Why is this important?

The most important factor in achieving accurate ice-loss calculations are high quality climatic input data.

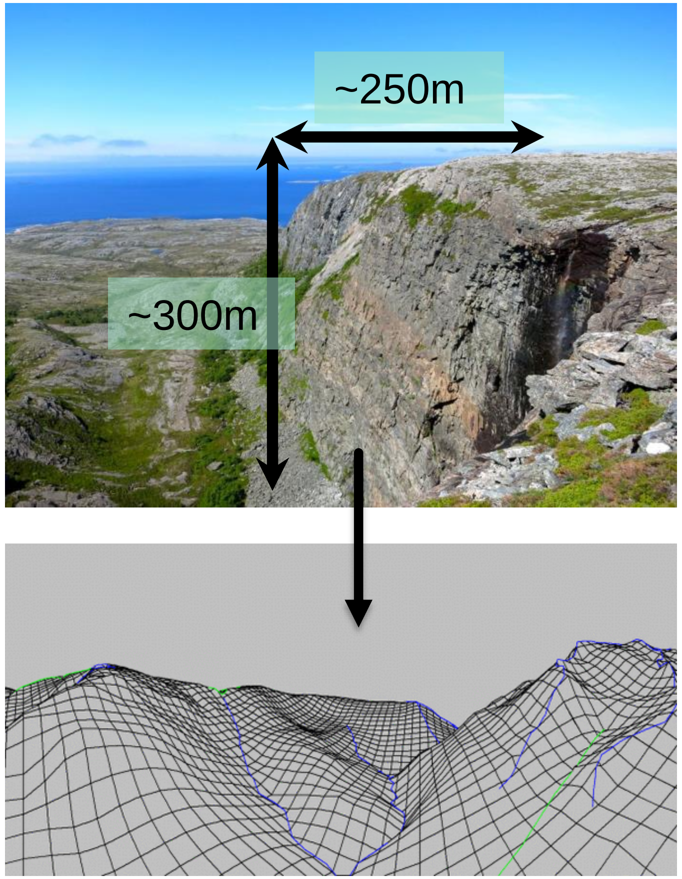
The majority of ice loss calculations are driven by numerical weather forecast information. The accuracy of such simulations is highly dependent on:

- Physics parameterization
- Terrain/mesh resolutions
- Input data (topography, roughness, boundary conditions etc.)

The most important climatic parameters for ice-loss modelling in Scandinavian conditions are:

- Liquid cloud water content
- Temperature
- Wind conditions

Typically verifications are not possible due to lack of cloud water measurements.



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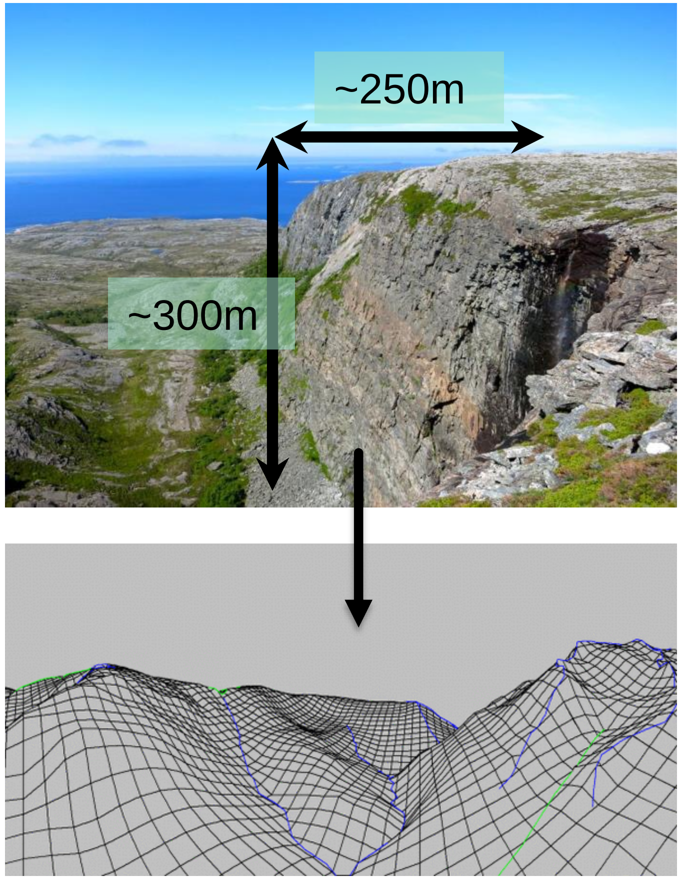

