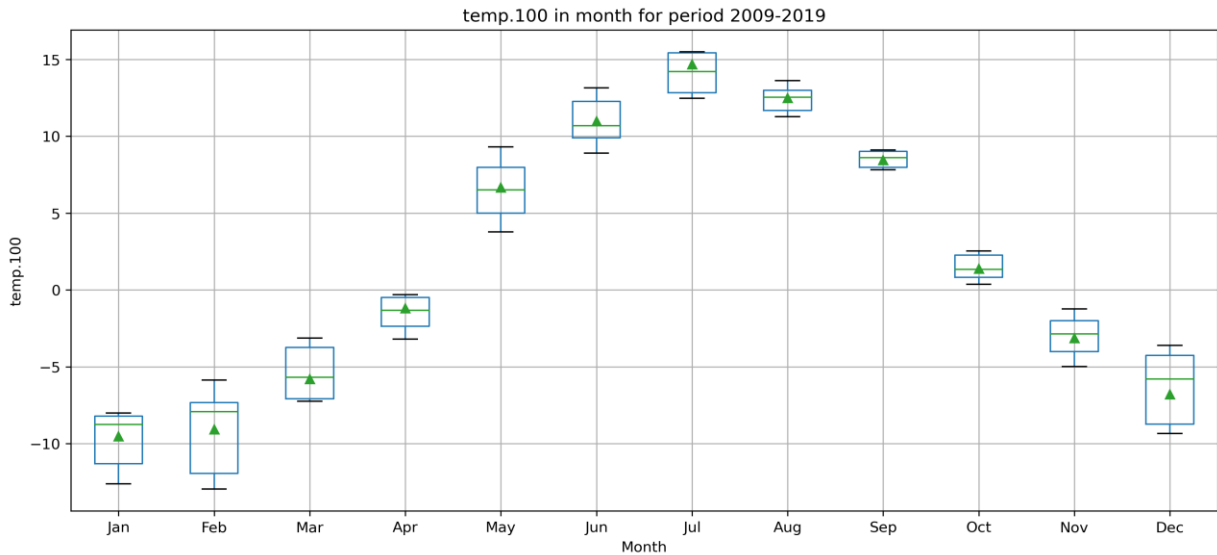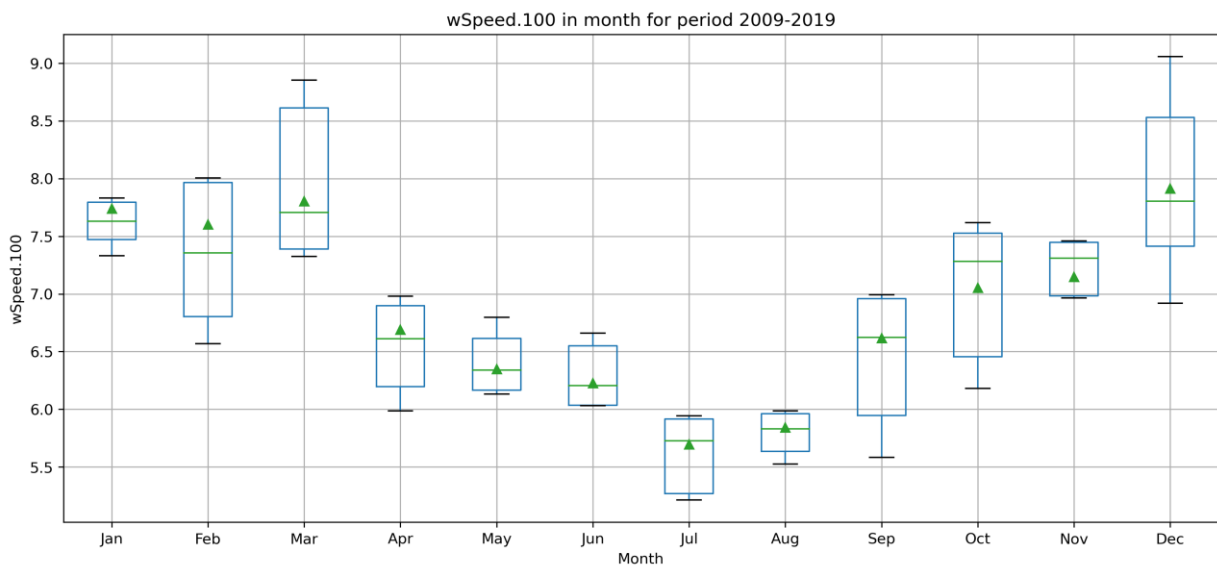The results are divided into a seasonal summary of modelled icing followed by an estimate of the site losses using the IEA Task 19 classification system and the approach by Ø. Byrkjedal (2009) [5]. All results are supported by the summary sheets and complete timeseries also accessible from the analysis using EMD's Icing Model.

The seasonal summary provides the modelled number of meteorological and instrumental icing hours and an icing index of the seasons. The icing index is very useful for long term correction of the results when good measurements are available. Please consult EMD International [6] for more information on this topic.

Please be aware, that the results are general and based on the meteorological conditions of the site. We do not take specific wind turbine type behavior into account. Thus, one should be aware that wind turbines might respond differently during icing conditions, depending on e.g., the blade types, the control strategies, and the specified safety margins.

3.1 Site Icing Characteristics

An overview of the modelled meteorological icing and instrumental icing over the 10 years covered are shown in the box-and-whiskers figures shown next. The green triangle is the mean value, the green line the median, while the box reflects the 25% and 75% percentiles. The whiskers reflect the minimum and maximum values.

