Validation of remote sensing methods for ice detection

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1 Introduction

Installing wind turbines in cold and icing climates is growing rapidly mainly due to good wind resources at low population density areas. . According to a recently published market study done by IEA Wind Task 19, the cumulative size of cold climate wind markets were 127 GW by end of 2015 and is expected to further grow with an annual growth rate of 12 GW up to 2020 representing a market segment three times the size of offshore wind power (Table 1). [1]
However, cold climate introduces special challenges for the turbine operation, one of which is ice accretion on the wind turbine blades. Ice on the blades causes production losses due to reduced aerodynamic performance of the blades. Falling ice can also cause health and safety risks in cold climate sites.
The large number of installations in exisiting and future cold and icing climates means that there is need for better method for ice detection and icing condition assessment.

Table 1: Cold Climate wind power market size [1]

Cumulative installed capacity by end of 2015 [MW]		Forecasted capacity by end of 2020 [MW]	
Low temperature	Icing	Low Temperature	Icing
40 500	86 500	62 500	123 000
Total 127000		Total 185500	

2 Icing terminology

Icing is divided into two categories: meteorological and instrumental icing [4]. Both are measures of time. Meteorological icing refers to the time during which meteorological conditions are favorable to icing, there is liquid water and temperature is below zero Celsius. Furthermore, meteorological icing can be either in-cloud icing, or freezing rain. In-cloud icing refers to events where structures or instruments (or wind turbine blades) come to contact with cloud droplets allowing ice to form. Freezing rain refers to events where rainwater freezes on impact with structures, causing ice to form. The remote sensing methods discussed here are used to detect in-cloud icing. [2]

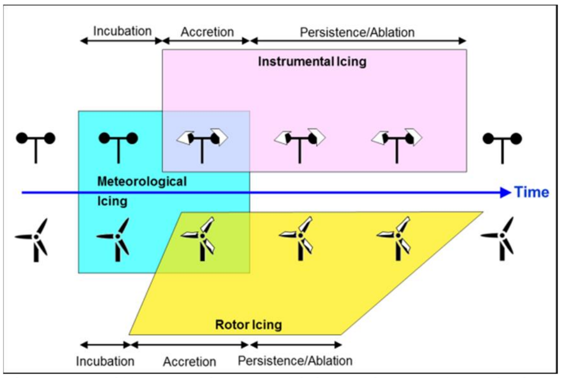

Figure 1: Different phases of icing relevant for wind power [3]

Instrumental icing refers to the time ice stays on the instruments (by definition an unheated cup anemometer) once it has started to form. Once accreted, ice will eventually disappear from instruments and structures due to melting, sublimation wind erosion or mechanical shedding. Instrumental icing is used to describe the time there is a detectable amount of ice on the measuring instrument. [2]

Figure 1 illustrates a typical icing event, from the start of meteorological icing to the end of an instrumental icing event. Also important detail in Figure 1 is the fact that icing time of instruments is slightly different form icing time of wind turbine rotor.

Instrumental icing measurements are most often done by comparing the outputs of heated and unheated anemometers. Ice forming on the unheated instrument will slow down the rotation of the anemometer causing wind speed readings to fall. Comparing the wind speed measurements allows the use of these wind speed measurements as an indicator of instrumental icing.

It is also possible to use a wind turbine to estimate instrumental icing. The idea behind the so called rotor icing is to compare the output power of the turbine with a reference calculated based on the turbine power curve. Ice building on the turbine blades changes the blade aerodynamics and reduces the amount of power the rotor is able to produce at a given wind speed. If the turbine output power drops substantially in sub-zero conditions, this can be used as evidence of icing. It is important to note that rotor icing duration is typically different (shorter) to instrumental icing. [3] [6]

Of the measurement methods used in this study the remote sensing methods measure meteorological icing and all other used methods measure instrumental icing.