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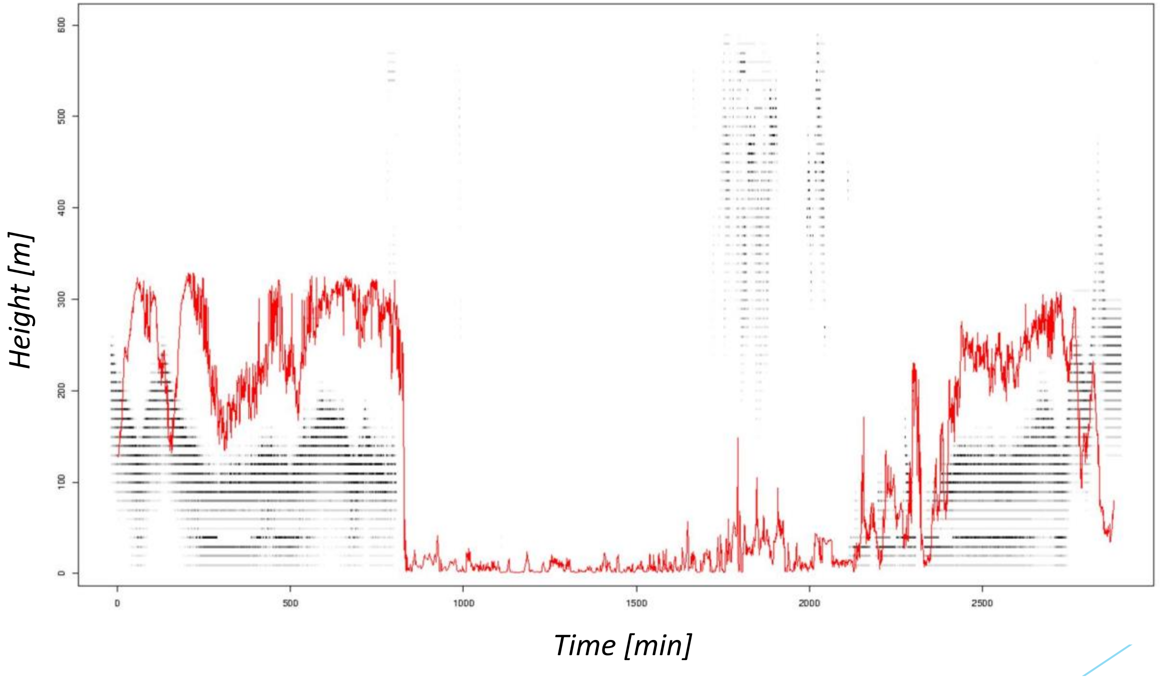
Access to ceilometer data from Statkraft

In this work we had access to Ceilometer data from Statkraft to validate different WRF configurations. This gives us measurements of the cloud base height and the opacity in a vertical column.

Two Ceilometers were placed in the complex coastal terrain of the Fosen area in Norway as well as two inland forested sites in northern Sweden.



Opacity integrated between 50 and 200 m. The more dense the cloud (black marks) is between 50 and 200m, the higher opacity (red line) value.

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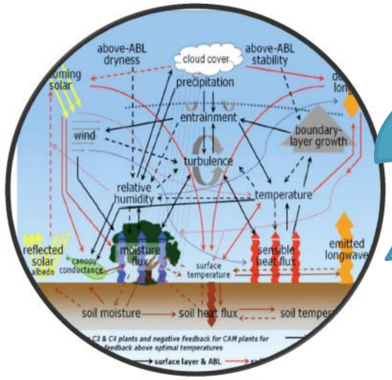
The road to better ice loss estimations

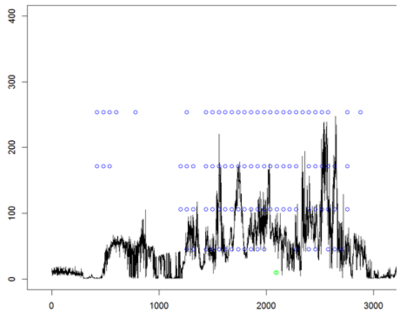
Step 1: Calibrate WRF data towards ceilometer measurements.

WRF simulation



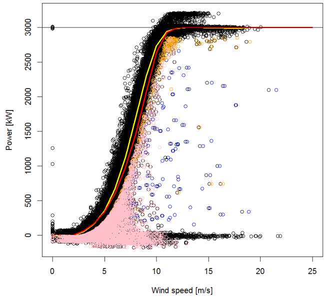
- ✓ Parameterization
- ✓ Resolution
- ✓ Elevation data

Ceilometer vs WRF verification



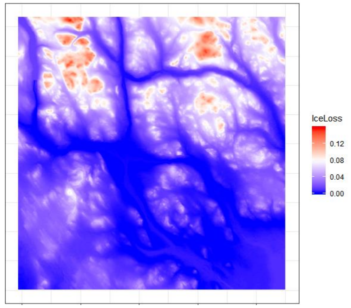
Step 2: Quantify ice loss based on SCADA data and relate it to climatic conditions.