Figure 4 shows the meteorological icing distribution and Figure 5 shows the instrumental icing distribution.
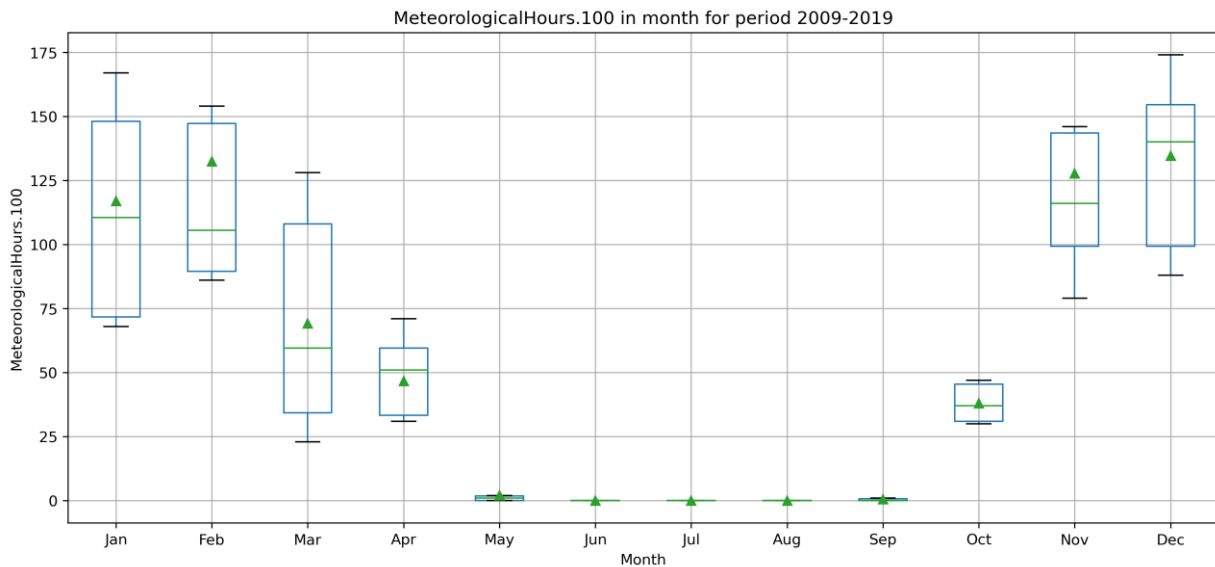
Figure 4: The mean number of meteorological icing hours (MeteorologicalHours.100) distribution on different months at 100m agl.
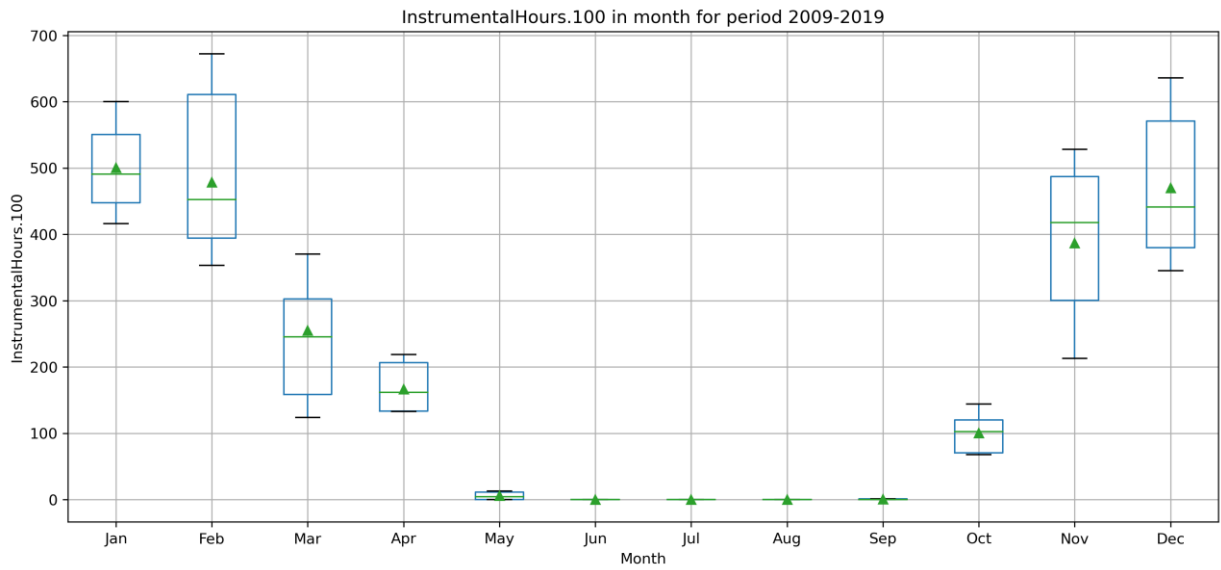
Figure 5: The mean number of instrumental icing hours (InstrumentalHours.100) distribution on different months at 100m agl.

3.1.1 Seasonal Results

Figure 6 shows the mean number of modelled meteorological and instrumental icing over the seasons covered.
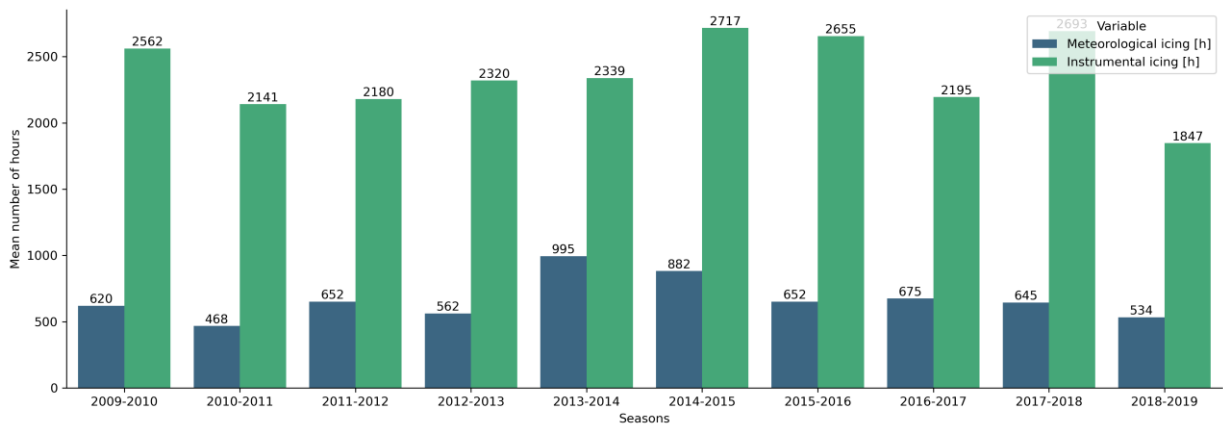
Figure 6: Modelled meteorological and instrumental icing – mean seasonal values.

Table 2 summarizes the seasonal values of modelled icing, average temperature, and wind speed.

Table 3 provides the seasonal icing index based on modelled meteorological icing or instrumental icing respectively.

Table 2: Seasonal summary of icing hours, wind speed and temperature at 100m agl for the 10 winter seasons covered by: 2009-07-01 to 2019-06-30.

SEASON	METEO. ICING [HOURS]	INSTRU. ICING [HOURS]	WIND [M/S]	TEMP. [°C]
2009-2010	620.0	2562.0	6.62	0.2
2010-2011	468.0	2141.0	7.03	0.73
2011-2012	652.0	2180.0	7.13	1.88
2012-2013	562.0	2320.0	6.69	0.92
2013-2014	995.0	2339.0	7.01	2.38
2014-2015	882.0	2717.0	7.01	2.23
2015-2016	652.0	2655.0	6.62	2.21
2016-2017	675.0	2195.0	6.82	1.77
2017-2018	645.0	2693.0	6.75	1.04
2018-2019	534.0	1847.0	7.23	2.55
Mean Value	668.5	2364.9	6.89	1.59
Standard Deviation	158.22	286.5	0.22	0.81

3.2 Icing Losses

Estimated icing losses for the site at 100m agl are presented in this section.