2.1 IEA ice classes

IEA Wind Task 19 has defined site ice classification (Table 2) that can be used as a tool to compare measures of instrumental and meteorological icing. The classes can be used here as a minimum requirement for accuracy of different methods. If the remote sensing method is able to correctly determine the ice class, it can be used for site classification. [4]

Table 2: IEA ice classification [4]

IEA Ice Class	Duration of Meteorological Icing [% of Year]	Duration of Instrumental Icing [% of Year]	Production Loss [% of AEP]
5	>10	>20	>20
4	5-10	10-30	10-25
3	3-5	6-15	3-12
2	0.5-3	1-9	0.5-5
1	0-0.5	<1.5	0-0.5

3 Remote detection of icing

3.1 Benefits of remote sensing

Icing is difficult to measure directly. For wind turbine applications, a perfect icing measurement would cover the area of the entire rotor, not just measure at e.g. nacelle level. As turbines get larger and larger, the distance between top of nacelle and the highest blade tip height keeps getting larger and larger. Cloud conditions can and do change in that distance, it is possible that the blade tip is covered in clouds but the nacelle is not [7, 8]. In these cases measuring at nacelle height will give misleading results.

Even in site assessment phase measuring at different heights has many benefits. The icing conditions do change as a function of height and knowing this icing profile is very useful in determining the actual icing conditions of the site as related to the turbines that will be installed. Looking at the icing profile, the effects of different tower heights and turbine heights too the actual observed icing conditions at turbine tip level can be seen easily.

As turbines get larger and larger having icing measurements done from a mast at turbine blade tip height will at some point become prohibitively expensive. A ground based remote sensing solution would not require mast construction so it is easy and quick to set up and move from location to location.

3.2 Remote sensing method

The goal of remote ice sensing is to be able to remotely identify in-cloud icing conditions. This is done by using optical equipment to monitor the cloud base height and use that measurement and outside temperature measurements as a proxy for icing conditions.

The cloud measurement can be done using a ceilometer (a remote sensing device designed for detecting clouds and height of cloud base) or using VTT developed method for a standard wind LIDAR. [5]

Both of these methods are based on the same principle: the ground based device shoots a laser vertically upwards and measures the strength of the signal reflected back. By observing the intensity of this so-called backscatter signal it is possible to pinpoint the height of a more dense substance in the air. This can be used as an indicator of clouds in the air (see Figure 2 for a simplified explanation). The underlying assumption is that there is liquid water in clouds. When these droplets of liquid water hit a surface in sub-zero temperatures, ice will form on the surface. [5]

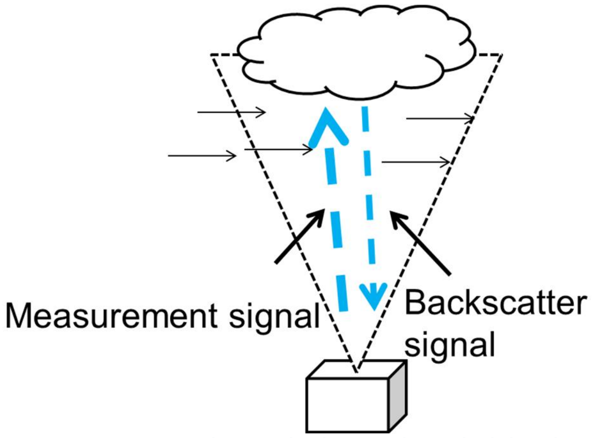

Figure 2: Remote sensing method operating principle. The strength of the backscatter signal indicates the presence of a cloud.

This kind of remote sensing allows for determining whether or not the conditions are favorable for icing or not, it does not allow for measuring the actual mass of ice building on structures such as instruments or wind turbine blade.

Because of this the output of the remote sensing method is a binary indicator signal that tells whether the conditions are icing or not. This signal can then be used to calculate icing times or to estimate conditions at a site based on how much icing there was on the site during the measurement period. Knowing the icing hour count or the fraction of time how long the site has had meteorological icing makes it possible to classify sites based on IEA Ice Classification according to the site specific icing conditions.

4 Dataset

The extensive dataset consists of four separate datasets from three different countries containing Ceilometer and wind LIDAR measurements, wind turbine production data, and other meteorological measurements including temperature, wind and icing measurements. The wind measurements contain data for heated and unheated anemometers.
The goal is to asses icing at all sites and to compare the measurement accuracy of the remote sensing methods with instrumental icing measurements (selected as the reference ice measurement method) gathered by comparing heated and non-heated anemometers and to an ice sensor that measures ice mass on a rotating cylinder.
Details of the dataset are assembled in Table 3.

