Sensitivity study of important parameters for icing modelling and measurements

Elforsk report 13:14

Peter Schelander and Johan Hansson

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Preface

Wind power in cold climate requires good knowledge of the risk of icing, which in turn can cause production losses and problems for the environment. Within Vindforsk III the project V-313 has studied methods for ice-mapping. The methods used in V-313 rely on modeling of meteorological parameters, as e.g. wind, liquid water content and droplet size, and then using a semi-empirical formula for calculating ice accretion.

In comparing the calculated ice accretion with measurements, errors in the calculation can stem from both the modeling of meteorological parameters and from the semi-empirical formula. The lack of suitable methods of measuring liquid water content and droplet size is however a problem in making comparison of calculated and real values of these parameters.

Project V-359 was therefore started with the research program Vindforsk III to propose a plan, for verification measurements of the interim result achieved from the first modelling of meteorological parameters.

The project has been carried out by Peter Schelander and Johan Hansson at Vattenfall Power Consultant. The final report writing has been carried out by Peter Schelander, now at Pöyry SwedPower.

This is the final report from the project V-359.

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Sammanfattning

Vindforsk finansierar ett projekt (V-313) vilket har som mål att generellt öka kunskapen kring hur vindkraftsanläggningar eller enskilda verk påverkas i regioner med kallt klimat och nedisning. I detta åtagande ingår att ta fram metoder för en iskartering utifrån numeriska vädermodeller. Detta görs genom att koppla två modeller, en för modellering av meteorologiska parametrar och en för den ispåbyggnad som uppstår som följd av den första modellens resultat.

Målet med denna studie är att specificera behovet, och att föreslå en mätplan för verifieringsmätningar av resultatet efter det första (meteorologiska) modelleringssteget. Om osäkerheten är stor hos inparametrarna till andra modellen kommer givetvis slutresultatet att vara än mer osäkert. Likaledes, om en specifik utparameter från första modellen har stort inflytande på slutresultatet måste extra vikt läggas vid dess noggrannhet och den resulterande osäkerhet som den bidrar till. Detta undersöktes genom en känslighetsanalys.

Känslighetsanalysen påvisade att vindhastigheten har störst inverkan på den modellerade ispåbyggnaden, medan temperatur och lufttryck är av underordnad betydelse.

Vidare påvisade känslighetsanalysen att antagande om droppstorleksfördelning och luftens innehåll av flytande vatten kan vara av vikt för den modellerade ispåbyggnaden. Det beror, för studiens standardnedisningsobjekt [1], helt och hållet på vilka värden dessa två storheter antar under de nedisningsförhållanden som typiskt råder på den plats som undersöks. Om variationen under ett nedisningstillfälle är stor finns det ett behov att förbättra precisionen på indata till ismodellen.

En mätplan har tagits fram med målsättningen att öka kännedomen om den tidsmässiga variationen av droppstorleksfördelningen och luftens innehåll av flytande vatten. Detta kan göras genom en indirekt metod genom att använda tre islastgivare med olika cylindriska dimensioner. Ledtid för att ta fram den utrustning som behövs är skattad till mindre än sex månader. TV-masten söder om Sveg, vilken redan nu används för ismätningar föreslås primärt som installationsplats.

[1] Standardnedisningobjektet är en 0,5 m lång roterande cylinder med 30 mm diameter [ISO 12494:2001].

Summary

Vindforsk is financing a project (V-313) with the aim to increase the general knowledge of how wind turbines perform in regions exposed to low temperatures and icing. Included in the task is the development of a methodology for mapping of icing. This is done by coupling two numerical models, one modelling meteorological parameters and one where the ice accretion resulting from the output of the first model is calculated.

The aim of the present study is to specify the need, and propose a plan, for verification measurements of the interim result achieved from the first model. If uncertainties are large for the output parameters from the first model the end result will naturally be even more uncertain. Likewise, if the influence from one specific output parameter is large, this calls for particular attention for accuracy and knowledge of the resulting uncertainty. This is investigated through a sensitivity analysis.

Through the sensitivity analysis it was concluded that the wind speed is the most important variable in the modelling of ice growth while temperature and pressure are of minor importance.

It was further found that droplet size distribution and liquid water content of the air could be very important. For the standard sized object[2] used for ice load observations referred to in this study, it all depends on the range of values that the two parameters can attain during typical Swedish icing conditions. If the variability between weather situations is small, approximate numbers can be used in the ice load modelling without significantly affecting the quality of the result. If the variability is large, however, there is a strong need for improving the input data for the ice load calculations.

A measurement plan was proposed aiming in increasing the knowledge of the time variability of droplet size distribution and liquid water content. A possible solution would be to use a minimum of three ice load sensors with different cylindrical dimensions. Lead time for preparing the necessary modifications to existing equipment is estimated to six month. The Sveg high (323 m) TV mast is the primary proposed installation site.

[2] The standard sized object is a 0.5 m vertical and rotating cylinder with a diameter of 30 mm [ISO 12494:2001].

Innehåll

1 Introduction

Prediction of icing on wind turbines will be used for different purposes. The first, and likely the most important, is the financial investment decision. Wind farms planned in northern Sweden, with typical installed capacities of 50 - 100 MW, render an investment on the order of 1 billion SEK[3]. Future large wind farms will require an investment one order of magnitude larger than that. This initial investment is balanced by the income from power production over 2-3 decades. A miss-prediction of the impact of icing on production may therefore lead to either an underestimated project value or underestimated production. It is thereby of interest for both project developers and wind farm owners to understand the risk and uncertainty involved in the prediction of icing of structures.

Secondly, predicted icing will also be an important factor in the process of choosing the most suitable turbine for a site. The climate at the site is a crucial fact to the optimal choice of turbine. Miss-predictions at this stage may lead to unnecessary additional investment costs, lost production and risk of additional unexpected wear on the turbine.

As indicated above, prediction of icing becomes important during different phases of the development and operation of a wind farm. Thus, most actors within the industry, like project developers, turbine suppliers and wind farm owners will be some kind of ‘end users’ of an icing prediction and benefit from a better understanding and more accurate prediction of icing on turbines.

1.1 Objective

V-359 is intimately connected to V-313. A brief description of V-313 is therefore necessary to fully understand the purpose of V-359.

The objective of V-313 is to increase the general knowledge of how a wind farm or a wind turbine performs in regions with cold climate and icing. Included in the task is the development of a methodology for mapping of icing. This is not a straightforward task and the uncertainties in the end result are considerable. The main objective of V-359 is to help reduce the uncertainties in the development of the icing-mapping methodology in V-313. A spin off is that V-359 will put the spotlight on the difficulties and uncertainties in ice modelling.

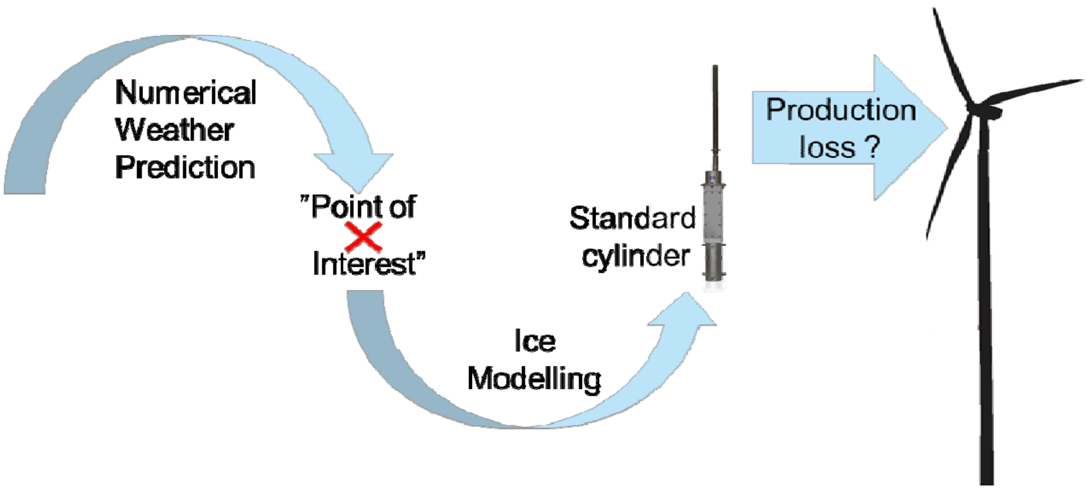
In brief, the scope of work outlined in V-313 is as follows:

1. A numerical weather prediction model (NWP-model) is used to model the weather over a region.
2. The output from the NWP-model is used in an icing model that calculates the ice accretion on a small cylinder, in accordance with [ISO 12494:2001].

[3] 1 EUR = 8.35 SEK (2013-03-15)

3. The ice accumulated on the cylinder is related to the performance of a wind turbine. The icing rate might in this context prove to be more relevant than the ice load.

If the input to the icing model is of low quality, the result of the model will be associated with high uncertainty. The challenge in the chosen approach is to achieve good enough output data from the NWP-model to allow the output from the icing model to be of such accuracy that it becomes useful in, for instance, wind power investment decisions. To do so, all parameters relevant to the icing process must be produced by the NWP-model. The complete process is schematically described below, indicating the "point of interest" for this study.



V-359 proposes that the output from the NWP-model is verified thoroughly by measurements. By doing this it is possible to better estimate the uncertainty in the modelled icing. This will increase the value of using the results of V-359 in wind power project development. A thorough verification also makes it possible to pinpoint where more research is needed.

Input to the ice model in step number 2 consists of wind speed, temperature, pressure, liquid water content and droplet size distribution. Forecasting temperature and pressure can be done with reasonable accuracy using a NWP-model. Forecasting wind speed, liquid water content and droplet size distribution is more difficult. The latter is not provided at all.

For verification purposes, wind speed, temperature and pressure can be routinely measured with high accuracy at a reasonable cost. The opposite is the case for liquid water content and droplet size distribution.

High quality measurements for verification of the NWP-model should be a major part of the foundation on which the result in V-313 rests on.

1.2 Background

Icing that substantially affect the turbines mainly occur when the rotor is swept in clouds at sub-zero temperatures. Thus, high elevation locations in northern Sweden are particular favourable for icing. Freezing rain can also cause heavy icing on turbines, but the occurrence is quite rare in Sweden, at least close to the ground.

Estimations of the ice load on structures such as power line towers and high communication masts have been important for dimensioning reasons in areas with cold climate for many years. Wind turbines have during the last few years to a greater extent been built in high elevated, cold climate areas. This has augmented the need for information about icing conditions. The fact that the hub heights of modern wind turbines can be considerable more than 100 meters only enhances the need for icing knowledge.

Ice accreted on the turbine blades affects the turbine in several ways.

- The shape of the turbine blade is altered and this will reduce the energy production.
- The loads on the turbine induced both by the aerodynamic influence of ice and the weight of the accreted ice can cause material fatigue.
- Lumps of ice can be thrown from the blades being hazardous to people and animals around the turbine.
- Increasing noise levels.
- Unexpected degradation of the energy production due to ice will ruin short term energy forecasts used in the day to day trading on the electricity market as well as the long term production estimates that were used as a decision basis for the entire project.

The economical loss caused by icing can be substantial and there is obviously a break point when the cost of the energy losses exceeds the cost for investing in de-icing equipment. A simple example with approximate numbers follows.