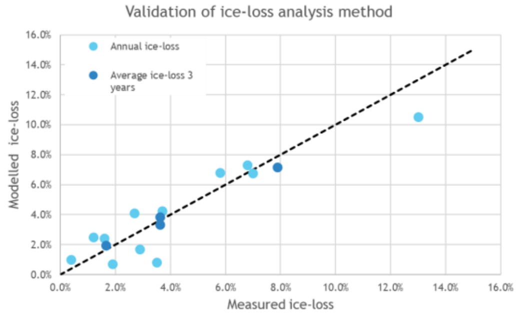
SCADA data ice analysis



Step 3: Use the combined knowledge from the previous steps to develop a physics based numerical ice loss model.

Numerical ice loss analysis





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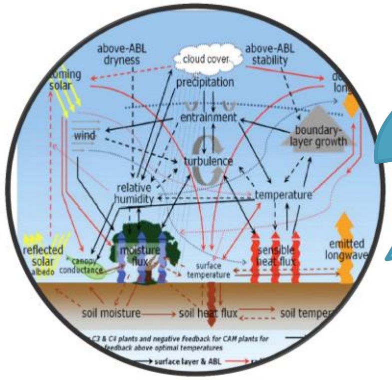

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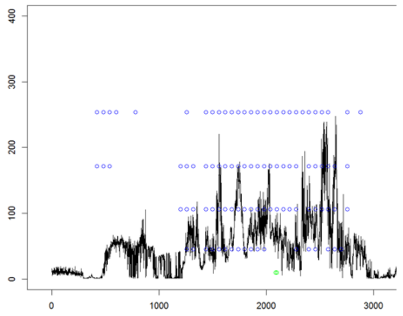

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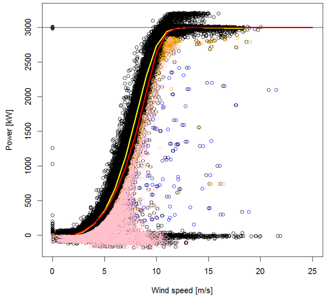

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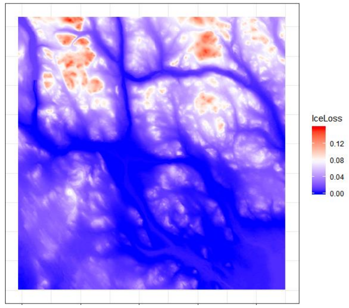
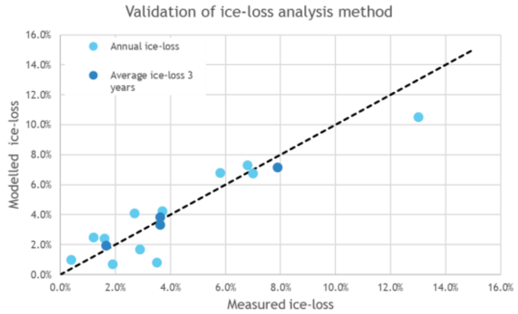