3.2.1 IEA Ice Classification of Site

The IEA Task 19 has developed a system for classification of sites Baring-Gould et al. 2011 [7]. This system relates production losses with the duration of meteorological icing and the duration of instrumental icing. Table 4 shows the IEA Task 19 Icing Classes, which is used next to give an estimate of the expected production loss of the site at 100m agl.

IEA ICE-CLASS	DURATION OF METEOROLIGICAL ICING [% OF YEAR]	DURATION OF INSTRUMENTAL ICING [% OF YEAR]	PRODUCTION LOSS [% OF AEP]
5	> 10.0	> 20.0	> 20.0
4	5.0 – 10.0	10.0 – 30.0	10.0 – 25.0
3	3.0 – 5.0	6.0 – 15.0	3.0 – 12.0
2	0.5 – 3.0	1.0 – 9.0	0.5 – 5.0

| 1 | 0.0 – 0.5 | < 1.5 | 0.0 – 0.5 |

Table 4: IEA Task 19 ice classes [7]. Meteorological icing is referred to as; meteorological icing and instrumental icing to; instrumental icing in this report.

In the validation study of the EMD-WRF OD ICING modelling chain (published at IWAIS 2022 [8]) SCADA losses from 6 wind farms in Scandinavia were compared to modelled site losses using Table 4. The study showed, that using the modelled *Instrumental* icing in Table 4 gave too conservative results, whilst using the modelled *Meteorological* icing gave reasonable results. Because of those results, we recommend to always use the modelled meteorological icing as entry in Table 4. In the next section the estimated production loss (% AEP) of the site is shown.

3.2.2 Production Losses for the site

For this site at location: 64.223, 18.358 (lat, long) at 100m agl. the modelled production loss (% AEP) is: 15.5 %, see Table 5. This number is based on the mean number of modelled meteorological icing hours of the 10 winter seasons covered by: 2009-07-01 to 2019-06-30.

Table 5 summaries the IEA losses based on Table 4. EMD recommends using the IEA loss based on Meteorological icing for this site based on results from [8]. In Table 5 you also find an estimate from the industry accepted approach by Ø. Byrkjedal (2009) [5]. In the paper, Ø. Byrkjedal propose a linear relationship between meteorological icing and productions losses as follows: $P_{loss} = 0.021 \cdot hours_{active\ icing}$ [%].

Table 5: Summary of estimated mean site losses for the 10 seasons at 100m agl. The loss based on Ø. Byrkjedal (2009) takes only meteorological icing as inputs. The 668.5 hours of Meteo. Icing corresponds to 7.59 [% of year] and the 2364.9 hours of Instru. Icing corresponds to 9.96 [% of year].

ICING:	ICING HOURS	IEA CLASS	IEA LOSS	Ø. BYRKJEDAL
METEO.	668.5	4.5	**15.5**	14.0
INSTRU.	2364.9	4.0	11.0	-

4 Icing Distributions

This section gives an analysis of the modelled icing as a function of the wind direction and wind speed. This will be shown by a; sector frequency plot, wind roses, wind speed histograms and by a bin/sector occurrence table. The analysis covers meteorological icing and instrumental icing, respectively. The following figures present results at 100m agl for the 10 seasons.

4.1 Meteorological icing

Figure 7 shows the sector frequency plot of modelled meteorological icing and clearly indicated the most severely influenced sector(s) .

Figure 7: Sector frequency of meteorological icing over the total number of years.

The wind roses in Figure 8 show the occurrences of the wind speeds in the 30-degree sectors, where each color denotes a 2.5 m/s interval. The left-hand figures show the distribution for the full period, while right-hand figure shows the directional distribution during the meteorological icing events. From the wind rose the sector wise icing is combined with the wind speed distribution.
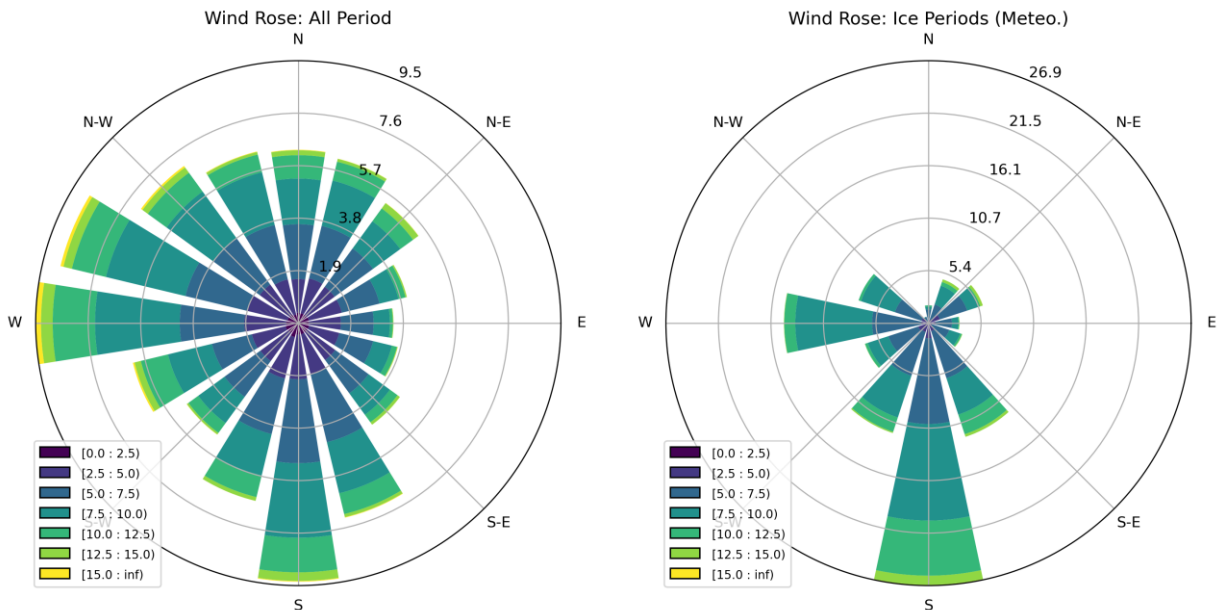
Figure 8: Left: all data and right: only during meteorological icing periods.