The total investment cost for a turbine without de-icing equipment is around 15 kSEK/kW, hence a 2 MW turbine without would cost 30 MSEK. A de-icing system adds approximately 2 percent two the total investment cost. The annual cost for running the turbine is at least 100 SEK / MWh. To this must be added the fact that the de-icing equipment consumes energy. Older figures based on de-icing of small turbines [Ronsten 2004] show that the consumption can be between 1 and 5 percent of the annual energy production. However, there should be a considerable inter-annual variation due to the fact that the weather varies from year to year. Nevertheless, we assume that the technology matures, and thus lowering the energy consumption, and that the annual energy consumption by the de-icing equipment, by average, is 2 percent of the annual energy production.

We also assume that the period when icing mainly occurs is between December and February. The period could however be considerably longer in large parts of northern Sweden. The energy production during December – February is roughly 35 percent of the annual energy production. We also assume that the energy loss is linear with respect to time.

If the annual energy production from a 2 MW turbine without de-icing equipment is 5256 MWh, the interest rate is 6 percent, the depreciation time on the investment is 20 years and no standstill due to icing occurs, the annual profit is approximately 280 000 SEK.

The corresponding annual profit if the turbine has de-icing equipment is 150 000 SEK. This assumes that no standstill due to icing occurs but that the de-icing is active and consumes energy corresponding to 2 percent of the annual energy production.

The difference is significant and the wind energy prospector will have to motivate a purchase of de-icing equipment to potential investors. It is favourable to invest in de-icing when the turbine stands still long enough during winter due to icing for the annual income to decrease more than the annual cost. In the example above this happens after two weeks. This is shown in Figure 1. This is the essence of what the results from V-313 can be used for in early project development: providing the prospectors with a tool to estimate if there is a need for investing in de-icing equipment.

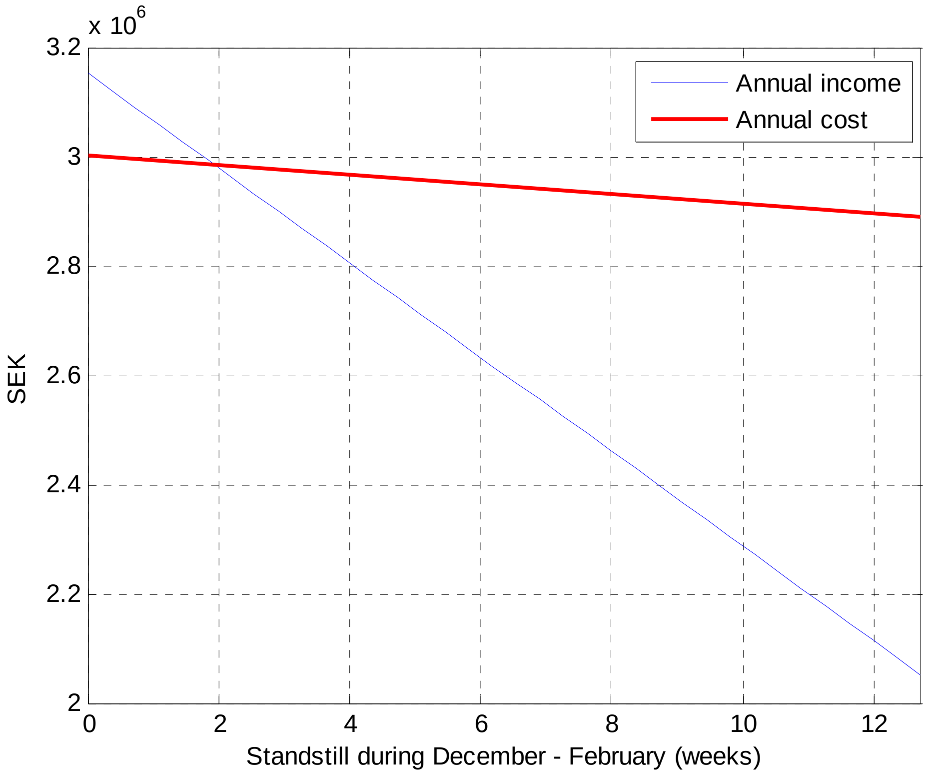


Figure 1. Blue curve: The annual income from a turbine in relation to standstill during winter. Red curve: The annual cost for a turbine including costs associated with de-icing in relation to standstill during winter.

The example above shows that the need for knowledge about icing conditions at a location that is investigated for wind power purposes is a necessity. Some attempts to shed light on the matter have been made. The most straightforward way is probably to use measurements from meteorological

SYNOP stations to make an estimation of the frequency of occurrence of conditions favourable for icing. This approach has been used several times, see for example [Tammelin, Säntti, 1998]. The drawback of this method is that icing can be strongly dependant on the location, and the SYNOP networks are normally quite sparse. The approach can however give an early, although rough, indication of whether de-icing equipment needs to be considered at all in a certain area.

Icing-products based on computer simulations in combination with observations are provided by for example Vortex (www.vortex.es) and Kjeller Vindteknikk (www.vindteknikk.no). There is little information about how the products are made and there is no verification presented at the product websites that can be used to properly estimate the uncertainty of the result. The main problem with computer simulations are that they provide reasonable, good looking figures that are easily adopted by the end user. But nice wrapping doesn’t necessarily mean that the content is of high quality.

2 V-313 methodology review

This section contains general information about NWP-models, a description of the ice model used in V-313 and a discussion of the obstacles that needs to be overcome for the project to be successful.

2.1 Numerical weather prediction

The advance of computers in the 1950s made meaningful weather forecasting possible. The ever increasing computer capacity since then has resulted in significant improvements in the forecasts. However, chaotic amplification of forecast errors effectively stops us from determining the weather with considerable skill[4] more than 5-7 days in advance. The models are based upon a set of nonlinear differential equations to which no known analytical solutions exists. To solve them, numerical methods are a necessity. The pioneering work by Edward Lorenz [Lorenz, 1963] in the early 1960s showed that the solutions of a system of nonlinear equations were unstable. Small changes in the initial conditions were shown to produce completely different results. This is today more known as "the butterfly effect", implicating that the flapping of the wings of a butterfly could result in a major weather event several days later. Edward Lorenz, father of the chaos theory, have been said to coin the phrase during a speech in Washington 1993; "Does the flap of a butterfly's wings in Brazil stir up a tornado in Texas?". This he denies in [Lorenz 2006] where he gives Joe Wexler credit as "the original butterfly man"; Lorenz had previously referred to a seagull and did not set the title of his 1993 speech himself.

Numerical weather prediction (NWP) is today the foundation in all operational meteorological centres around the world. The basic idea is, as mentioned above, to let computers numerically solve a set of nonlinear differential equations given initial conditions and then use the equations to calculate the state of the atmosphere a certain time later. Numerous weather prediction models are available, ranging from global, covering the entire earth, to regional limited-area models (LAMs) covering only a small part of a country.

The global models normally use observations in combination with the last forecast as a starting point for the calculations, this can also be the case for regional models but they require large scale driving on the boundaries, (Lateral-Boundary Conditions, LBCs). The LBCs are normally taken from a global model with lower resolution and different physics. The LBCs can therefore induce forecast errors that propagate over the domain of the regional model. Some of the sources of errors are described in [Thomkins Warner 2011] and among them are

[4] Considerable skill in this case mean that the products derived from the NWP-model are useful for decision making

- Low resolution of LBC data
- Errors in the meteorology of the LBCs
- Lack of interaction with lager scales
- Physical-process parameterization inconsistencies between the global model and the LAM

The last source of error above is touching upon the very core of the "problem" with NWP-modelling: The numerical models are inevitably a simplification of the real world. Modellers use parameterizations to calculate parameters that for some reason aren't described by the model physics. In the parameterizations, estimations of different properties of the atmosphere are combined with model variables provided by the NWP to calculate the desired variable. The simplifications result in forecast errors which of course can be transferred from a global model to a LAM through the LBCs. The use of different parameterizations in the model providing the LBCs and the LAM can, as mentioned above, further enhance the forecast error.

Even if the equations used to describe the atmosphere were known in detail, and all processes could be described without simplifications, uncertainty in the initial conditions will cause errors; we can never exactly know the state of the atmosphere. Thus the upper limit for useable forecasts is, in the ideal case, thought to be in the vicinity of two weeks.

Considering chaos, uncertainty in initial conditions and the NWPs simplified description of reality, it is quite amazing that useful weather forecasts can be produced at all.

Three NWP-models used in V-313 are:

- AROME (http://www.cnrm.meteo.fr/arome/)
- COAMPS (http://www.nrlmry.navy.mil/coamps-web/web/home)
- WRF (http://www.wrf-model.org/index.php)

One reason for using three different models is that it provides a way to estimate the plausibility of the result. If only one NWP-model is used there are only subjective means, based on experience, by which the plausibility of the forecast can be estimated. One way of estimating the plausibility and sensitivity of the model in a more statistical way is to use an ensemble-technique. The general idea when using only one NWP-model is to perturb the initial conditions and run the model again. This is repeated several times with different perturbations. The result is an ensemble of forecasts from which different statistics can be computed.

In V-313 no perturbations are made but thespread in the end result caused by using three different models will give an indication of the uncertainty.
Parameter changes in one NWP model may also be used to indicate the uncertainty.

The output from the three models is used as input for a model that calculates ice growth on a cylindrical object. The ice model is described in the next section.

2.2 Modelling of ice accretion

The ice modelling in V-313 is made with an equation described in [Makkonen 2000]. The rate of icing is obtained from

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 wvD \tag{1}$$

where D is the diameter of a cylinder, v is the wind speed, w is the liquid water content (LWC), α_1 is the collision efficiency, α_2 is the sticking efficiency and α_3 is the accretion efficiency. α_1 – α_3 are correction factors that can vary between 0 and 1.

Input to the model used in V-313 is time series of LWC, temperature and wind speed. In addition, constant values of the cloud droplet concentration, the time step used in the calculations and the initial diameter of the cylinder are required.

The NWP-models provide almost all necessary input for (1), the exception is the droplet concentration (used in the calculation of α_1) that has to be estimated (guessed). The output from the NWP models is used in non-linear expressions when calculating α_1 – α_3 which make the behaviour of dM/dt non-intuitive. α_1 – α_3 are described below along with a brief description of the parameters that are used to calculate them.

2.2.1 α_1 - collision efficiency (collection efficiency)

α_1 is the ratio of the flux density of the particles that hit the object to the maximum flux density. The droplet trajectory is determined by the forces of aerodynamic drag and inertia. For small droplets the aerodynamic drag forces are dominant and the droplet tends to follow the streamlines of the air around the object. The inertia forces will be dominant for larger droplets causing more of them to hit the object.

The relative magnitude of the inertia and drag on the droplets depends on the droplet size, the velocity of the airstream and the dimensions of the object [Makkonen 2000]. The calculations are complicated and computer demanding. To greatly simplify the calculations the object is assumed to be cylindrical, hence the use of a cylinder and not a turbine blade in the ice accretion modelling.