Table 3: Data used for the analysis

Site	Country	Instrumentation	Time period
Site A	Finland	• Vaisala CL31 ceilometer • Wind turbine • heated/non-heated anemometers [100 m agl]	Dec 2015-Apr 2016
Site B	Germany	• Leosphere WindCube LIDAR • Jenoptik/Lufft CHM 15K • Heated/nonheated anemometers [190 m agl] • webcam	Oct 2012 – Feb 2014
Site C	Norway	• Leosphere WindCube LIDAR • Combitech IceMonitor ice detector [90 m agl] • webcam	Jan 2012-Jun 2014
Site D	Finland	• Leosphere WindCube LIDAR • Vaisala CL31 Ceilometer	Fed 2016-Jun 2016

The 10-minute values could not be compared directly, so some pre-processing was needed. A ceilometer gives a measurement of the cloud base height and requires a temperature as an input to produce an icing alert. The temperature is not read at the cloud height so the temperature reading is corrected by assuming that air temperature drops 0.65K / 100m.
Temperature measurements were done at 100m on site A, sensor was at wind turbine nacelle, at site B the temperature measurement was at 187 meters in a met mast and at site C and D the temperature measurements were done at ground level.

The LIDAR based method gives an estimate of the cloud base height, but with a more rough resolution at pre-defined elevations above ground level. The backscatter signal analysis will be used to estimate cloud base height on one of these pre-defined measurement heights..

A ceilometer can be used instead of a wind LIDAR using a similar approach. A ceilometer provides cloud base height measurements on a sliding scale with a higher measurement range than the wind LIDAR. The ceilometer can also give an estimate of cloud thickness, which can be useful in some cases.

The Combitech Icemonitor ice sensor on site C measures ice mass on a cylinder. From this signal, it is possible to construct both instrumental icing signal (ice on the cylinder) and a meteorological icing signal (mass is growing). This meteorological icing signal does not represent the entire meteorological icing event; it only contains the accretion part but not the incubation period (see Figure 1). Both of these were then compared to the output of the remote sensing icing detection method.

The instrumental icing signals on sites A,B and C were built comparing the wind speed measurement of an unheated cup anemometer to the wind speed reading of a heated anemometer. If the output of the cup anemometer was below 80 % of the output of the heated anemometer, it was assumed that the anemometer is iced if temperature was also below zero at the same time.

Icing has a detrimental effect on wind turbine aerodynamics by decreasing lift and increasing drag [9]. Ice accretion on the turbine blades causes the turbine to produce power in a sub-optimal way. This drop in output power can be used for ice detection. The wind turbine warning signal is produced by comparing output power to a reference power curve and controlling for outside temperature. The IEA Wind Task 19 “T19IceLossMethod” software was used to analyse the output power and if the turbine drops below the 90th percentile (the so called P90 value) of the reference (non-iced) power curve for at least 30 minutes, there is enough ice on the blades that it starts hindering the turbine operation and for a positive rotor ice detection signal. [6]

5 Results

5.1 Overview of the data

All different icing signals were converted into a set of binary on-off type signals on a ten-minute interval. The actual analysis of the icing alarms was done by comparing these time series for each