Next, Figure 9 presents four histograms during meteorological icing. Top two figures compare all data to iced data by numbers of hours (count) and the bottom two shows the normalised percentage of meteorological icing as a function of temperature and wind speed.
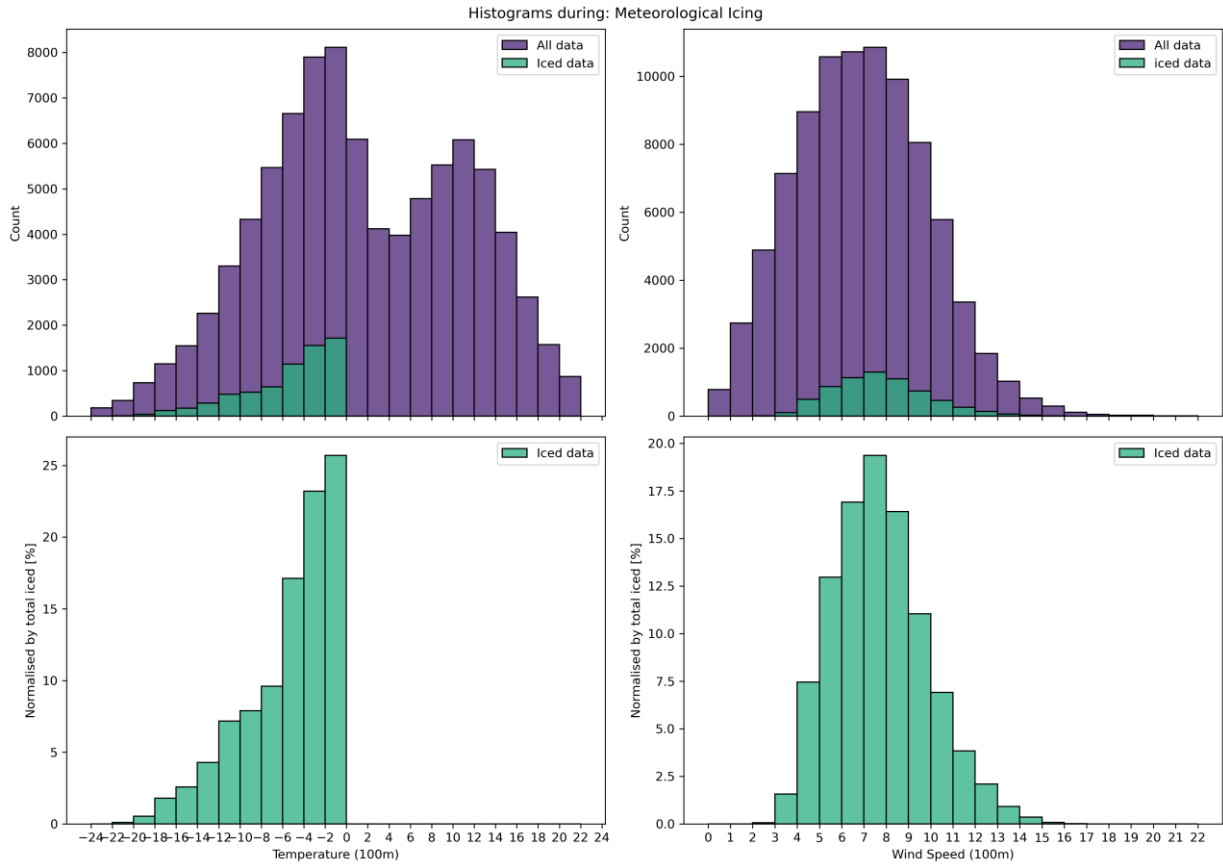
Figure 9: Wind speed histograms during meteorological icing periods. Top two as a function of the number of counts and bottom two, as the normalised percentage (%).

And finally, the meteorological icing analysis is finished by the bin/sector occurrence table, as seen in Figure 10. The table unpacks the results of the wind rose and frequency table during meteorological icing.

Bin/Sector occurence Table of: Meteorological icing (total hours - 668.5)

m/s - deg	0.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	%
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.2	0.0	0.0	0.1
3	0.2	0.5	2.2	1.6	0.2	1.0	1.4	0.9	0.9	0.6	1.0	0.0	1.6
4	2.0	2.1	5.9	3.2	2.3	4.6	8.8	5.4	6.4	4.1	4.0	1.0	7.4
5	2.1	2.6	11.3	4.5	4.0	12.4	18.6	11.1	7.0	6.8	5.1	1.2	13.0
6	3.6	5.7	6.7	4.6	5.4	14.6	27.8	14.4	8.4	13.4	6.9	1.6	16.9
7	2.8	6.8	3.3	4.1	4.8	12.5	29.3	13.9	11.2	26.8	13.2	0.8	19.4
8	0.3	6.5	3.4	1.7	3.7	11.5	25.5	14.2	6.6	23.6	12.6	0.1	16.4
9	0.2	2.7	2.8	0.7	2.3	9.1	23.6	8.0	3.1	15.6	5.7	0.0	11.0
10	0.5	1.4	0.4	0.3	0.7	8.9	18.3	6.8	1.2	6.2	1.5	0.0	6.9
11	0.4	0.9	0.8	0.1	0.3	3.5	14.4	3.2	0.6	1.2	0.3	0.0	3.8
12	0.1	0.6	0.8	0.3	0.4	2.8	7.9	0.5	0.3	0.3	0.0	0.0	2.1
13	0.0	1.0	0.7	0.1	0.2	0.5	2.7	0.7	0.1	0.1	0.0	0.0	0.9
14	0.0	0.7	0.7	0.0	0.0	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.4
15	0.0	0.0	0.1	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.1
16	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
%	1.8	4.7	5.8	3.2	3.6	12.2	26.9	11.8	6.9	14.8	7.5	0.7	

Figure 10: Bin/Sector occurence table of meteorological icing. The last row and the last column of the table show the percentage icing in each bin or sector.

In the next section follows a similar analysis for the modelled instrumental icing.

4.2 Instrumental Icing

Figure 11 shows a sector frequency plot of modelled instrumental icing and clearly indicated the most severely influenced sector(s) .