The following parameters are included in the calculation of α_1:

ρ_w – the density of water (constant)

d – droplet diameter

μ – viscosity of air (dependant on temperature)

D – the cylinder diameter

ρ_a – the air density (dependant on pressure and temperature)

v – the wind speed

2.2.2 α_2 - Sticking efficiency

An α_2 of 1 means that all droplets hitting the surface of the object freezes and does not bounce. For liquid, supercooled droplets the approximation $\alpha_2 \approx 1$ can be made. This approximation is used in the implementation of the ice accretion model that is used in V-313.

2.2.3 α_3 – Accretion efficiency (freezing fraction)

α_3 is the ratio of the rate of icing to the flux density of the droplets that stick to the surface. When $\alpha_3 = 1$ all the sticking droplets freeze on the surface, this is called **dry growth**. The ice resulting from dry growth is called "rime".

If the latent heat released upon impact cannot be transported away fast enough to make all the sticking particles freeze, some of the water mass is lost by surface run-off due to gravity and/or wind drag. This is called **wet growth** and is indicated by an α_3 less than unity. The ice resulting from wet growth is called "glaze".

α_3 is calculated using the complete heat balance of the surface of the icing object.

The following parameters are included in the calculation of α_3:

T – the temperature of the air

ρ_a – the air density (dependant on pressure and temperature)

D – the cylinder diameter

v – the wind speed

μ – viscosity of air (dependant on temperature)

w – the liquid water content

2.3 The key to useful modelling

The key to all useful modelling is verification, verification and verification. It is only when the models are verified against a measured reality the performance can be evaluated. The verification points out weaknesses which in turn can lead to improvements and in the end a better product. Even if the verification results can't be used to improve the model, it can be used to estimate the uncertainty in the model result properly. A product with an attached uncertainty is better than a product without.

In the case of V-313, where two different models are used in consecutive steps, it's crucial for the end result that all steps are verified and not just the last one. If only the end result is verified there is a chance that large errors in the first model (NWP) is transferred to the second model (ICE) affecting the ice load calculation in unpredictable ways.

Parts of the fundamental theories used in ice accretion modelling have been verified with good results. The calculation of the collision efficiency, α_1, was for example verified in a wind tunnel experiment, [Makkonen & Stallabrass, 1987]. However, in the real world, objects are not always small cylinders.

More advanced models than the one presented in [Makkonen 2000] exist, see for example [Meyers, 2002]. But since no verification is presented, there is no way of knowing how well the model performs.

2.4 Obstacles to overcome

As mentioned, measurements are a necessity in the work of determining whether the models that are being used in the simulations of ice accretion are producing reasonable and useful results. Wind speed, temperature and pressure can all be measured with very high accuracy, while LWC and droplet size cannot be measured with precision in an easy way. Robust and cost efficient ways of measuring LWC and droplet size would be very beneficial to V-313.

In V-313, calculated ice loads are verified against measurements made with the IceMonitor, constructed by Combitech AB. The qualities of the measurements are poor from time to time which of course will make a proper verification of the model difficult [personal communication with Stefan Söderberg and Hans Bergström from project V-313]. There is in general a strong need for an improved or new instrument for measuring ice load.

Another, perhaps even more difficult, task is to relate the calculated ice load on the small cylinder to the performance of a wind turbine. Ice load measurements are made on top of wind turbine nacelles in the scope of V-313. But considering the poor quality in the measurements of ice load and the fact that different blade types probably will respond differently to the same ice accretion, the task is very difficult.

The objective of V-359 is not to find solutions to all the above problems, focus is on coming up with a strategy for providing V-313 with high quality data for verification of the NWP-models. Measurement of the relevant parameters are described and discussed in the next section.

3 Measurements

3.1 Standard measurements of wind speed, temperature and pressure

It has been possible to conduct high precision measurements of wind speed, temperature and pressure for decades and measurement principles are thus not discussed here. We content ourselves by noting that useful data can be obtained with the right equipment and knowledge at a reasonable cost.

3.2 LWC and droplet size measurements

Several different methods and techniques have been developed during the years for measuring LWC and droplet size. The measurements can be made with thermal, optical or accretion techniques. [Arends et. al 1992] concludes that "most methods are less reliable resulting in errors of 50 % or more". [Ide, 1999] concludes that the thermal and accretion methods perform much better than the optical techniques evaluated.

The best candidate for measuring LWC and droplet size is probably a robust and automatic accretion technique. This, however, does not exist today.

The basics in the different measurement techniques are described below.

3.2.1 Thermal techniques

The thermal techniques are based on heating of several thin wires. Some different approaches are made

1. The wires are heated with a constant voltage. Water droplets that hit the wire will evaporate and cause the resistance in the wire to decrease. The change in resistance is then related to the LWC.
2. The wires are held at constant temperature and the extra power needed to keep the temperature constant when water is evaporating is related to the LWC.

A brief description of three such instruments can be found in [Ide, 1999].

This kind of instruments are originally designed for aircraft mounting and a supplementary air pump might be required to be able to use them on a stationary object [Arends et. al 1992].

3.2.2 Optical techniques

The same two instruments, the Forward Scattering Spectrometer Probe (FSSP-100) and the Particulate Volume Monitor (PVM-100) with optical measuring of LWC is evaluated in for example [Arends et. al 1992] and [Gerber et. al, 1999]. Both of the two instruments are using a laser to measure the LWC.

The PVM-100 registers the light scattered forward in a small angle related to the optical probing volume. There is a linear relationship between LWC and the scattered light flux.

The FSSP-100 is using a laser to count single particles. Several measurements are made in a short time and from the droplet distribution the volume of LWC can be calculated.

Depending on droplet size the measurements of LWC differ a lot between the two instruments.

3.2.3 Accretion techniques

Accretion techniques are less technical and consist of objects that the ice grows on. The accreted ice is then measured in different ways and related to the LWC. The technique has the drawback that no automatic instrument exists (yet), the instruments must be monitored and "read" manually.

A simple and inexpensive device consisting of a rotating H-shaped steel wire is described by [Rogers et al, 1983]. The rime accumulated on the steel wire must however manually be removed and weighed.

Another rather simple device that consists of several rotating cylinders of different dimensions was developed already in the 1940s. This device is described in [Makkonen 1992]. With this, both LWC and droplet size can be measured at the same time. When the dimensions of the cylinders are given, this "double-measuring" is possible knowing the weight of the ice on the cylinders combined with exposure duration, wind speed, air temperature and air pressure. The instrument is based on the foundation that the ice weight on a small cylinder of known dimensions can be modelled accurately when LWC and droplet size are known. According to [Makkonen 1984; Makkonen & Stallabrass 1987] this is indeed possible. One obvious drawback with the instrument is that the weighing of the cylinders has to be done manually.

4 Sensitivity analysis

A sensitivity analysis is made in order to establish the requirements on the input to the ice model. Input to the model is shown in Table 1. While most people have some ideas about the typical range for wind speed and temperature it's not so obvious for LWC and cloud droplet concentration. The LWC in stratus clouds, the cloud type responsible for the majority of the heavy icing events in Sweden, varies between 0.25 and 0.30 $g*m^{-3}$ [E. Linacre, B. Geerts 1999] and [Kampe, 1949]. A much larger span, 0.05 – 0.3 $g*m^{-3}$ with extremes up to 0.6 $g*m^{-3}$ is given in [Cotton and Anthes, 1989]. Much higher concentrations are found in convective clouds, but they will never have cloud bases low enough to cover the rotor of the turbine. The cloud droplet concentration can vary significantly, [E. Linacre, B. Geerts 1999], and is highly interesting in global climate studies for the reflection of incoming short wave radiation [Gultepe & Isaac 2004].

Table 1. Input to the ice model.

Parameter	Unit	Typical range	Comment
LWC (w)	$g*m^{-3}$	0.25 – 0.30	For stratus clouds over land
Temperature (T)	ºC	0 to -30	The temperature at hub height will rarely be below -30
Wind Speed (U)	$m*s^{-1}$	0 – 25	
Cloud droplet concentration (N_d)	cm^{-3}	80-300	
Pressure (P)	hPa	850-1060	Depending on height above sea level
Initial diameter of cylinder (D)	m	0.03	IEC-standard

The equation that is used to calculate the ice load on the cylinder is briefly described in section 2.2. See [Makkonen 2000] for a more detailed description.

4.1 The set-up of the sensitivity analysis

It is difficult to set the time for a typical icing event. An icing event is here defined as the period during which ice is being accreted on the turbine. In southern Sweden these events should seldom last longer than 24 hours. In northern Sweden where the terrain topography plays a bigger role the icing events could go on for several days.

In the sensitivity analysis the ice model is run for 24 hours with a time-step of 1 hour. The difference in calculated ice mass between using a one hour time-step and a ten minute time-step is very small.

During the 24 hour period that is modelled all parameters are assumed constant.

4.1.1 Air pressure

The air pressure can vary between approximately 850 and 1060 hPa in Sweden. This is the actual pressure on a site, not the pressure reduced to sea level. An air pressure of 850 hPa can occur at the highest mountains and 1060 at sea level.

Figure 2 shows the calculated ice load with constant wind speed (U), LWC (w), temperature (T) and cloud droplet concentration (N_d) for the air pressures 850, 1000 and 1060 hPa. The difference in ice load with 850 and with 1060 hPa after 24 hours is about 3.5 percent related to the 1060 value. It is quite a small difference in ice load for a 20-25 percent difference in air pressure. But it is nevertheless inducing an unnecessary error if only a standard pressure is used in the ice load modelling.

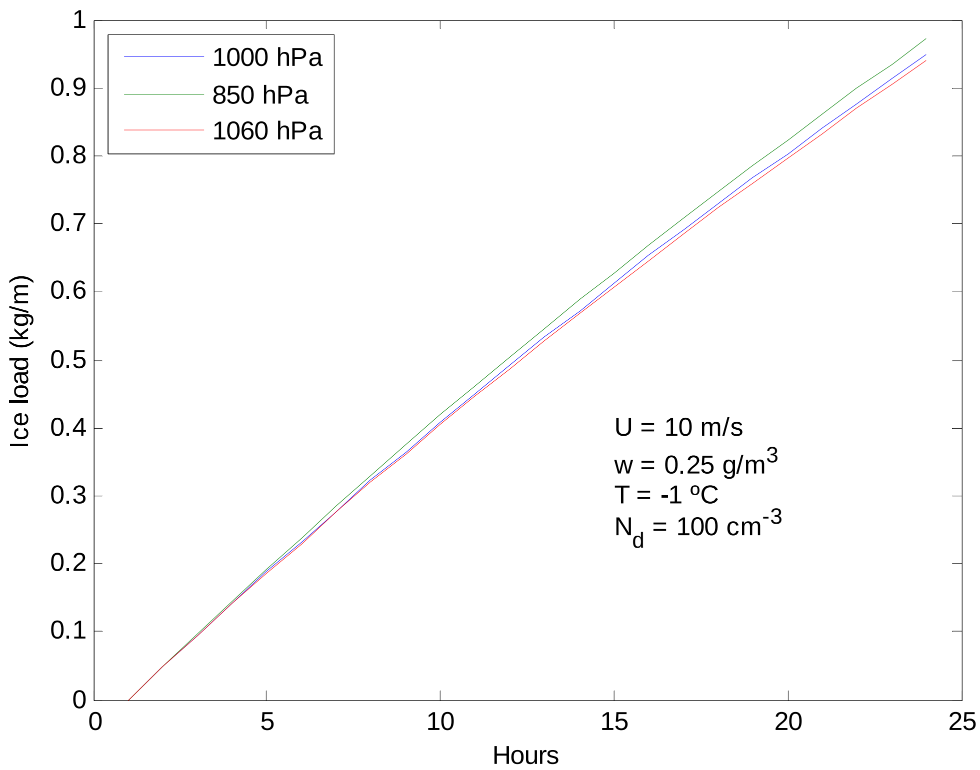


Figure 2. The calculated ice load for constant U, w, T and N_d for three different air pressures.