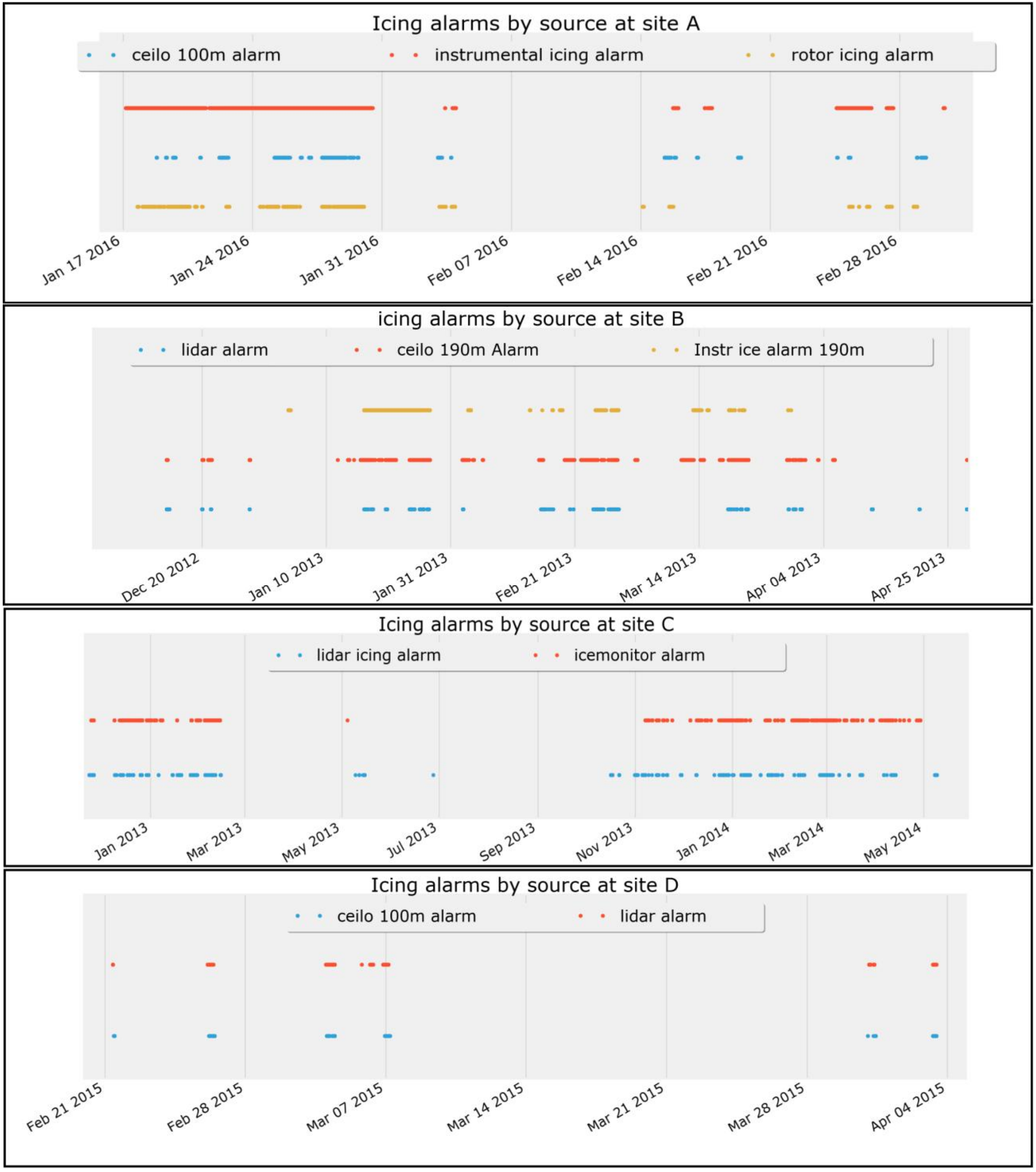

Figure 3: Timeseries plots of alarm signals at all sites

site separately. The data and different icing alarms are illustrated in Figure 3

The best option available was to see if different measurement methods lead to similar icing condition assessment for any one site in terms of IEA ice classes.
The direct correlation of the measurements was analyzed. The goal was to see if there is a clear correlation between icing times for specific time periods.

From the meteorological and instrumental icing data, it is possible to analyze the other ambient conditions during icing events. Especially interesting are wind speed, air temperature and LIDAR availability during instrumental icing events. These give some insight into how reliable the remote sensing methods are and also to assess typical icing events at different sites.

5.2 Data availability

Wind LIDAR measurements in all observed datasets had relatively low data availability. The graphs in Figure 4 and Figure 5 illustrate this problem at two of the sites. In both cases the wind LIDAR availability drops to a very low level especially at larger measurement heights. The availability increases noticeably during instrumental icing events.