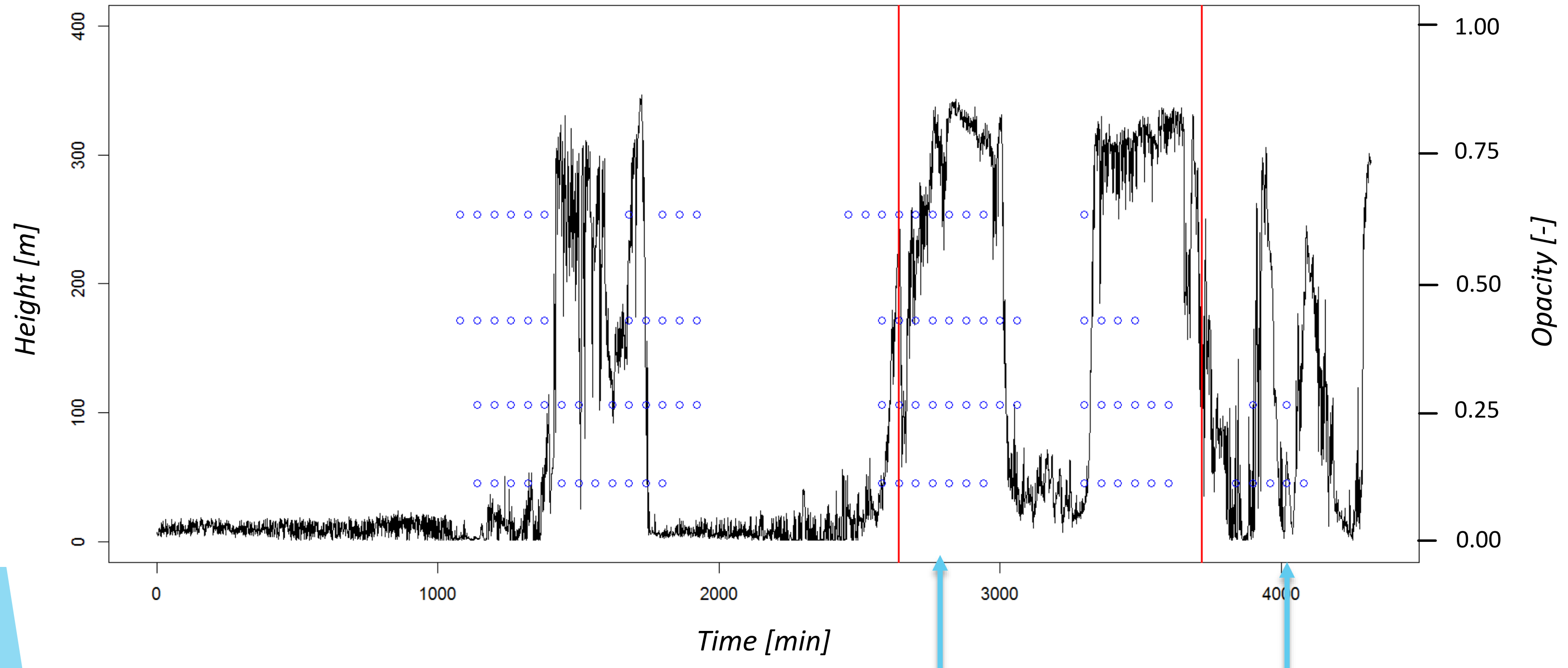


Step 1: Temporal verification of ceilometer opacity vs WRF cloud water presence.

Modern Energy

The Ceilometer has been used to verify the temporal distribution of cloud water in a vertical column.

With an appropriate WRF configuration the model is capable of capturing both fog and clouds at the correct heights, but in the individual events, start time and duration may differ slightly between WRF and observations.



- Black lines - Ceilometer opacity (50-200 m)
- Blue marks - WRF forecast liquid cloud water content above 0.05 g/m^3 at the specific height

Clouds covering the whole rotor disc, high opacity

Low fog, lower opacity

Statkraft

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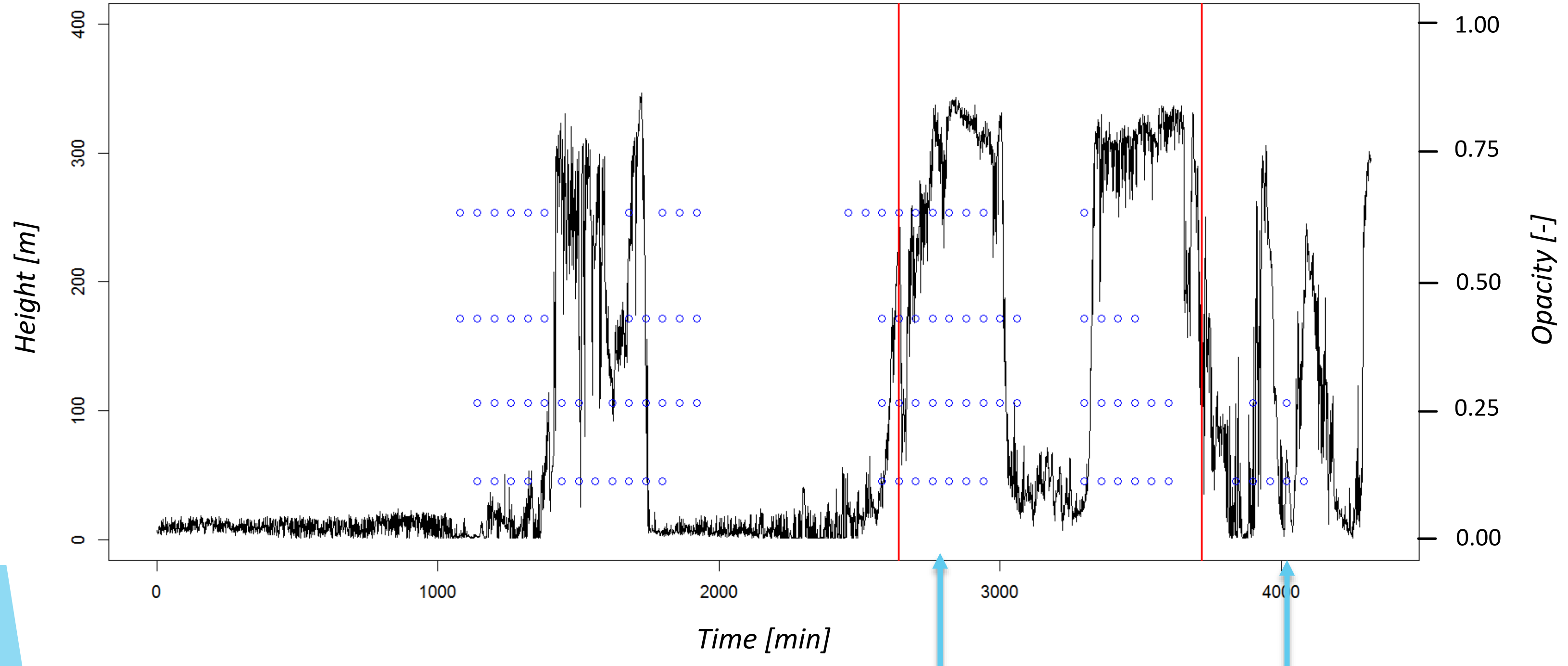