4.1.2 Temperature

Figure 3 shows the calculated ice load with constant U, w, P and N_d for several different air temperatures. Obviously the most interesting temperature interval is that around 0ºC.

The difference in ice load calculated with temperatures -0.5ºC and -2ºC after 24 hours is 1.8 percent related to the -2ºC value. The corresponding difference between -2ºC and -5ºC value is 2.2 percent related to the -5ºC value.

The difference between -0.1ºC and -0.5ºC is considerable bigger, about 70 percent related to the -0.5ºC value. The reason for this is that the freezing fraction is much lower for the -0.1ºC – calculation, see Figure 4.

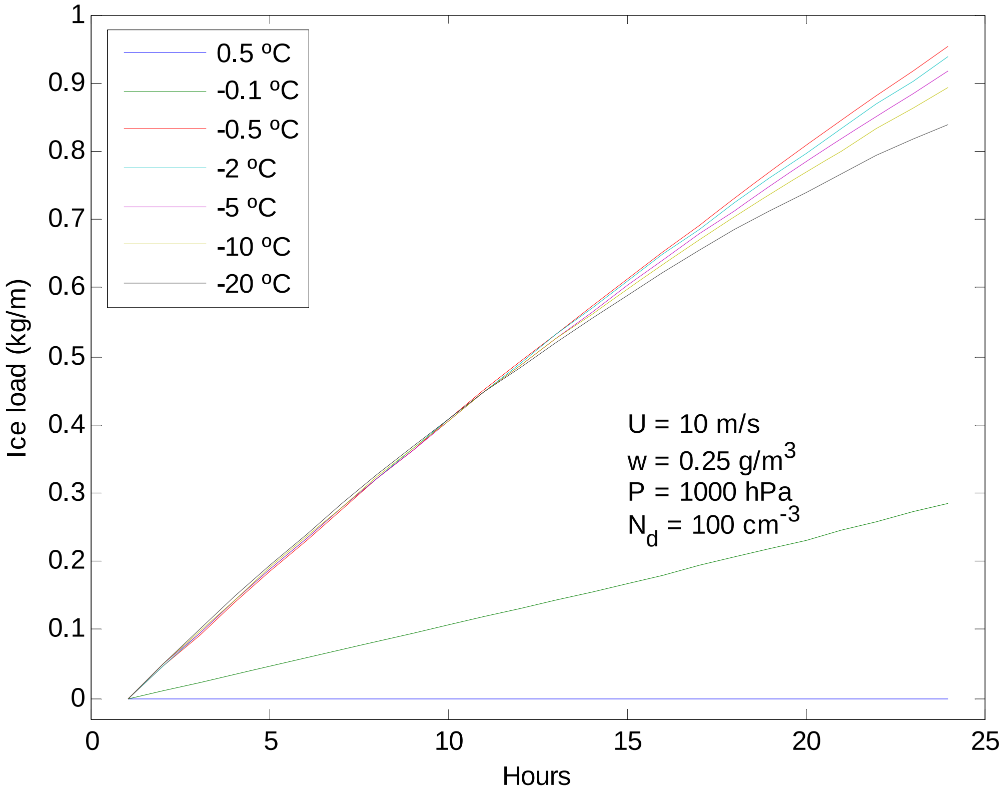


Figure 3. The calculated ice load for constant U, w, P and N_d for different air temperatures.

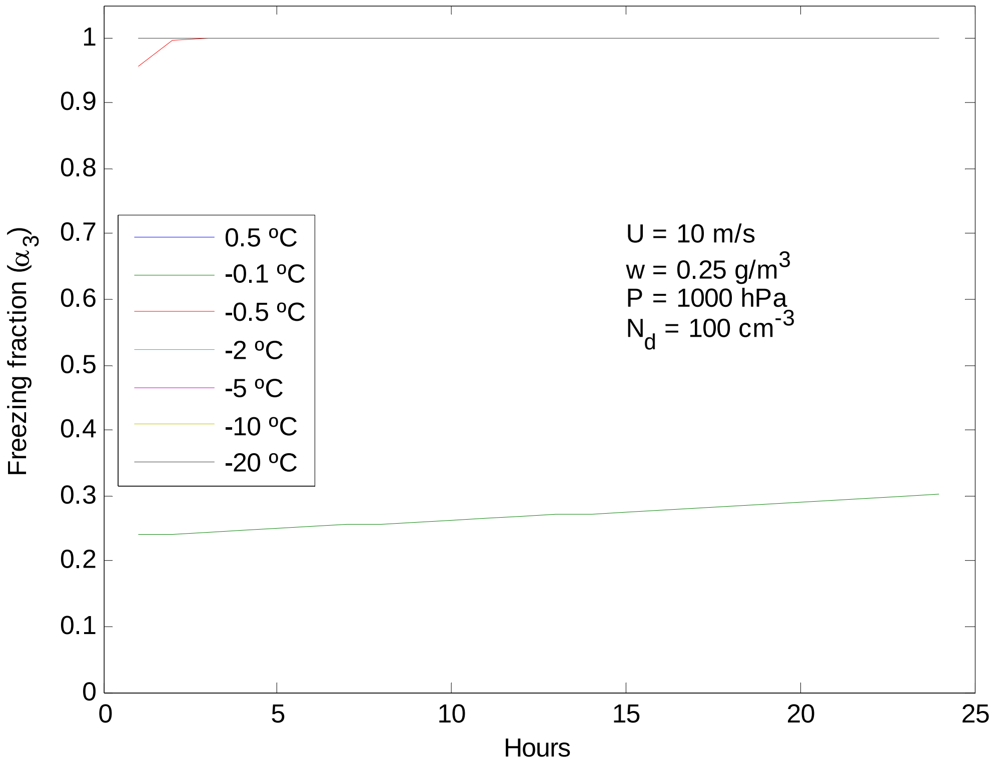


Figure 4. The calculated freezing fraction (α_3) for constant U, w, P and N_d for different air temperatures.

We can conclude that small errors in the temperature forecast around 0ºC can result in large errors in calculated ice load.

4.1.3 Wind speed

Looking at equation (1) it's clear that the wind speed is affecting the result in a more direct way then the previously examined parameters. This is also shown in Figure 5.

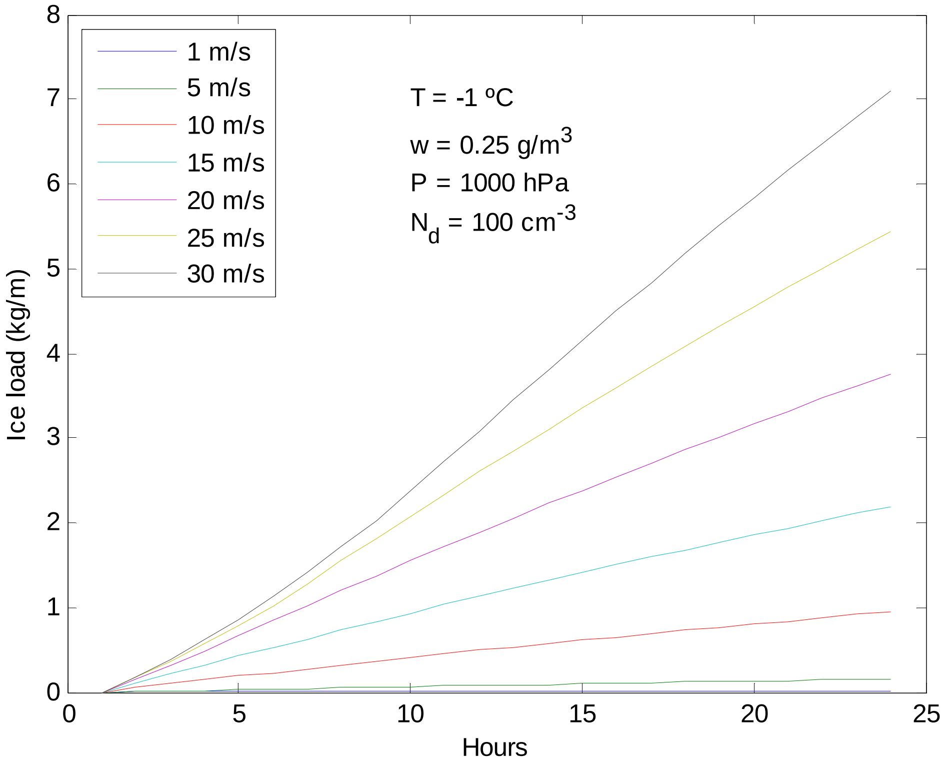


Figure 5. The calculated ice load for constant T, w, P and N_d for different wind speeds.

The very low and the very high wind speeds in Figure 5 is less interesting than winds in the interval 5-11 metres per second, which is the interval with the majority of the wind at a typical Swedish site. Calculations with wind speeds from this interval are shown in Figure 6. The difference in calculated ice load, in percent, between the wind speeds used in Figure 6 are shown in Table 2. The difference is related to the calculated ice load for the higher wind speed.

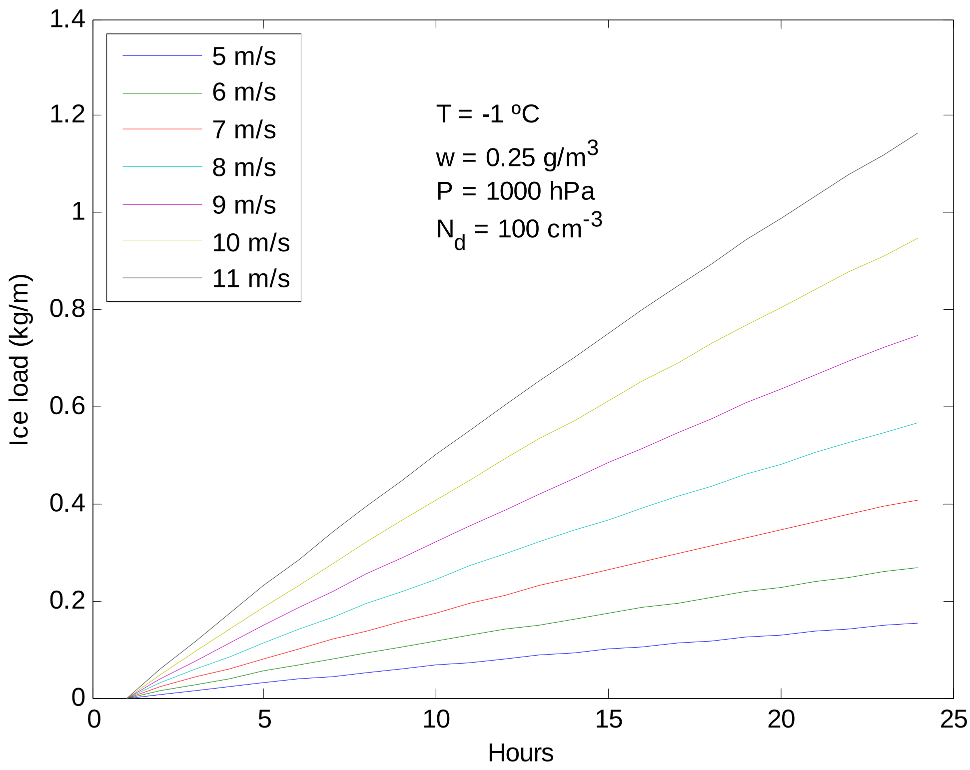


Figure 6. The calculated ice load for constant T, w, P and N_d for different wind speeds.