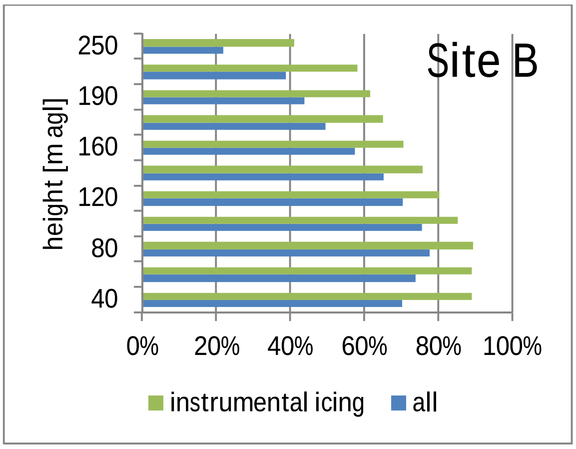

Figure 4: LIDAR availability at Site B through the entire dataset and during observed instrumental icing.

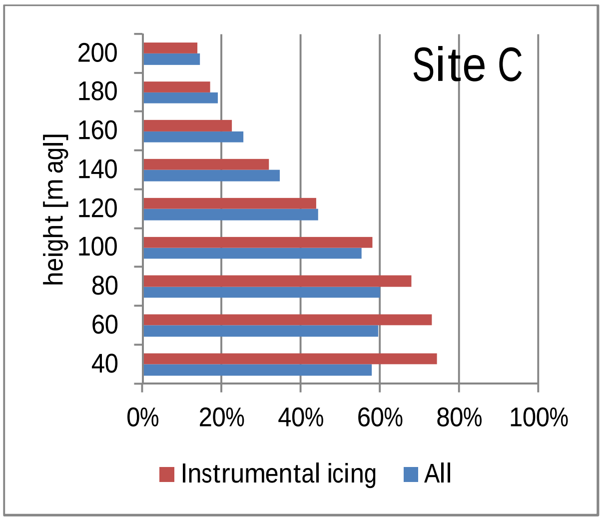

Figure 5: Lidar Availability at site C during observed instrumental icing and through the entire dataset

Wind LIDAR measures wind speed at a faster sample rate and then calculates an availability number based on the amount of successful measurements during a ten minute period. For the availability graphs in Figure 4 and Figure 5 the availability was filtered using an 80 % threshold. Meaning 10 minutes samples where the success rate of measurements was less than 80 were discarded.
At site C the reference icing measurement was done using an ice sensor located at approximately 90 meters higher than the LIDAR. In this case the increase in availability is small and it only happens below this level. At site B the instrumental icing reference was an unheated anemometer at 140 meters and there the increase in availability is clearly visible at all heights.
The ceilometer has in general a higher availability then the wind LIDAR used. The ceilometer data availability remains unchanged during icing events. Ceilometer takes a measurement every minute so for the sake of comparison a similar 80 % threshold was used for ceilometer as well. Table 4 illustrates this. Ceilometer did not suffer from any availability issues during the test period.

Table 4: Ceilometer availability compared with wind lidar availability at one height

Site	Height [m]	Ceilometer availability	Ceilometer availability during icing	Wind LIDAR availability	Wind LIDAR availability during icing
Site A	100	98 %	99 %	-	-
Site B	140	99 %	99%	57 %	68.3 %
Site C	90	-	-	55.3 %	58.1 %
Site D	100	100 %	-	80 %	-

5.3 Conditions during icing events

Figure 6 and Figure 7 presents the concurrent wind speed and temperature conditions during instrumental and meteorological icing conditions. From Figure 6 it can be seen that majority of icing events occur at low wind speeds and at temperatures close to -5 C. As expected, sites A and B show clearly lower temperatures for instrumental icing than meteorological icing. This is because instrumental icing includes the meteorological icing durations and is followed by an ice ablation period that might be in colder temperatures. From a wind power perspective this is a mildly positive thing: the icing events happen at times when the expected production is low, so the economic impact of potential production loss is smaller. On the other hand, ice build-up on turbine blades might cause the turbine to not produce enough torque at low wind speed thus preventing the turbine start-up all together.

There is also a clear difference between the shape of the wind speed-temperature distribution between site C and the two others. This is due to different measurement method. Site C uses a dedicated ice sensor and there instrumental icing is simply defined as a period in time when the ice sensor gives a reading for the ice mass. On the other hand, at sites A and B instrumental icing is calculated using anemometers.

Ceilometer measurements also give an estimate of the average cloud thickness for two sites. Mean cloud thickness was 368 m for site A and 551 m for site B.