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Clouds covering the whole rotor disc, high opacity

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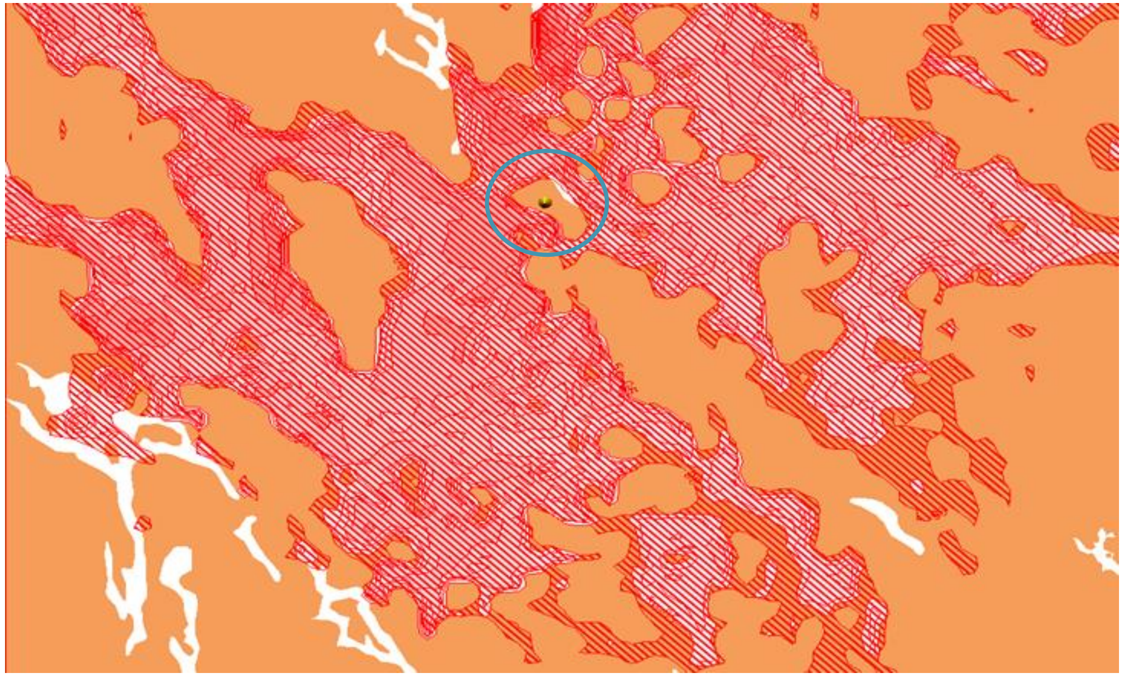
Statkraft

Step 1: Spatial verification of WRF cloud water presence.