Table 2. The difference in calculated ice load using the wind speeds in the first column. The difference between the different wind speeds are also in the table for reference. The difference in percent is related to the highest wind speed in each pair.

Wind speeds used in the calculation	Diff U (%)	Diff Iceload (%)
11-10	9	19
10-9	10	21
9-8	11	24
8-7	13	28
7-6	14	34
6-5	17	43

4.1.4 LWC

The LWC is the most uncertain parameter in equation (1). It is difficult to measure and the NWP-models are generally poor at predicting it in the lowest layers of the atmosphere, [Zhou et al., 2007]. LWC can be reasonably predicted if high resolution NWP-models with detailed microphysics is used [Nygaard 2011]. This is however computational very expensive.

Calculations of ice load with constant T, U, P and N_d for different w is shown in Figure 7. The difference, in percent, between the LWC:s used in the calculation of the ice load and between the resulting ice load is shown in

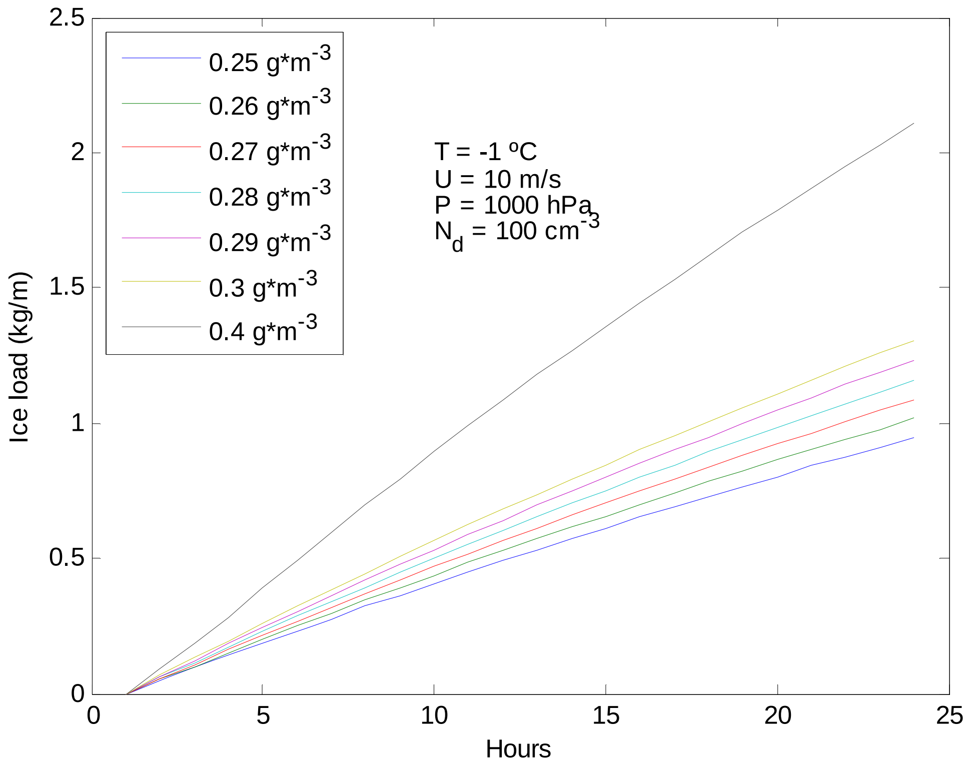


Figure 7. The calculated ice load for constant T, U, P and N_d for different liquid water content.

Table 3. The difference in calculated ice load using the LWC in the first column. The difference between the different LWS:s are also in the table for reference. The difference in percent is related to the highest LWC in each pair.

LWC used in the calculation	Diff LWC (%)	Diff Iceload (%)
0.40-0.30	25.0	37.9
0.30-0.29	3.3	5.7
0.29-0.28	3.4	6.0
0.28-0.27	3.6	6.2
0.27-0.26	3.7	6.5
0.26-0.25	3.8	6.8

4.1.5 Droplet concentration

The droplet concentration is not an output from NWP-models. As for the LWC, it is not straightforward to measure droplet concentration and the range of values found in the literature is large, 80-300 droplets / cm^3. The droplet concentration is used to calculate the average droplet size which in turn is used in the calculation of α_1. A higher value on the droplet concentration indicates smaller and lighter drops which easier can follow the airstream around the cylinder.

Calculations of ice load with constant T, U, P and w for different N_d is shown in Figure 8. The difference, in percent, between the droplet concentrations used in the calculation of the ice load and between the resulting ice load is shown in Table 4.

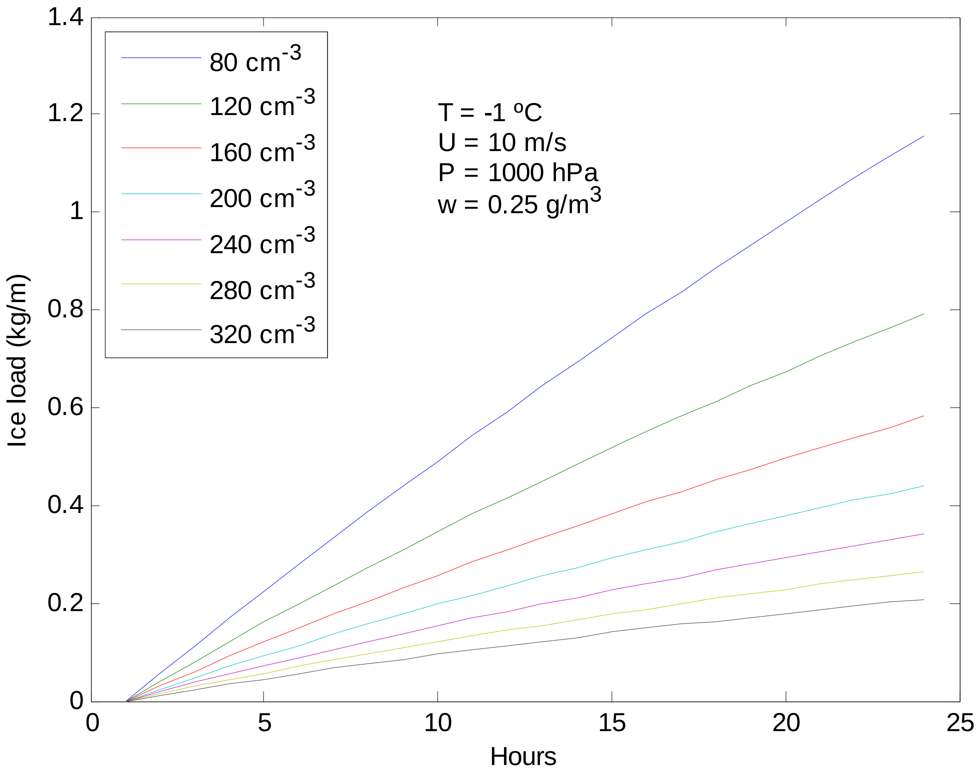


Figure 8. The calculated ice load for constant T, U, P and w for different droplet concentrations.

Table 4. The difference in calculated ice load using the droplet concentrations in the first column. The difference between the concentrations is also in the table for reference. The difference in percent is related to the highest concentration in each pair.

Droplet concentration used in the calculation	Diff Nd (%)	Diff Iceload (%)
320-280	12.5	-28.0
280-240	14.3	-28.2
240-200	16.7	-29.4
200-160	20.0	-31.9
160-120	25.0	-36.5
120-80	33.3	-45.9

4.2 Sensitivity analysis conclusions

The following rank over the variables importance on the calculated ice load is based on the sensitivity analysis:

1. Wind speed
2. LWC
3. Droplet concentration
4. Temperature
5. Pressure

We identify the wind speed as the most important variable in the modelling of ice growth on a cylindrical object while temperature and pressure are of minor importance if we disregard the fact that the temperature needs to be below zero for ice to be able to form.

Droplet concentration and LWC could be very important. But there is also a possibility that they are not. It all depends on the range of values that the two parameters can attain during typical Swedish icing conditions. If the variability between weather situations is small, approximate numbers can be used in the ice load modelling without significantly affecting the quality of the result. If the variability is large, however, there is a strong need for improving the input data for the ice load calculations.

5 The NWP output data

The approach to model ice accretion and its impact on wind turbine performance involves two separate models. The first model, the numerical weather prediction, feeds the second one, the ice accretion model with vital input data. As discussed in section 3 of this report, the sensitivity of the ice accretion model to changes in the individual input parameters is widely different.

In this section we thus continue by investigating the typical correspondence between the output data from the numerical weather prediction model and corresponding observations.

To illustrate the level of compliance between output data from the numerical weather prediction with observations, data has been made available from the high tower measurements outside Sveg. The setup of these measurements is further described in [Persson, 2009].

5.1 Available data

The available dataset contain seven months of hourly observational data from Sveg; from 2010-09-01 to 2011-03-01. The dataset was passed on to this study from V-313 together with output data from the numerical weather prediction model, and we have assumed all data are quality controlled and not modified.

The sensor setup in the Sveg tower is illustrated in Figure 9. There are four main observations levels; 15, 70, 155 and 240 metres above ground. In the following of this section, only data from the 70-metre level is shown.