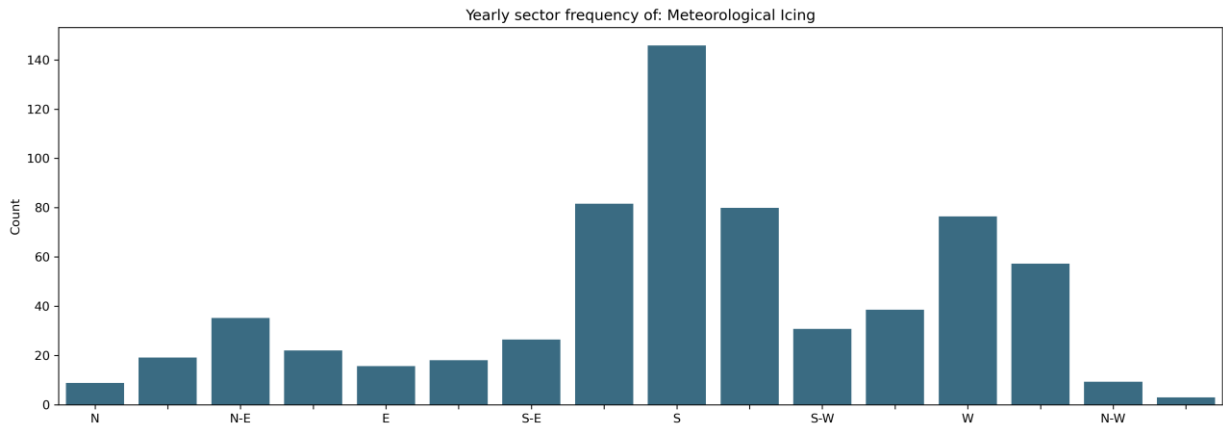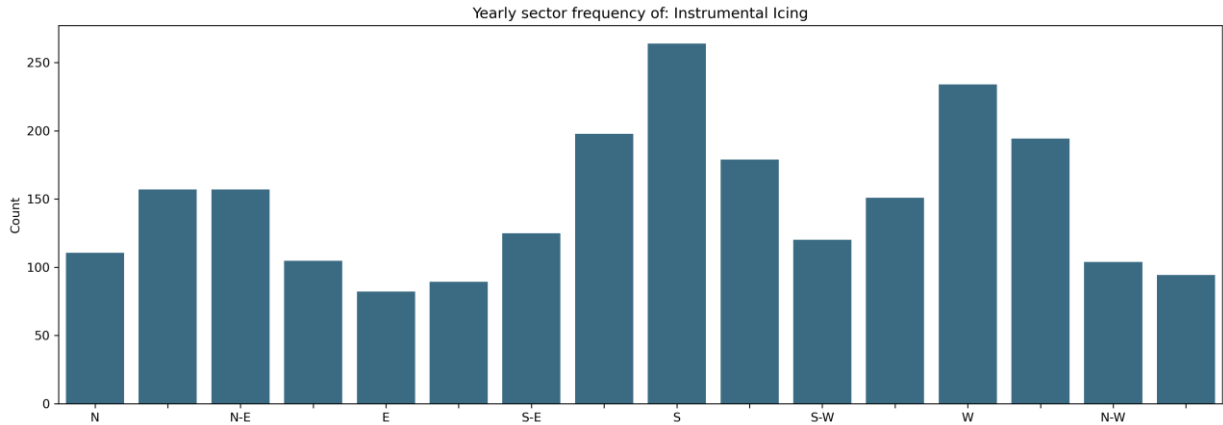*Figure 11: Sector frequency of instrumental over the total number of years.*

The wind roses in Figure 12 show the occurrences of the wind speeds in the 30-degree sectors, where each color denotes a 2.5 m/s interval. The left-hand figures show the distribution for the full period, while right-hand figure shows the directional distribution during the instrumental icing events. From the wind rose the sector wise icing is combined with the wind speed distribution.
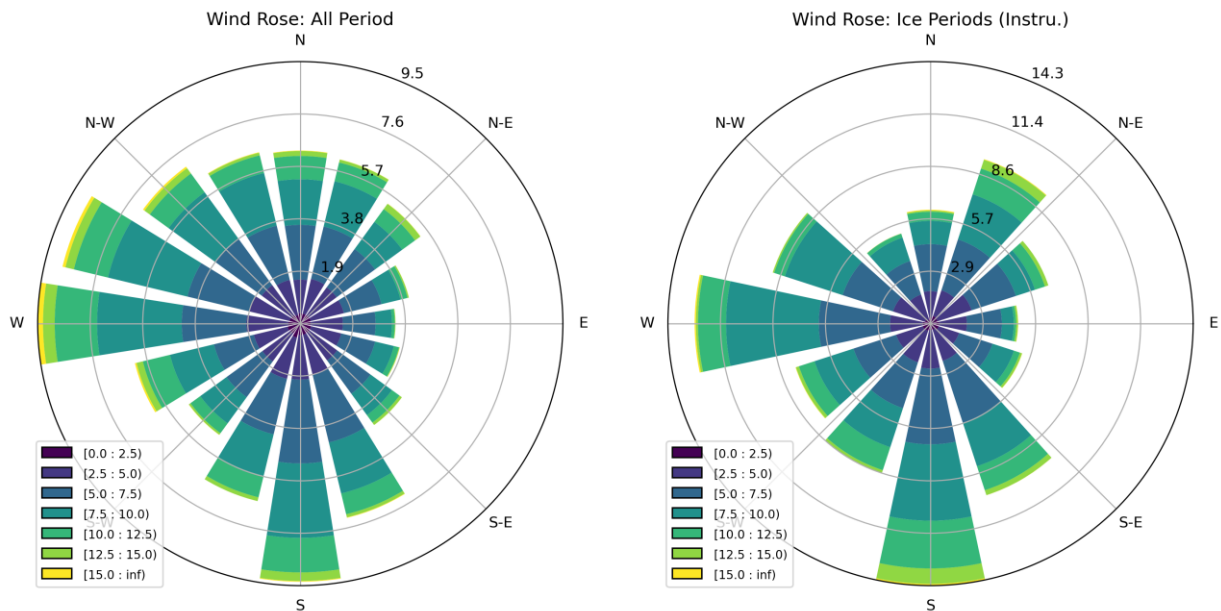