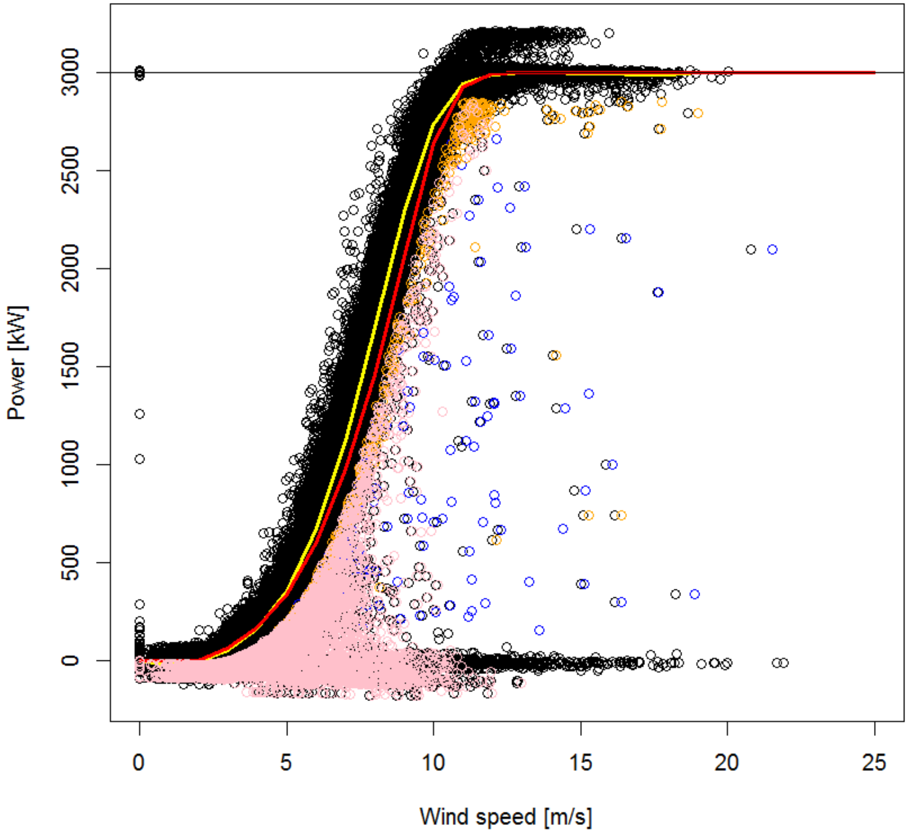
The Ceilometer has also been used to verify the importance of WRF resolution to capture the spatial distribution of cloud water.

Sufficient model resolution is not only important for orographic cloud formation. In the example below, a lower resolution would have given clouds/fog also on top of the hill in the wind farm area.



- The dot in the middle represent one of the Ceilometer locations on a hilltop in northern Sweden.
- The red fields shows cloud water content at about 100 m above ground.

Step 2: Quantifying ice-loss from SCADA data



- Yellow line is a binned power curve based on median power in each wind speed bin.
- Pink dots is defined as icing loss.
- Ice underperformance is determined by a wind speed shifted binned power curve.

Step 2: WRF forecast liquid cloud water content, cloud base and performance loss

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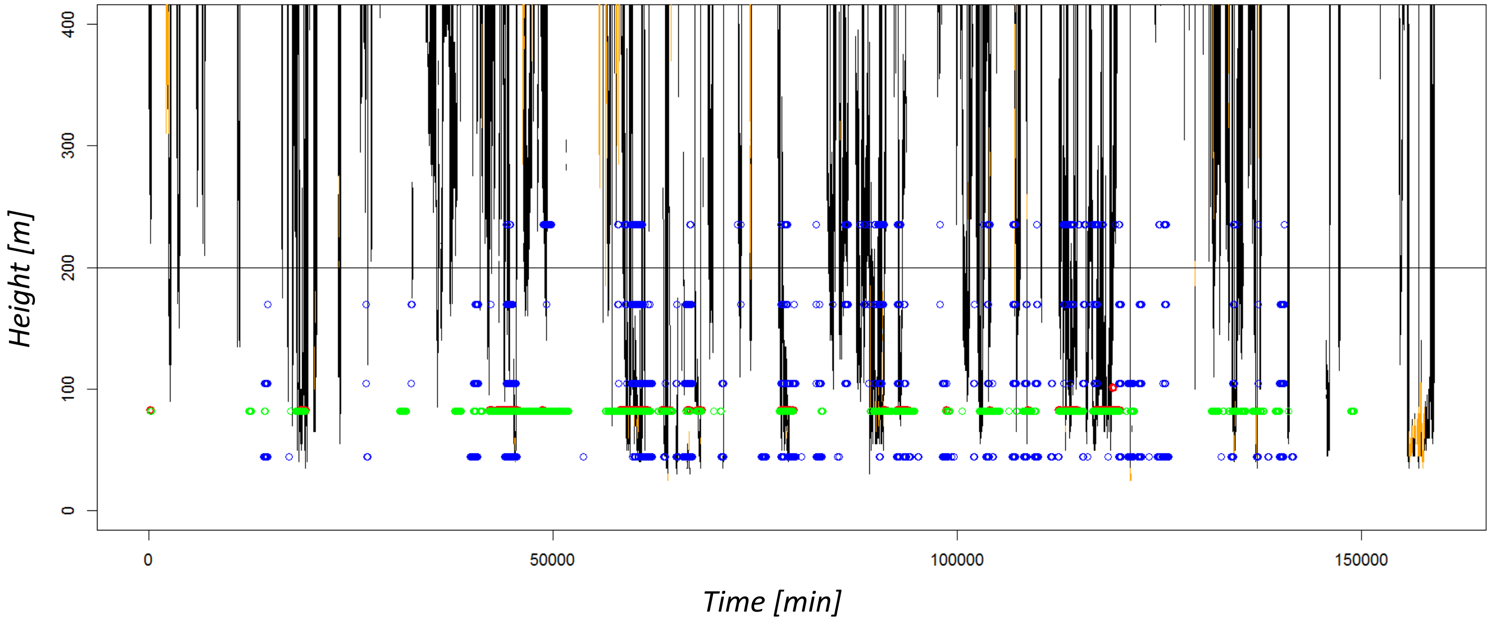
This figure confirms a good correlation between observed and modelled clouds with performance loss due to ice based on operational SCADA data.