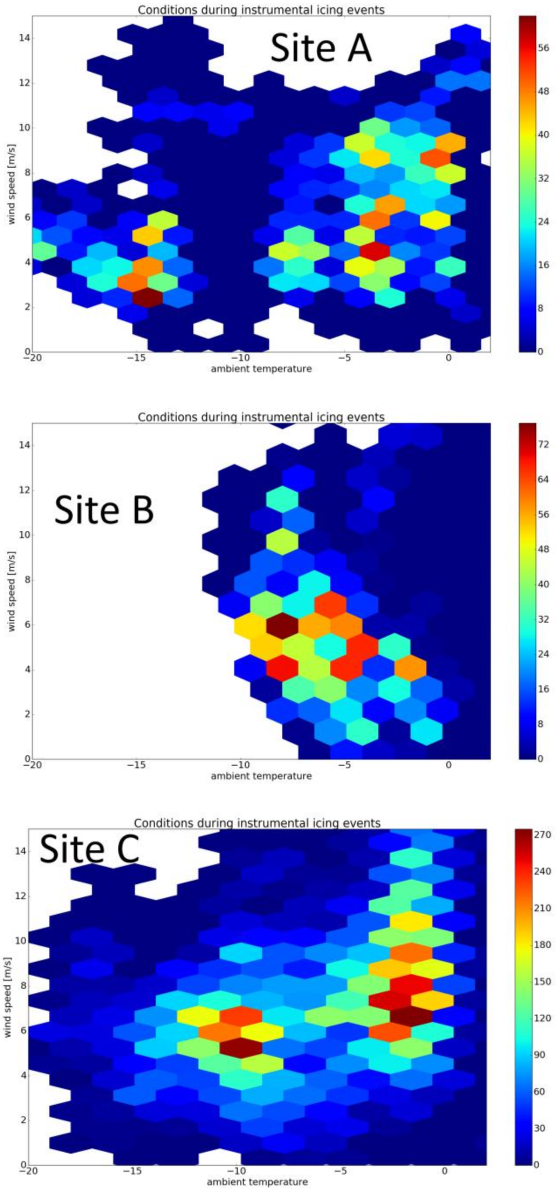

Figure 6: Conditions (Wind speed and temperature) during instrumental icing at different sites. The colors represent the number of measurements in each bin