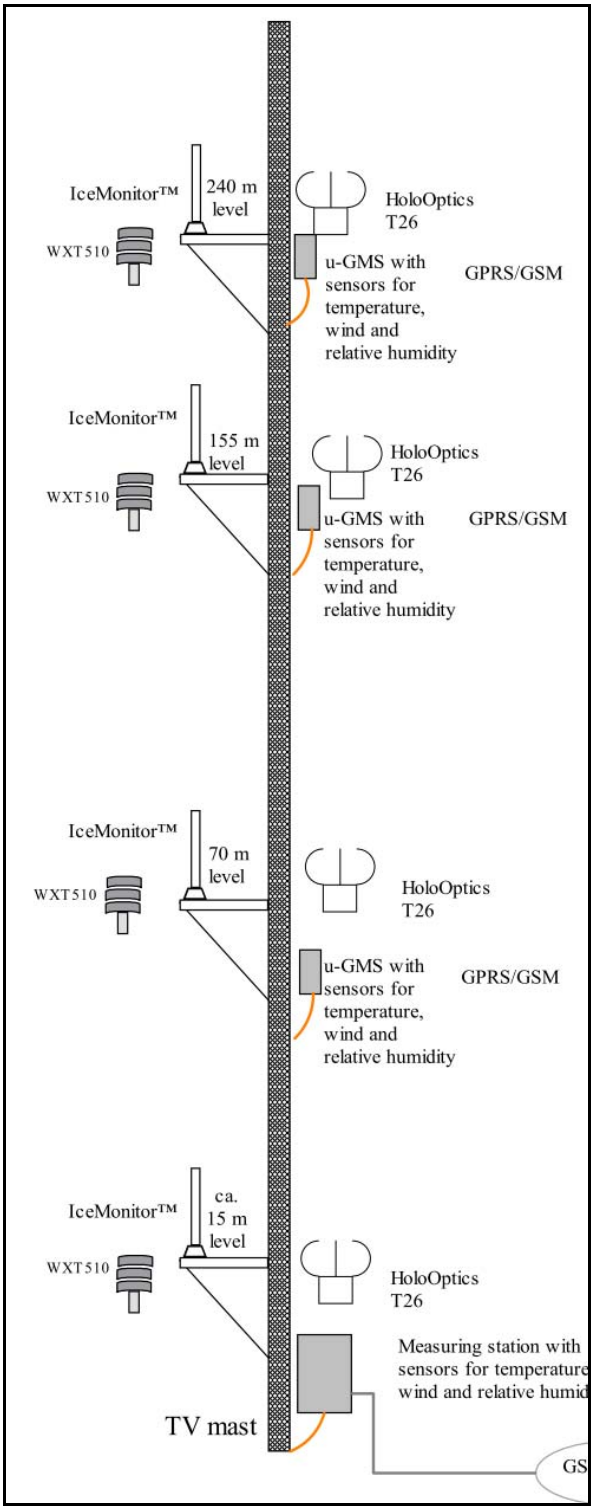


Figure 9. Schematic illustration of the sensor installation of the high tower outside Sveg. Illustration from [Persson 2009].

5.2 Temperature

A temperature below freezing is naturally a fundamental criterion for ice to form. In Figure 3 it was shown that the ice model is rather insensitive to temperature, as long as it is kept away from the melting point. A comparison between model output and observations from Sveg shows in general a good agreement, as seen in Figure 10. Correlation coefficient for hourly data over seven months is 0.96.

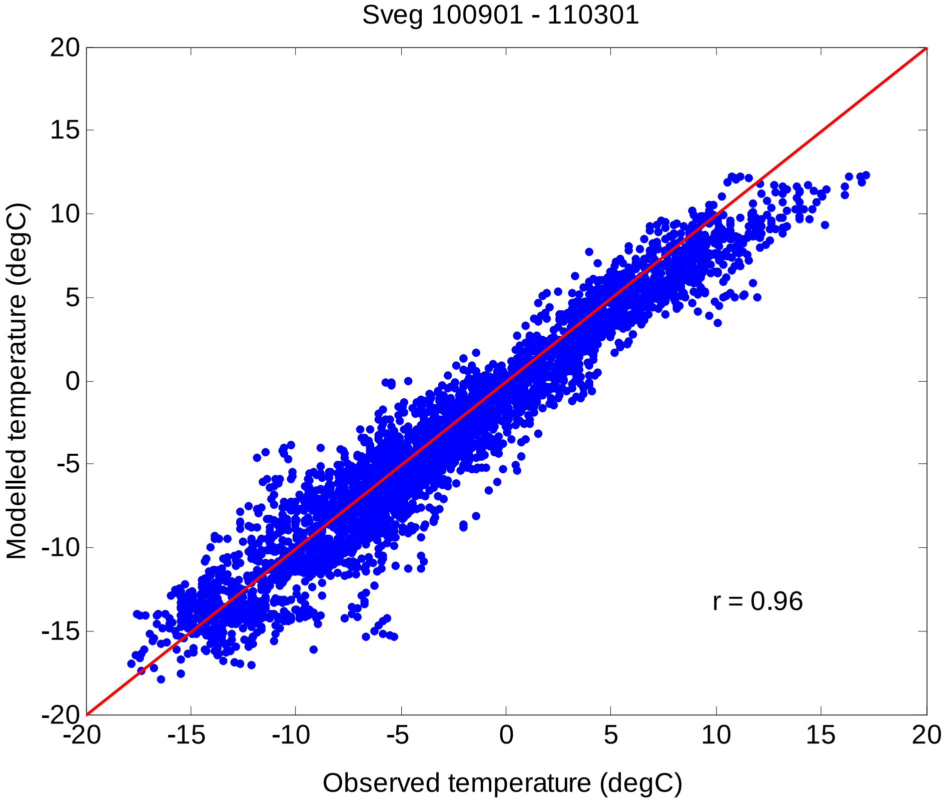


Figure 10. Comparing modeled temperatures in the period 100901 – 110301, at 70 metres a.g.l. in Sveg with observations. Synchronized data.

From Figure 11 we can see that the scatter fairly evenly distributed over time. In other words, there are no significant time periods of severe over- or under estimating of the air temperature.

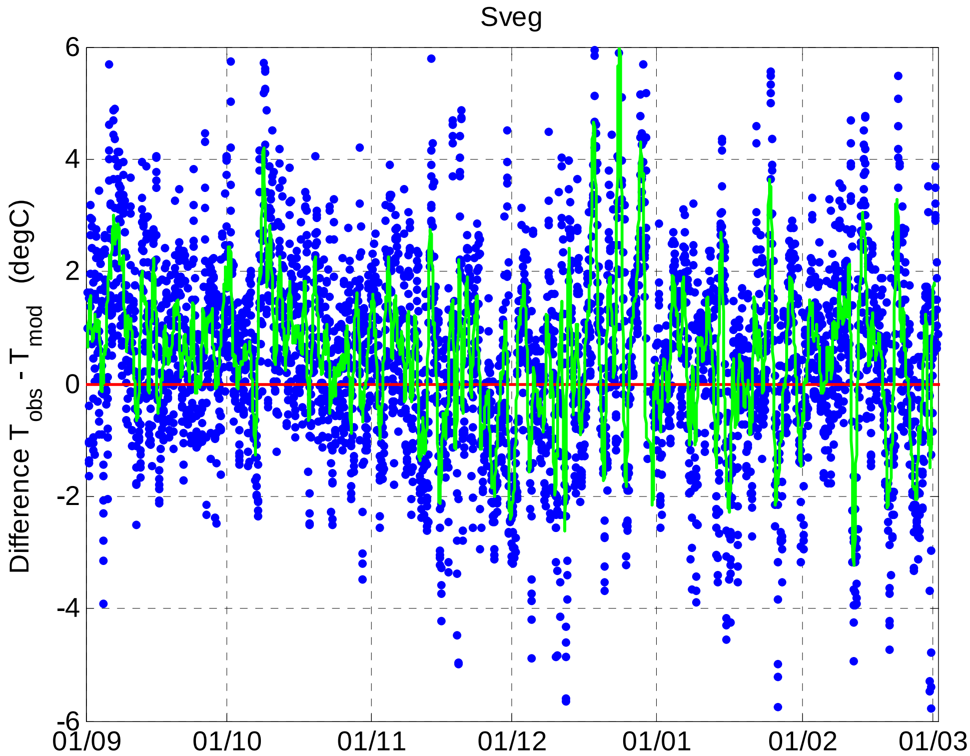


Figure 11. Comparing modelled temperatures in the period 100901 – 110301, at 70 metres a.g.l. in Sveg with observations. Time series of the difference between observation and modeled temperature. Green curve shows a 24-hour moving average.

5.3 Wind speed

The wind has both a large temporal and spatial variability. Depending on the resolution, a model may not have the ability to capture some of these variabilites. Comparing hourly averages of observations with output data from the numerical model we see from Figure 12 that the scatter is much larger for wind speed compared to temperature (as seen in Figure 10). Correlation is low, 0.60 for hourly values in this seven months period. There are no indications of a trend but the scatter around the 1:1-line (red line in figure) is large.

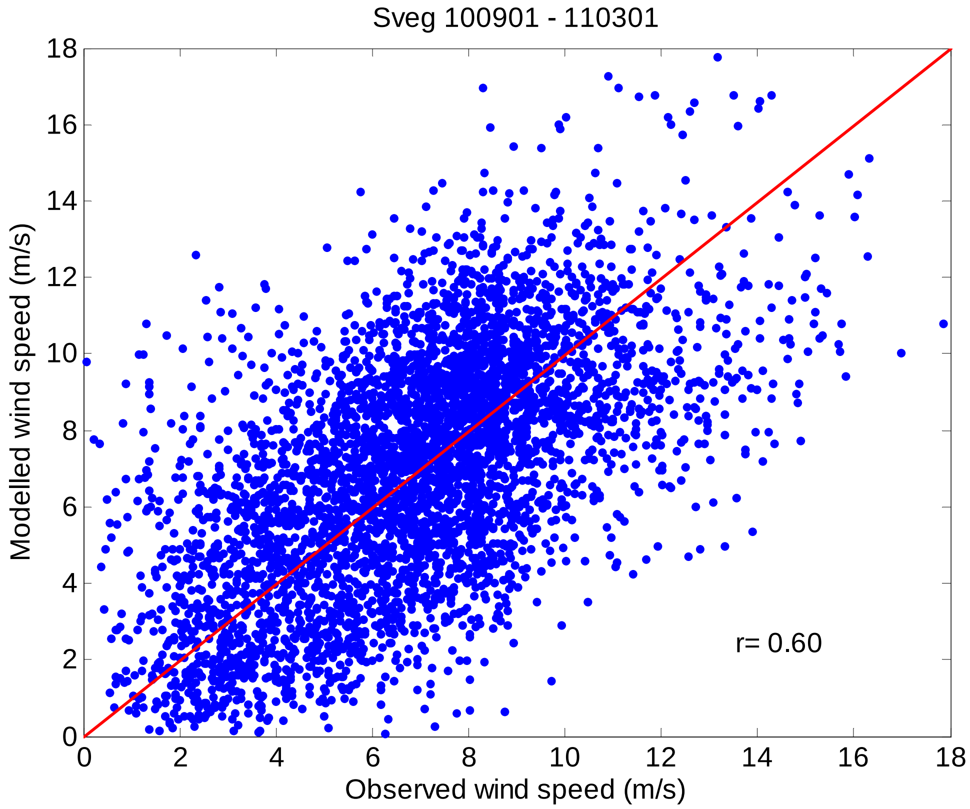


Figure 12. Comparing modeled wind speed in the period 100901 – 110301, at 70 metres a.g.l. in Sveg with observations. Synchronized data. Red line is indicating the 1:1 relationship.

We know from the sensitivity analysis that the wind speed is very important for ice accretion. Thus it is of interest to investigate if the difference between modeled and observed wind speed is close to random or if it is changing over time. In Figure 13 we see the normalized difference (per cent) between observations and modelled wind speed. Notably, there are time periods of days up to two weeks with fairly large under or over estimations. A negative difference, thus indicating a higher modeled wind speed than observed, could potentially be caused by ice on anemometers, if such data is not filtered out correctly in the quality control. But the contrary, a lower modeled wind speed than observed is unlikely caused by disturbed measurements. In this time period of seven months, there is one almost two week long period at the end of December where the wind is consistently over predicted. Ice accretion during such times may potentially then occur at a higher rate than predicted by the model. When looking at Figure 13 one should remember though that the differences are relative, and not revealing anything about the actual wind speed. In the case of these two particular weeks the wind was varying between 1 – 10 m/s, changes the model could predict to some extent. The large relative differences during that time naturally mainly occur when wind speed is low. But together with the scatter plot in Figure 12 we see that there are occasions when observed winds are as high as up to 10 m/s while the modelled wind stays only half of that. From Figure 5 we remember that such difference can rapidly lead to a large underestimation in ice accretion.