Figure 12: all data and right: only during instrumental icing periods

Next, Figure 13 presents four histograms during instrumental icing. Top two figures compare all data to iced data by numbers of hours (count) and the bottom two shows the normalised percentage of instrumental icing as a function of temperature and windspeed.
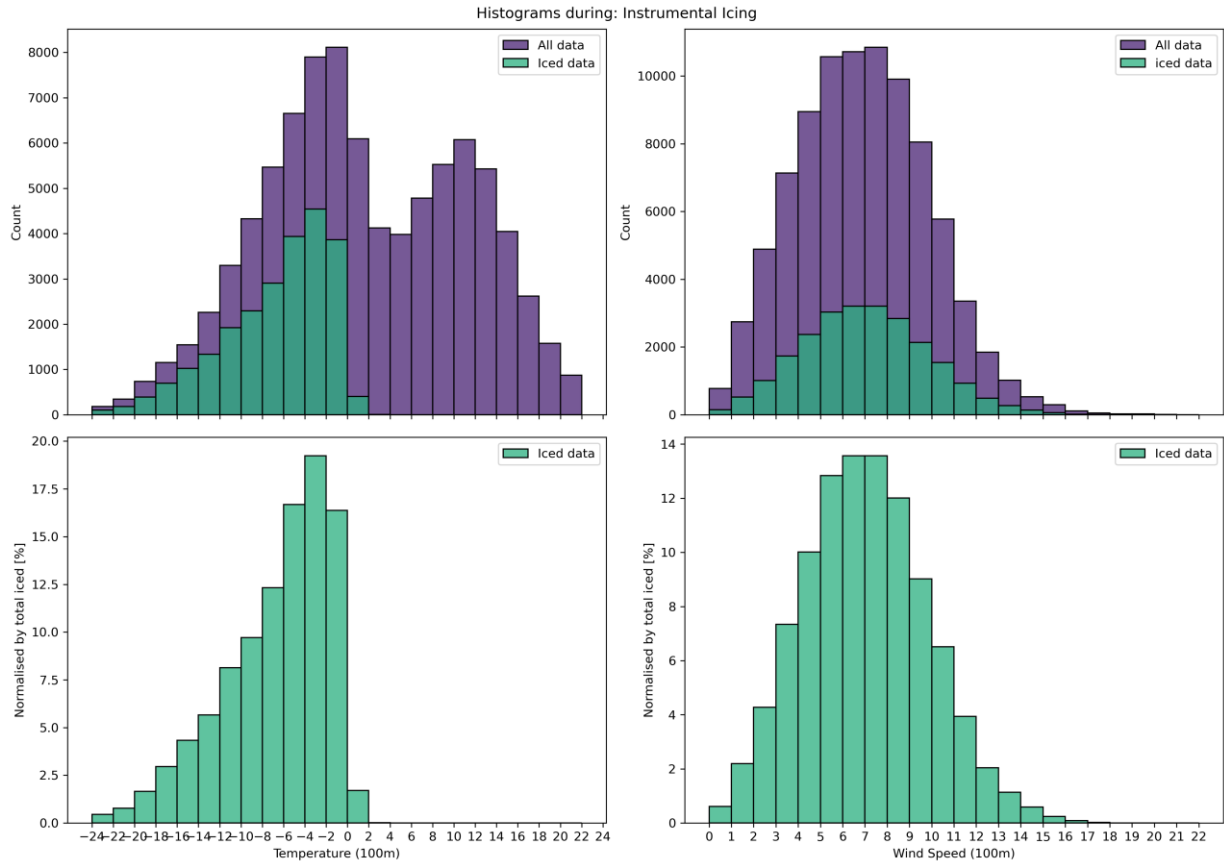
Figure 13: Wind speed histograms during instrumental icing periods. Top two as a function of the number of counts and bottom two, as the normalised percentage (%).

And finally, the instrumental icing analysis is finished by the bin/sector occurrence table, as seen in Figure 14. The table unpacks the results of the wind rose and frequency table during instrumental icing.

Bin/Sector occurence Table of: Instrumental icing (total hours - 2364.9)

m/s - deg	0.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0	330.0	%
0	1.2	1.5	1.4	0.7	1.1	0.7	1.0	1.7	1.6	1.6	0.7	1.2	0.6
1	3.5	5.4	4.3	5.1	4.8	3.4	4.3	5.3	5.1	4.6	3.1	3.0	2.2
2	8.1	7.6	9.0	10.1	9.3	9.8	8.2	6.7	9.3	8.7	9.0	5.4	4.3
3	12.0	11.9	17.1	13.8	10.4	16.2	17.5	17.4	11.9	15.3	16.9	13.2	7.3
4	17.0	18.8	23.8	17.1	13.1	20.4	27.0	21.4	18.7	21.9	21.1	16.6	10.0
5	26.8	24.6	29.9	22.0	16.0	33.1	35.1	24.3	20.0	30.5	21.6	19.6	12.8
6	22.6	30.7	23.8	16.9	19.8	34.5	42.0	28.0	23.1	35.4	27.0	17.2	13.6
7	20.3	29.2	11.8	10.9	17.5	30.9	44.7	21.9	27.5	52.3	36.6	17.3	13.6
8	13.6	26.9	11.4	6.3	13.2	24.7	38.8	25.5	21.8	52.7	35.0	14.1	12.0
9	7.5	18.9	9.0	4.3	7.8	19.9	35.9	15.6	18.2	40.5	26.4	9.2	9.0
10	7.4	16.4	6.4	1.8	4.6	19.1	30.7	16.8	12.0	24.0	10.4	4.3	6.5
11	3.7	13.8	5.6	0.5	2.5	9.2	22.6	12.4	7.5	10.6	4.0	0.7	3.9
12	1.4	8.4	3.1	1.5	2.0	7.2	14.9	3.6	3.2	2.2	0.4	0.4	2.0
13	0.6	5.3	1.8	0.9	1.2	3.0	9.1	1.2	1.5	1.3	0.9	0.1	1.1
14	0.3	3.0	1.2	0.6	0.6	0.8	4.3	0.9	0.9	0.7	0.6	0.0	0.6
15	0.5	0.9	0.1	0.4	0.4	0.2	1.6	0.1	0.4	0.8	0.1	0.1	0.2
16	0.4	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.2	0.7	0.1	0.1	0.1
17	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
%	6.2	9.4	6.8	4.8	5.3	9.9	14.3	8.6	7.7	12.9	9.0	5.2	

Figure 14: Bin/Sector occurence table of instrumental icing. The last row and the last column of the table show the percentage icing in each bin or sector.