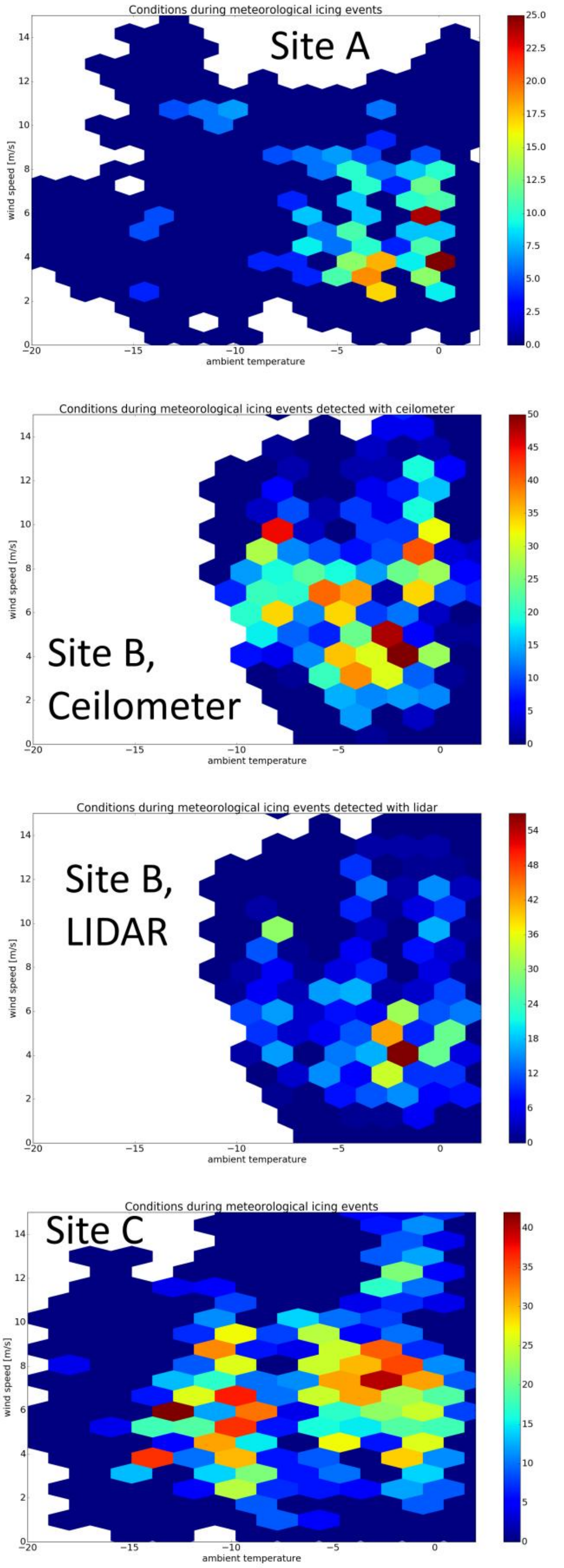

Figure 7: Wind speed and ambient temperature during meteorological icing events. The colors represent the number of measurements in each bin

5.4 Icing duration and ice classification

The overall icing duration is calculated from different sources and an IEA ice classification is derived for each site. Ice classifications are collected into Table 5

Table 5: IEA ice classes for different sites. Ice class only defined for sites with more than one year of data.

Site	Meteorological icing from Ceilometer [% of time]	Meteorological icing from wind LIDAR [% of time]	Instrumental icing [% of time]
Site A	5 %:	-	11.2 %:
Site B	3 %: Class 2 (Ceilometer)	1.8 %: Class 2 (LIDAR)	3.8 %: Class 2
Site C	-	2 %: Class 2	14.9 %: Class 3
Site D	1.6 %:	2.0 %:	-

The data collected from different sites covers a different timeframes. The IEA ice classification is defined as percentage of a year, but in some cases there was not a full year of data. In that case the figure is percentage of the total data.
The site IEA ice classification from remote sensing methods and instrumental icing result to the same class except at site C. It is possible that the low availability at site C contributes to this difference. Calculating the meteorological icing from the ice sensor at site C gives a value of 4.4% of meteorological icing, which would put the site in icing class 3. Meteorological icing here is defined as all the periods when the ice mass on the sensor is growing.

5.5 Correlation between icing measurements

Two sites had both a wind LIDAR and a ceilometer, so for these two datasets we can count a direct correlation between two remote sensing methods. The correlation coefficient was r=0.66 on site D and r=0.36 on site B.

Due to differences in measured variables (one meteorological, one instrumental icing) the different measurements could not be compared directly. Even though the different sensors measure different things, they are still both affected by the same phenomenon; therefore it was assumed that a statistical correlation exists between the meteorological icing and the instrumental icing measurements.

The statistical relationship between the two different icing measurements over a longer time frame was analyzed. At this point the application in interest is assessment of site icing conditions and for that purpose correlation over a longer time period is assumed acceptable.

The R^2 correlation between remote sensing based meteorological icing and cup anemometer based instrumental icing was tested by increasing the sampling rate of the time series by increments and calculating then the correlation coefficient between the two variables. The resampling was done by increments of 1, 2, 4, 12, 24 hours and the 5, 10, 15 and 30 days (Figure 8).

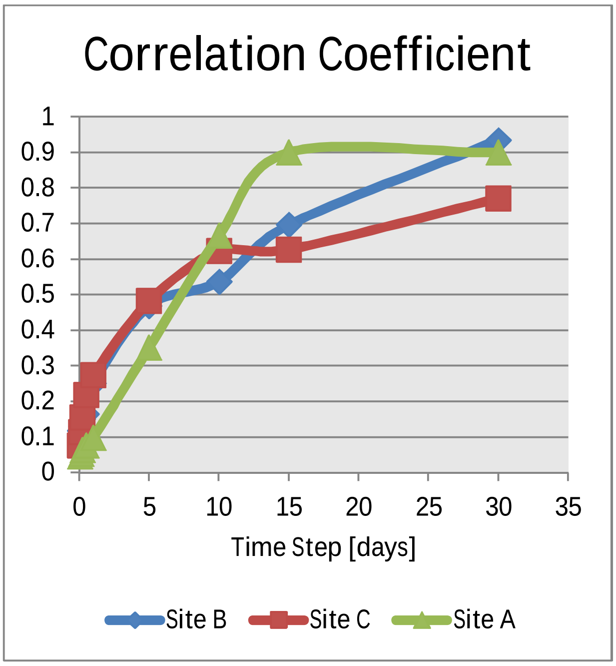

Figure 8: R^2 correlation coefficient between meteorological icing measured with remote sensing instrument and instrumental icing at different sites

From Figure 8 it can be seen that the two variables start to correlate only after the time step is several days long reaching highest correlation values for time increments on 30 days for all sites.