An example from observations in November is following, where one can see the influence on the difference a wind speed deviation will have on the modelled ice load.

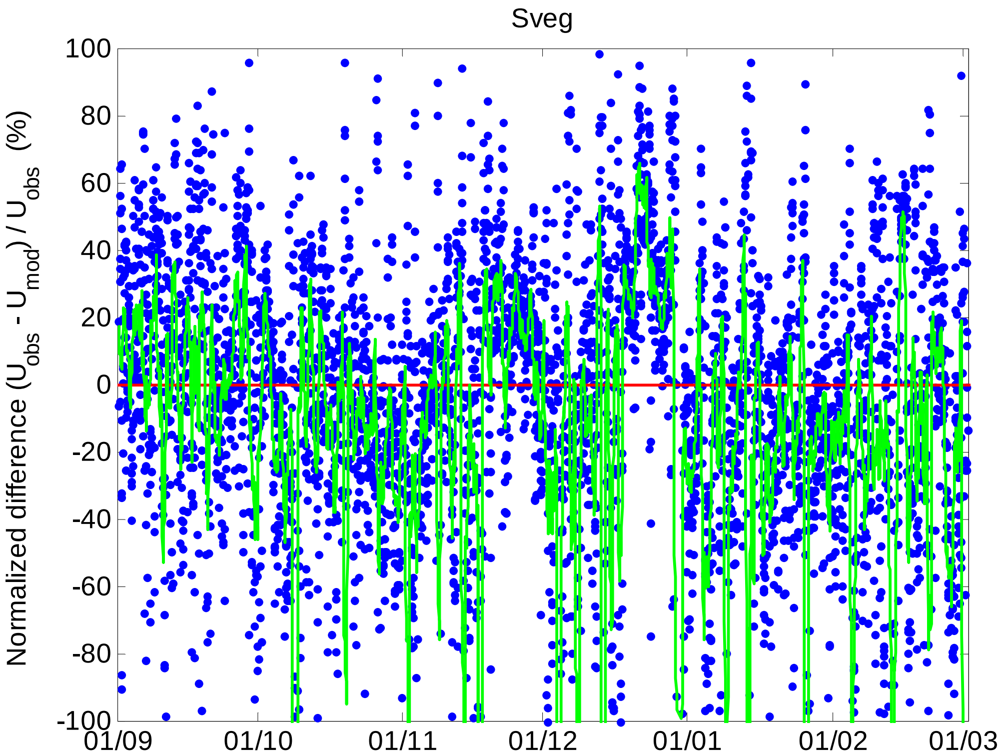


Figure 13. Comparing modelled wind speed in the period 100901 – 110301, at 70 metres a.g.l. in Sveg with observations. Time series of the difference between observation and modeled wind speed. Green curve shows a 24-hour moving average.

The top panel in Figure 14 shows the calculated ice load during a period in November. The calculations are based on temperature, wind speed and pressure from a NWP model (red curve) and *in situ* observations (blue curve). Stratus clouds are assumed to cover the site and LWC and droplet concentrations are assumed constant at 0.25 gm^{-3} and 100 cm^{-3} respectively. The observed and modelled wind speed during the period is shown in the middle panel while the observed and modelled temperature is shown in the lower panel. It is quite clear that the erroneous forecasted wind speed is responsible for the difference in calculated ice load. This is also consistent with the results from the sensitivity analysis in chapter 4. But bear in mind that this only shows how forecast errors affects the modelling of the ice load, not anything about the actual measured ice load.

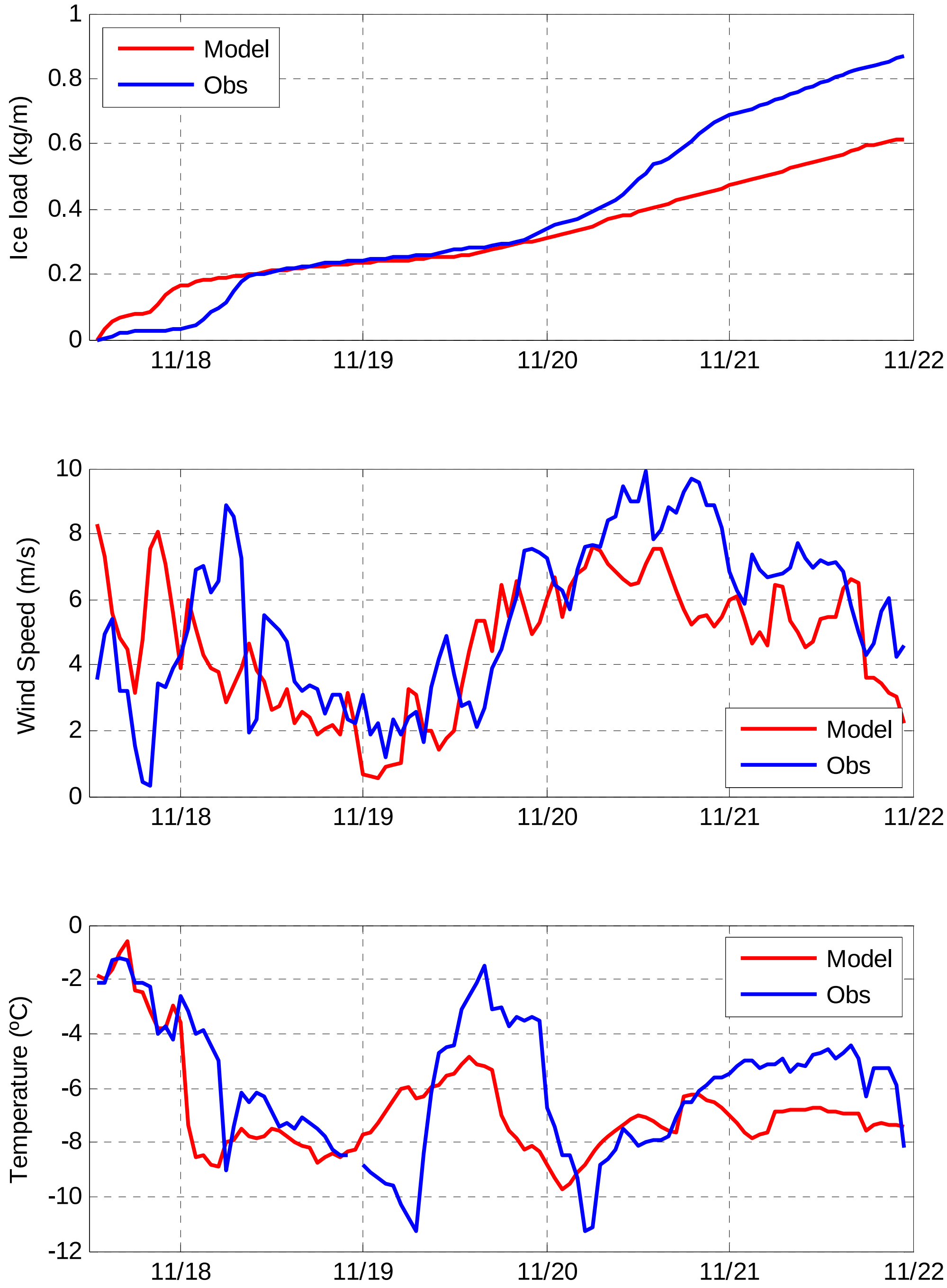


Figure 14. Top: Calculated ice load based on NWP and observed data with constant LWC and droplet concentration. Middle: Wind speed from observations and model. Bottom: Temperature from observations and model.

6 Verification measurement plan

Some of the parameters that are included in the ice load calculations are fairly easy to measure while others are both difficult, time consuming and expensive to measure.

6.1 Temperature and pressure

Temperature and pressure has been possible to measure with precision for a long time and numerous high quality instruments are available at a reasonable cost. We have also seen that they are of minor importance in the ice modelling. Thus, measurements of temperature and pressure are not discussed here.

6.2 Wind speed

Whether or not wind speed measurements can be made during cold conditions with high enough accuracy is mainly dependant on three things:

1. The quality of the instrument
2. The mounting of the instrument
3. The heating capabilities of the instrument

There are several manufacturers providing high quality anemometers, for example Vaisala, Thies, Vector and Risø. The mounting of all anemometers should be in accordance with IEC-recommendations to minimize tower disturbances.

Heating is the most important thing when designing a measurement campaign in which the main objective is to verify icing conditions. The anemometer will give useless information if heating is insufficient. Instruments with full heating in both bearing and cup are not only desirable but essential.

The verification measurements should of course be made at as many of the locations and altitudes that are being modelled in V-313 as possible. It is important to stress that a good verification of the NWP-model at one particular location doesn’t necessarily mean that it performs well at another location.

6.3 Liquid water content and droplet concentration

One important finding during the sensitivity analysis of this study was that the importance of accurate droplet size/concentration and LWC is unclear. As described in section 4 it could be very important. But there is also a possibility that they are not. It all depends on the range of values that the two parameters can attain during typical Swedish icing conditions. If the variability between weather situations is small, approximate numbers can be used in the ice load modelling without significantly affecting the quality of the result. If the variability is large, however, there is a strong need for improving the input data for the ice load calculations. Thus, the first step in verifying the quality of the input data given to the ice model is attempt to collect high quality data on the time variability and range of values of LWC and droplet concentration. This should be the primary goal in a verification measurement plan, rather than aiming on long time series.

Several techniques exist for measuring LWC and droplet concentration. The techniques are described and discussed in section 3.2. The accretion methods are robust and less technical advanced than the optical and hot wire methods. But the accretion methods are typically very resource demanding in the sense that much manual labour is required in order to ensure the collected data keep required quality.

There are no automatic means of directly measuring high quality LWC and droplet concentration for longer periods of time. Thus making it difficult to include several locations in a measurement plan for verification measurements. If direct measurements should be performed it would first be necessary to chose one or two measurement techniques and evaluate them at one or two locations. The objective would be to get a better understanding of the measurement techniques and how LWC and droplet concentration varies with time in the lowest part of the atmosphere in Sweden during the winter season. The knowledge about this today is very limited and more information would of course improve the usability of an icing-mapping product. If, for example, the LWC is shown to vary between 0.25 gm^{-3} and 0.28 gm^{-3}, the LWC can be approximated with 0.275 gm^{-3} in the calculations of the ice load without a distinct increase in uncertainty. A similar reasoning can be done for droplet concentration.