5 Icing Maps

For the area shown by the digital elevation map in Figure 1, icing maps have been created. Figures 15, 16 show EMD's Icing Maps colored by IEA Ice class, IEA Ice loss based on meteorological icing. And Figure 17 shows the distribution of Meteorological icing hours for 100m agl. The maps have been created by modelling icing at 15 heights agl and downscaling to the elevations of the digital elevation map in Figure 1. Afterwards the values have been lifted to 100m agl. From windPRO you can access the time-series of modelled icing at 15 heights agl. Furthermore, you can access the icing maps from windPRO and place your wind turbines. All maps are based on the 10 winter seasons covered by: 2009-07-01 to 2019-06-30.
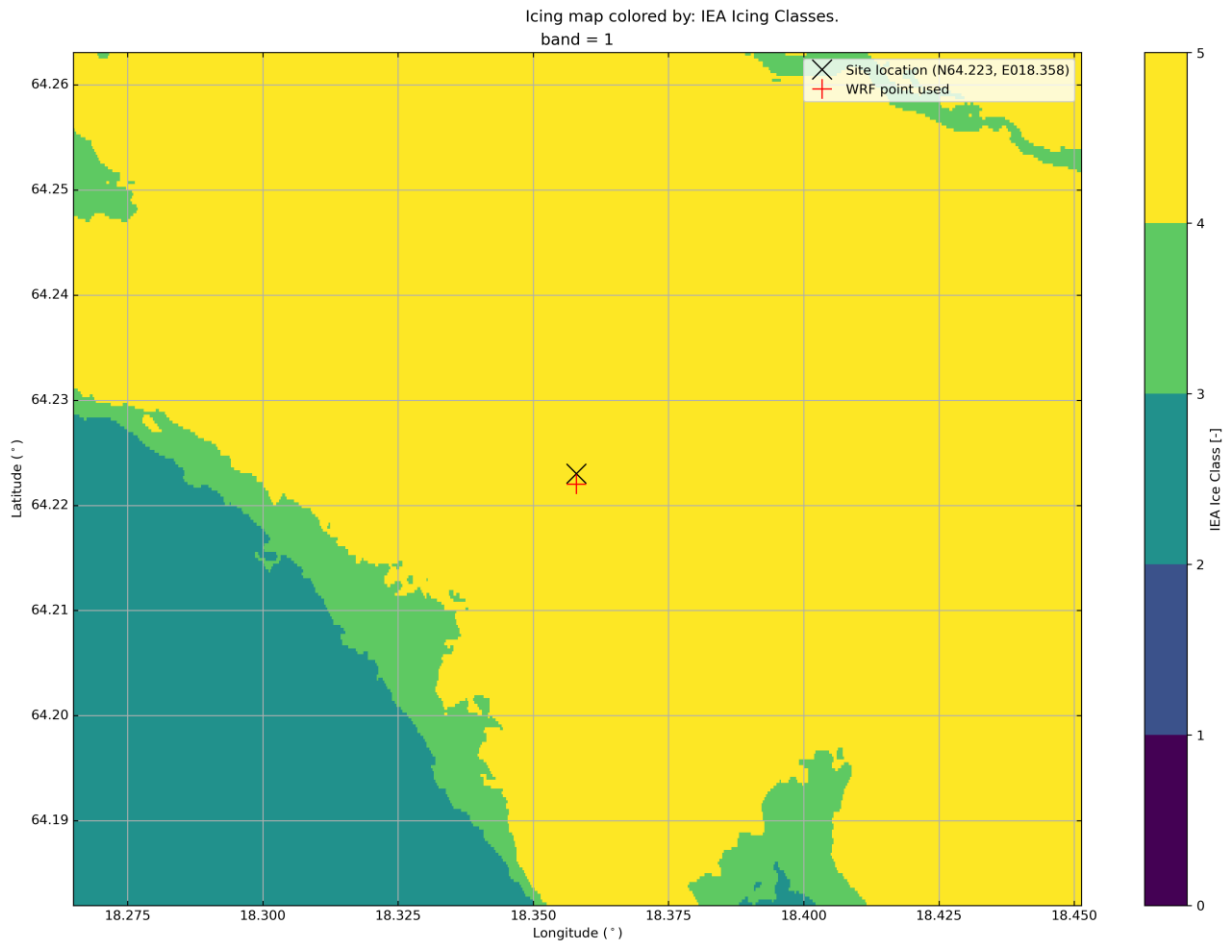.