- Black lines - Ceilometer cloud base
- Blue marks - WRF forecast liquid cloud water content above 0.05 g/m^3 at the specific height
- Green marks - Performance loss in SCADA data

Statkraft

Step 1 and 2 key findings

- Wind farms are common at hilltops and a sufficient model resolution is needed to capture orographic cloud formation as well as clouds/fog during temperature inversions.
- A horizontal model resolution of 1-1.5 km is sufficient in most cases, although in extreme terrain it can be beneficial to use 667m resolution.
- High terrain resolution of 500 m was found beneficial at WRF model resolutions of <=1.5 km.
- With an appropriate WRF configuration the model is capable of capturing both fog and clouds at the correct heights.
- On average the frequency and dynamics of clouds are correct, but in the individual events start time and duration may differ slightly between WRF and observations.
- Our analysis shows a good correlation between observed and modelled clouds with performance loss due to ice based on operational SCADA data.
- Our study shows that the droplet size distribution (dependent on aerosol concentration) is an important parameter to determine the severity of the icing events .

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Step 3: Ice-loss analysis methodology

Modern Energy

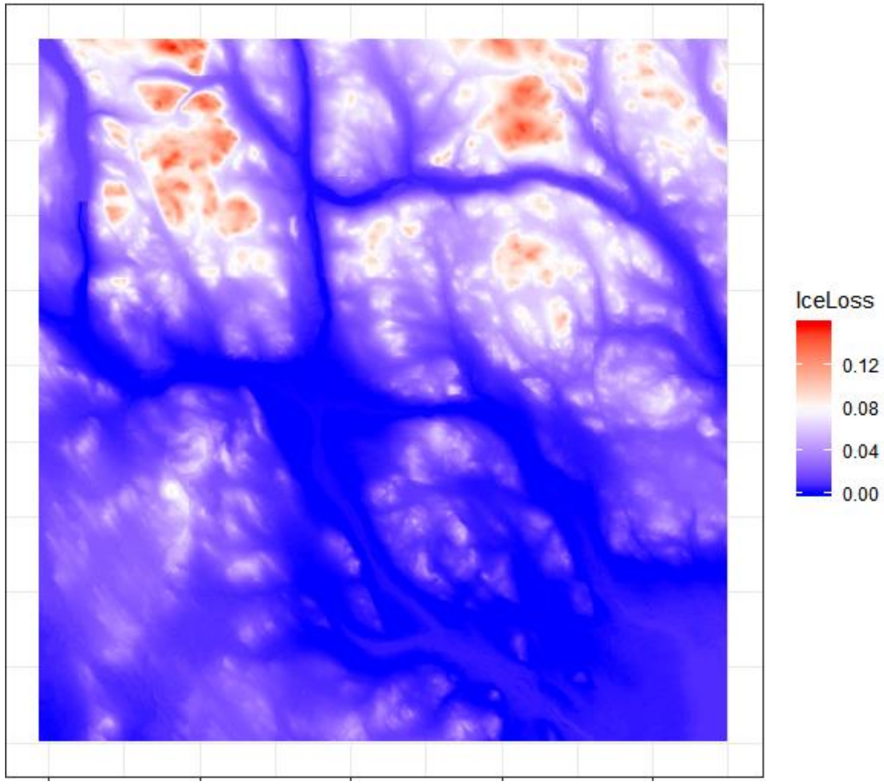
The ice-loss model consist of the following steps:

1) Time series of local weather conditions
Local temperature, liquid cloud water content and wind conditions give the potential for icing.

2) Numerical simulation of Ice-dynamics up due to local conditions
This includes ice-accretion, reduction (melting, sublimation & mechanical shedding) as well as loss of turbine performance.

3) Turbine specific control strategy
Production losses due to ice are dependent on turbine control strategy and trigger points.

4) Turbine specific de-icing system characteristics
The effect of a de-icing system vary based on technical configuration, turbine control settings and local weather.



The ice-loss model produce time series of ice-loss at each turbine. The model also generates an ice-loss map, which enables wind turbine layouts to include the effect of ice-loss already at the planning/optimization stage.