6.4 Suggested measurement approach

From the sensitivity analysis described in chapter 4 we propose verification measurements should focus on the variability of LWC and droplet concentration. Earlier attempts measuring these parameters through optical and thermal techniques have been reported in literature as either inaccurate or labour intense (see 3.2). Thus, current instruments available on the marked using such direct measurement techniques are not suitable for the sought verification measurements. We rather propose the verification is done through the use of indirect measurements. From icing measurements the influence on icing by LWC and droplet concentration should be evaluated using the accretion technique described by [Makkonen, 1992], see section 3.2.3.There, the approach was to distinguish the influence of the relevant physical properties of the air (temperature and wind) from water related properties (LWC, droplet size distribution). The described manual instrument using rotating cylinders should then be replaced with sensors using automated ice load weighing and de-icing. Considering the available instruments of today, modified IceMonitors (illustrated in Figure 15) manufactured by Combitech AB would require least effort to reach a set of sensors to do so. Realistically, three IceMonitors with different cylinder diameters should be used in parallel, mounted sufficiently close to each other to ensure they are exposed to the same physical properties of the air.

Figure 15. IceMonitor. Photo: Combitech

6.4.1 Necessary modifications

Current version of the IceMonitor cannot be used for these verification measurements. A few elementary modifications are necessary to be able to detect the different impact the variation in LWC and droplet size will have on the icing of the cylinders. The accretion technique itself requires different cylinder diameters. We propose three sensors to be used, thus one sensor should be equipped with a smaller cylinder than the standard version (30 mm), and correspondingly one sensor with larger cylinder.

In order to define certain exposure times for an icing event de-icing is necessary. The time of exposure thus begin when the heating is deactivated and continues until certain criteria are met. One criterion must likely be that a certain mass of the ice is reached in order to avoid large measurement uncertainties. It is important to remember that the method assumes a cylindrical build-up of ice and a certain relationship between the diameters of the sensors. Thus, exposure times cannot be too long, which would allow a growth of ice which is deviating too much from any of these two assumptions.

It is important to remember that the amount of heat stored in each of the three cylinders will be different at the beginning of the exposure. In the event of ice forming immediately after beginning of a new exposure this must be taken into account for. During the test phase of the new equipment this must be carefully investigated as described in 6.4.2.

Related to the de-icing a third modification becomes necessary from current version of the IceMonitor. As ice will be melted from the cylinder at the end of each measurement it is important to ensure no refreezing or other complications occur. User experience of current version of the IceMonitor repeatedly report problem with ice forming between the cylinder and the body of the instrument. This typically results in erroneous data. To avoid melt water from refreezing below the cylinder it is necessary to modify the sensor for measurements in a hanging position.

From user experience it is well-known that the wind driven rotation of the cylinder is often not enough to ensure a cylindrical ice growth. The shape is crucial to the success of these verification measurements, and thus the rotation must be forced mechanically by the sensor itself.

According to Patrik Jonsson [personal communication 2012] at Combitech none of the proposed modifications imply any demanding development to the current version of the IceMonitor. In fact, parts of the proposed modifications have to some extent already been investigated by Combitech at an earlier stage in the development of the senor.

6.4.2 Necessary testing

The required modifications call for thorough testing prior to installation. It is necessary to perform some of the tests in an icing wind tunnel, and such test must likely already be integrated during the process of performing the proposed modifications. In particular the de-icing calls for careful testing. The optimal heating must be balanced between efficient de-icing while not causing the difference in heat stored in each cylinder to become unnecessary large. In addition it must be investigated how the cooling of recently heated cylinders depend on temperature and wind. The different dependencies for the three cylinder is important to document, in order to compensate for variable exposure times.

6.5 Instrument Mounting

As mentioned, the set of three modified sensors should be mounted in such way they are exposed to the same physical properties of the air. This means they should be mounted on a horizontal boom keeping enough distance between sensors to minimize the flow distortion they will mutually generate. The boom should preferably be directed across the prevailing wind direction at the site to even further minimize the risk of flow distortion.

From our own experience, together with experience from other users of IceMonitor data (e.g. Krohn 2012; Norén 2012) we know the instruments will need to be carefully monitored at regular intervals to ensure they perform well and high quality data is collected. Despite the necessary modifications proposed, measurement experience in cold climate tells us there are numerous reasons for instrumentation to not operate satisfactorily for extensive periods of time. In addition to the three modified IceMonitors it would be an advantage in the analysis of the data to access visual images of the instruments during icing events. Thus, the three sensors should be monitored by a suitable camera device storing images of the sensors.

6.6 When to measure

Measurements must naturally take place in wintertime and preferably as soon as possible. Lead time for the necessary sensor modifications is realistically a few months. Some additional equipment will also be necessary, such as camera device, mounting booms, cabling and perhaps a peripheral data storing unit (depending on what is available at the selected site of installation). Nothing of the additional equipment should take longer time to acquire than the modification of the sensors. Mounting of the described equipment will naturally be weather dependent but is likely possible to carry out during one day.. Indicatively, the described equipment could be in operation within four to six months from the time of order. Thus, depending on the time of order it is realistic to perform the first verification measurements during the winter season 2012/2013.

6.7 Where to measure

In this study, data from the numerical weather prediction model was compared with observations from the high tower close to Sveg. We propose it should primarily be investigated if the same tower can house the suggested verification measurements. One obvious advantage of this choice is the already on-going documented high quality measurements, including IceMonitors in operation. The measurement at the Sveg site has also been used extensively by V-313 for verification of modelled weather data.

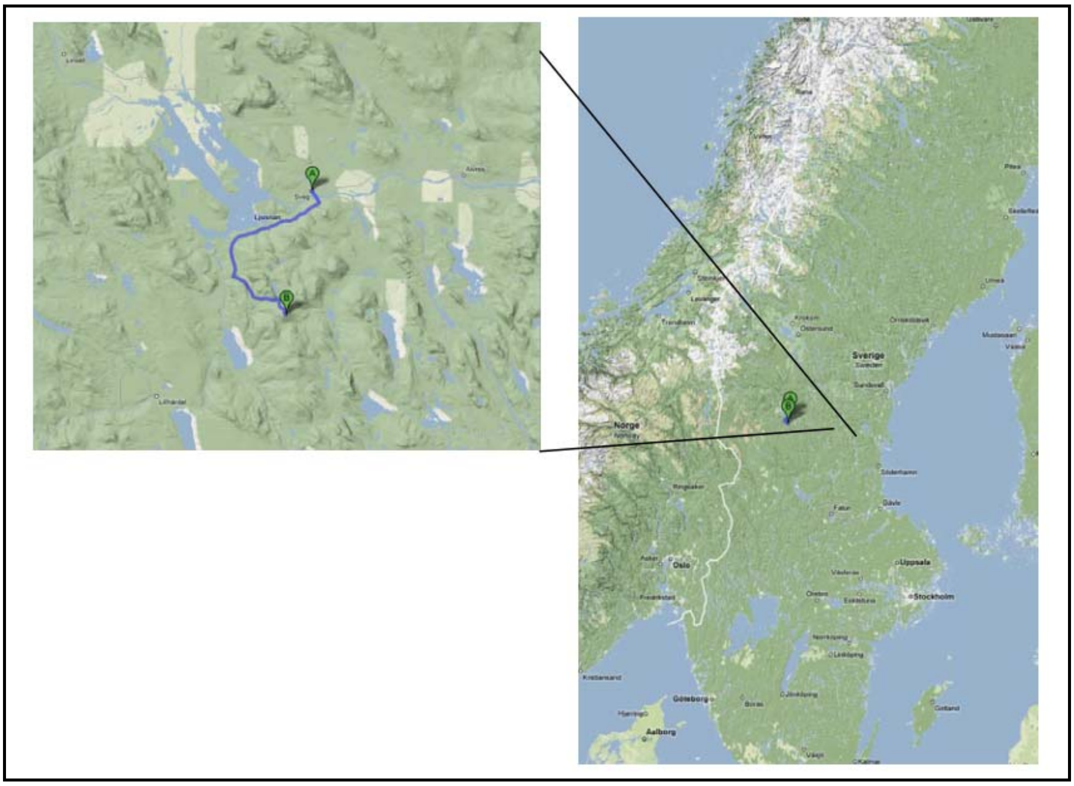


Figure 16. Maps showing the location of the proposed high tower measurement site (B) close to Sveg (A). Maps from [Persson, 2009].

If the Sveg site for some reason would not be able to house the verification measurements there are a number of measurement masts in northern Sweden, owned by some of the Vindforsk member companies, where icing measurements are already in operation and could easily be complemented with the suggested verification measurements. In such case, there are in addition sites with well documented wind direction dependent severe icing which would make it simpler to ensure the sensors are installed in a way they are not influencing each other (flow distortion) during an icing event.

7 Conclusions and discussion

The wind resource in many parts of inland Sweden is balancing on the level of a profitable investment. Even small uncertainties/errors in the investment calculation can be the difference between a profitable project and 25 years of constant losses. One factor that definitively can make the project become non-profitable is standstill during winter caused by icing.

Information regarding icing conditions at a site is therefore important to consider already in the planning process of a wind farm. If the periods with icing conditions are underestimated and no de-icing equipment is decided necessary, unplanned standstills during periods with high wind can cause a substantial loss of income. The opposite can also occur: de-icing equipment is installed unnecessarily, thus reducing the profit.

Unplanned standstills are not only causing a loss of income but can also induce a cost for energy producers when they can't deliver the amount of energy promised.

A high quality icing map is thus one tool in the toolbox used in the planning of wind farm projects. But there are several important issues that must be addressed and resolved along the way:

1. NWP-output used as input in the ice-model must be verified against observations
2. The ice-model output must be verified against measured ice loads.
3. The ice load on the small cylinder must accurately be related to turbine performance.

The last step is turbine dependant and something that turbine manufacturers ideally should provide.

Both the NWP-models used in V-313 and the equation used when the ice load are calculated (1), are full of parameterizations and simplifications which of course induces uncertainties. The uncertainties must be determined in order for the mapping of icing to be useful.

The sensitivity analysis in section 4 showed that it is important to use the correct wind speed when calculating the ice load. The figures in section 5 show that it is difficult to forecast wind speed with high accuracy. If measurements of LWC and droplet concentration can be shown to be of minor importance according to the reasoning in section 6.3, more resources can be focused on the correct modelling of wind speed.

Measurements of LWC and droplet concentration are difficult, but even limited measurement campaigns will help increase the knowledge a lot from the level of today and thus being beneficial to V-313.

From the review of available instruments using optical and thermal techniques in LWC measurements we have concluded them not suitable for these verification measurements. In particular when the focus for the measurements should be rather on its variability. Either requirements on measurement accuracy are not met or the method required to be used will become labour intense.

We propose measurements aiming on investigating the variability of the influence on ice accretion from LWC and droplet size to be performed, in order to verify the relevance of today's parameterisation of these quantities. If the variability between weather situations is small, approximate numbers can be used in the ice load modelling without significantly affecting the quality of the result. If the variability is large, however, there is a strong need for improving the input data for the ice load calculations in order to reduce uncertainties.

The verification measurements as proposed in this study should be done using (preferably three) modified IceMonitor ice load sensors, manufactured by Combitech AB. In addition, during operation the ice load sensors should be monitored by a camera device, enhancing the precision in the coming analysis of ice load data. If the Sveg high tower has the possibility to house these verification measurements, this would be the proposed location. The location should not be critical though as there are several measurement towers in northern Sweden suitable to house these measurements. Lead time to prepare the necessary equipment should be less than six month after ordering, which means that the winter season 2013/2014 is within reach for these verification measurements.

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