Figure 15: EMD Icing Map coloured by IEA Ice Class at 100m agl based on modelled meteorological icing.
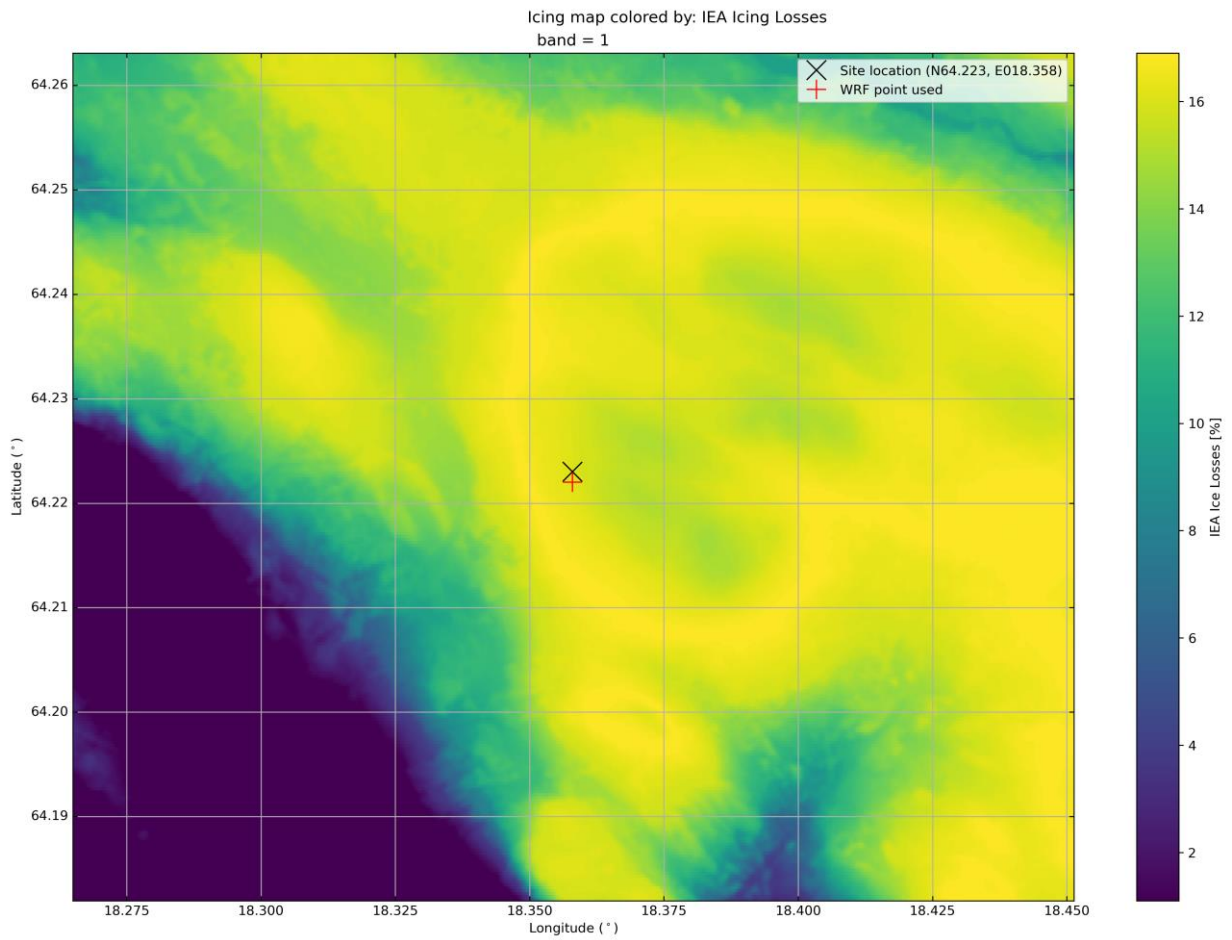
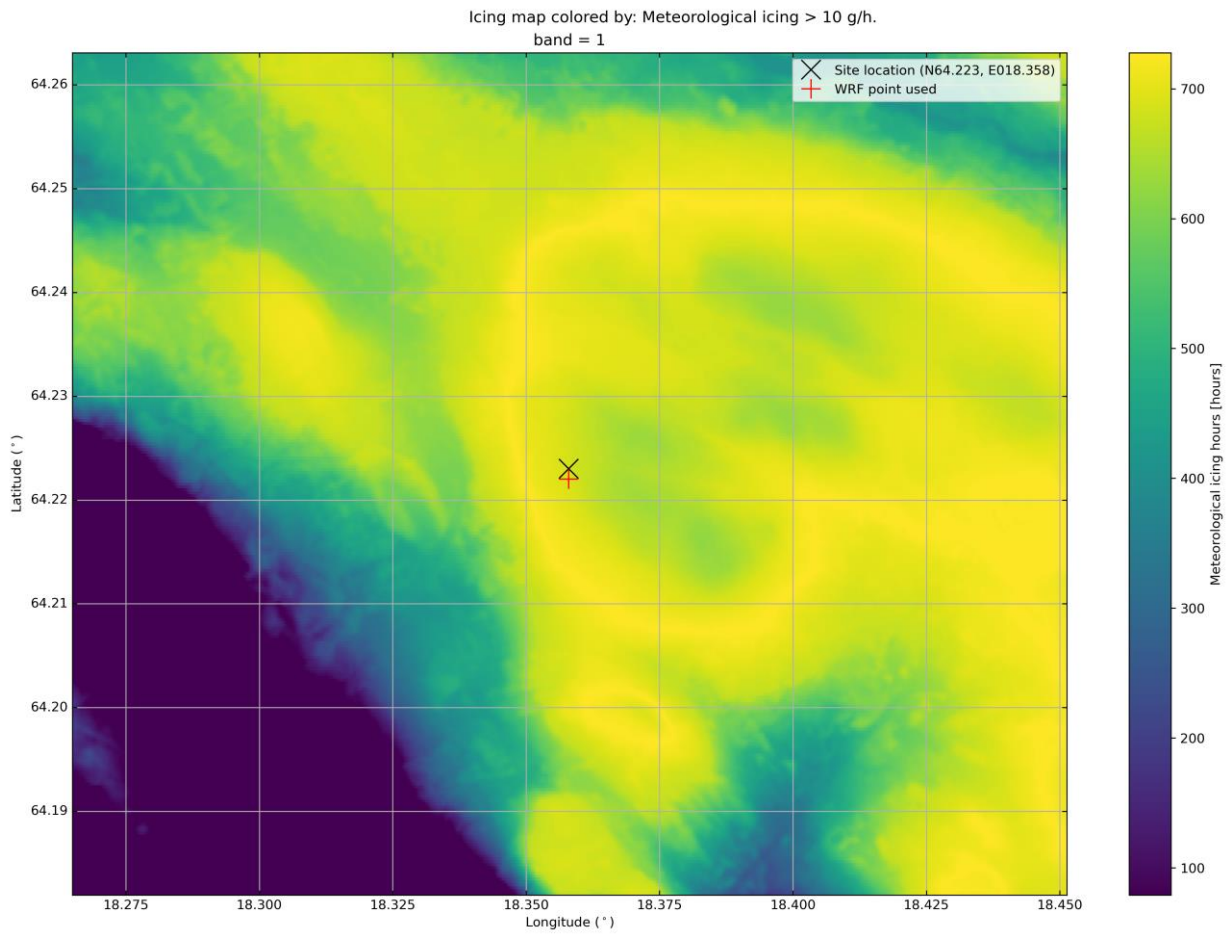*Figure 16: EMD Icing Map coloured by IEA Ice Losses at 100m agl based on modelled meteorological icing.*

Figure 87: EMD Icing Map coloured by Meteorological Icing at 100m agl.

References

[1] EMD, "EMD Online Help - windPRO Knowledgebade," EMD INternational A/S, [Online]. Available: help.emd.dk. [Accessed 31 January 2022].

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Appendix A: Model Data and Configuration

Please also find more on EMD's Mesoscale Wind Data at help.emd.dk[1].

A.1 Mesoscale Data Source

Name:	EMD-WRF OD (icing) Mesoscale Data (driven by ERA5 data)
Spatial Resolution:	3 km
Temporal Resolution:	1 hour
WRF point Location:	Longitude E
	Latitude N
WRF point Elevation:	420.53 m above sea level
Period:	10 years
	(2009-07-01 - 2019-06-30)
Height:	100m above ground level

A.2 Icing Model Setup

Name:	ISO 12494 [2], L. Makkonen 2000 [8] and Makkonen 1984
Main Model Parameters:	Criteria: Meteorological icing > 10g/h
	Cylinder: Diameter ~ 3 cm; Height ~ 100 cm
	Visibility < 500 m
Model Version:	2021-12-01/MCP

A.3 Icing Model Output

The model output and analysis parameters are as follows:

Icing intensity [g/h]:	Modelled icing rate on standard cylinder [2] [8] – dM_{ice}/dt
Ice load (kg/h):	Modelled ice mas on standard cylinder [2] [9] – M_{ice}
Meteorological icing [-]:	Binary signal when Icing intensity > 10g/h
Instrumental icing [-]:	Binary signal when M_{ice} > 10g
LWC (kg/m^3):	Estimated liquid water content from modelled cloud water
MVD (m):	Estimated median volume diameter [10] [11]

A.4 Icing Maps

EMD's Icing Maps are based on modelling icing at 15 heights agl. (from 0 m – 1000 m agl.) using minimum 10 years of mesoscale data (EMD-WRF OD ICING) to create a mean vertical distribution of icing for the site. A digital elevation map (default is the Copernicus DEM-GLO30) is colored by interpolating in the modelled icing distributions. Afterwards the values are lifted to actual height of interest – for this report: 100m agl.
EMD's Icing Maps are available in windPRO for more interactive use.

Based on:	Meteorological Icing
Icing maps values:	IEA Ice Class, IEA Ice Losses and modelled Meteorological Icing hours
Modelled heights:	[10, 25, 50, 75, 100, 150, 200, 300, 400, 500, 600, 700, 800, 900, 1000] m agl.
Height (hub height):	100m agl. (in windPRO 100 m, 150 m and 200 m)