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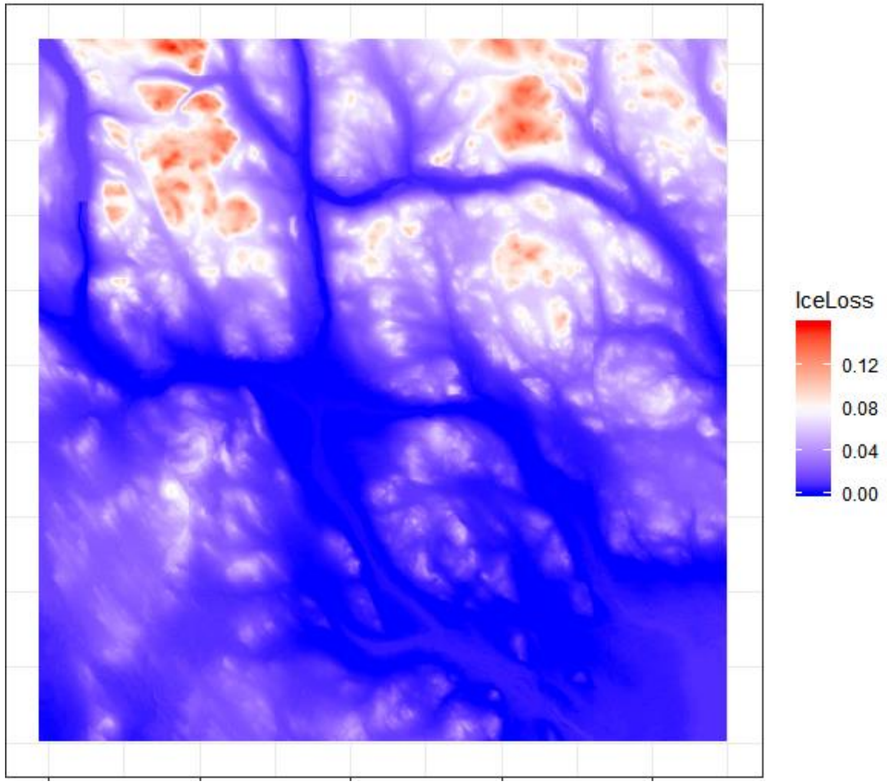

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Step 3: Validation of Ice-loss analysis method

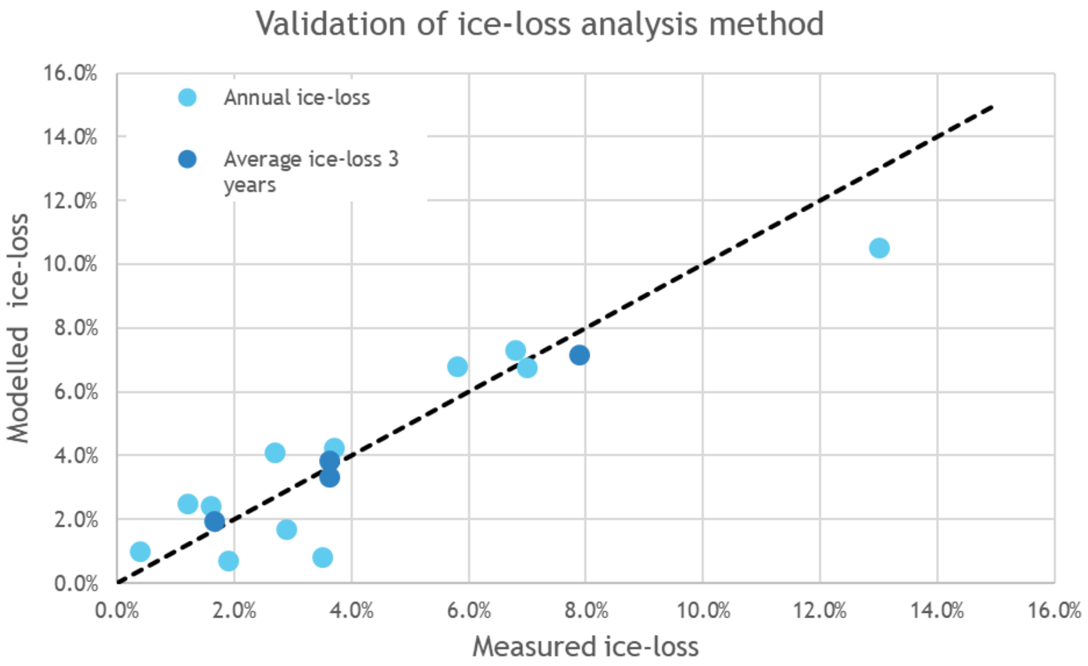
Modern Energy

The ice-loss analysis method has been calibrated against production data from both inland and coastal sites in Norway and Sweden.

The figure shows model validation against field data from four wind farms with low, moderate and high ice-losses over a period of three full years.

Overall fair agreement is achieved for all sites both in terms of long term ice-loss and annual variability.

There is one “extreme” year for one of the sites which is captured well considering the abnormal conditions for that location.



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