6 Discussion and future improvements

The main challenge with the validations presented is that in all cases, the comparisons were made between meteorological and instrumental icing. The relationship between meteorological and instrumental icing depends on icing conditions and the instrument used to measure the instrumental icing in general.

Ice can be removed from instruments because of melting wind erosion, sublimation, and mechanical shedding. In practice it is always a combination of several factors. How quickly ice builds up and how quickly ice is removed depends on ambient temperature and wind speed. The conditions during and after the meteorological icing event, when the ice builds on the instrument, have an effect on the length of the instrumental icing events. This introduces variability into the duration of the instrumental icing events and finding correlations between the two different icing phenomena can become challenging.

There are two easily identifiable sources of inaccuracy in the measurement dataset chosen for this study: 1) data availability of the optical measurements and 2) cloud composition.

The first, data availability is a known challenge for LIDAR measurements, if atmospheric conditions are not suitable (fog, snowfall, not enough particles in the air for the laser to reflect back), the results are shown as gaps in the data. Especially in remote sites in Northern Scandinavia with clean and clear skies, LIDAR measurement availability can be quite poor. And it is possible that the availability issues cause gaps to the data during icing conditions. This will lower the estimates of meteorological icing durations produced by the remote sensing method to some degree.

Second issue with cloud composition is related to the fact that clouds do not contain 100 % liquid water at sub-zero temperatures, a pre-requisite for ice formation on structures. Some clouds might have large portions of ice crystals not resulting to ice growth. High cloud ice crystal amounts are possible, especially in colder weather. The remote ice detection method flags these conditions as in-cloud icing and can result to false positive icing alarms.
This poses a challenge as detailed cloud composition data is very hard to obtain as commercially available liquid water content sensors are missing. A detailed cloud composition would require measuring the droplet distribution of the cloud or knowing is the ratios of ice and water contents.

7 Conclusions and future work

The analyzed remote sensing method for icing detection using a ceilometer shows promising results and is able to determine the IEA ice class correctly on a long-term average level in two of the three observed datasets. In short-term time sampling correlation analyses, good results are achieved when estimating meteorological icing durations on a monthly level. One clear benefit of the remote sensing ice detection method is that it also gives an indication how icing conditions at the site change as a function of measurement height (relevant for large modern turbines with high hub heights and large rotors), which can be expensive and challenging to perform using a traditional met mast approach. There are still some challenges in the remote sensing method impacting its accuracy mainly concerning data availability and missing information on detailed cloud composition regarding liquid water content and droplet size distribution.

Remote icing detection can be done using either ceilometer or a standard wind LIDAR, out of these two the ceilometer is shown to be more accurate and reliable.

The availability issues with wind LIDAR can be addressed by changing the method used to generate the alarms. We could assume that average cloud thickness is large enough to cover the measurement range of the LIDAR. This will increase the availability significantly.

The biggest challenge in the approach used in this study is not related to the reliability of the selected remote sensing technologies but to the missing measurements of reliable, reference meteorological icing. The validations performed in this study were done via proxy; comparing meteorological icing to instrumental icing durations. In order to improve the results, an “apples-to-apples” comparison of different methods of meteorological icing detection would be needed.

The sensitivity to ground-based temperature threshold should be addressed; the used assumption of 0.65K/100m is only valid for neutral atmospheric stability.

As future work to further assess the accuracy of remote sensing methods for icing detection, reference meteorological icing measurements or cloud composition regarding liquid water content are needed and methods to increase data availability are to be investigated. Also comparison of the remote sensing icing detection method to turbine output power data and rotor icing durations can be used to assess the method accuracy further.

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