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Addressing forecast uncertainty of wind turbine icing with deterministic sampling

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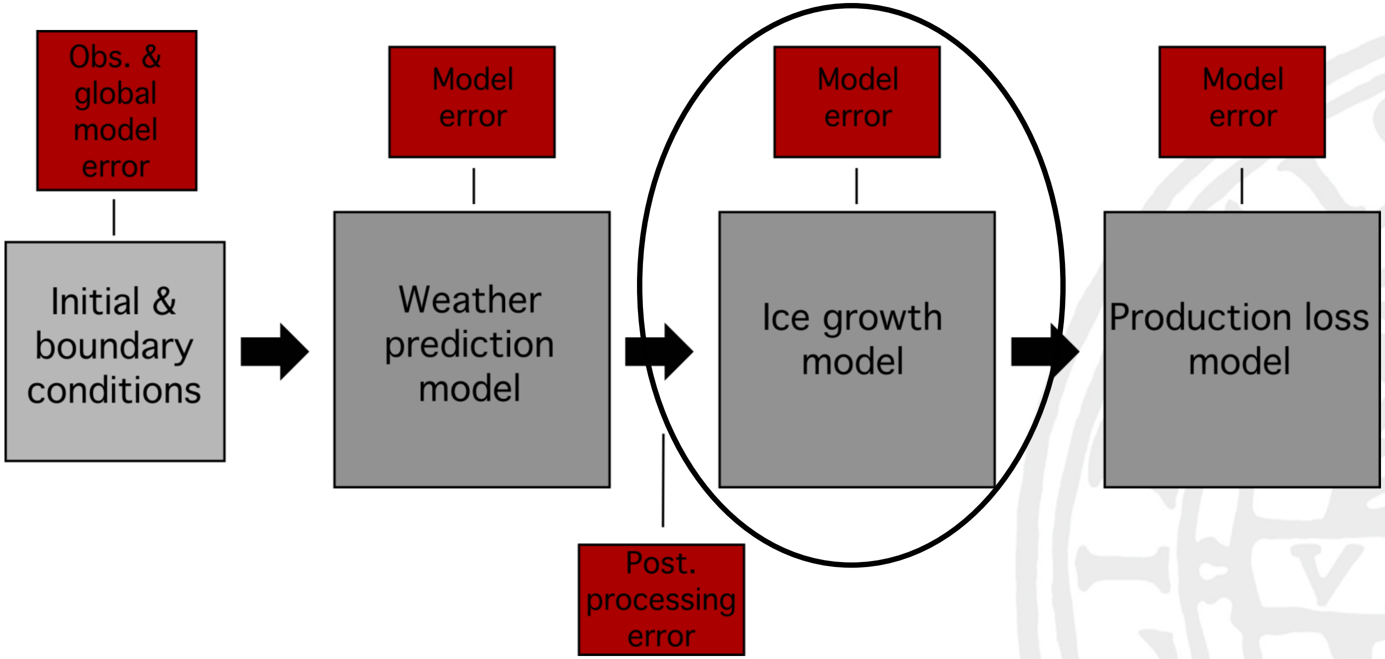
Energimyndigheten SMHI WeatherTech VATTENFALL

Motivation - Uncertainties in the modelling chain

Multi-physics icing-model ensemble
Uncertainty quantification as well as probabilistic forecasts provide estimations of forecast uncertainty and increase forecast skill.



Previous study on initial condition and post. processing uncertainty contribution:
Probabilistic forecasting of wind power production losses in cold climates: A case study, J. P. Söderman et. al. Wind Energy Science, Discussion paper, https://doi.org/10.5194/wes_2017_28

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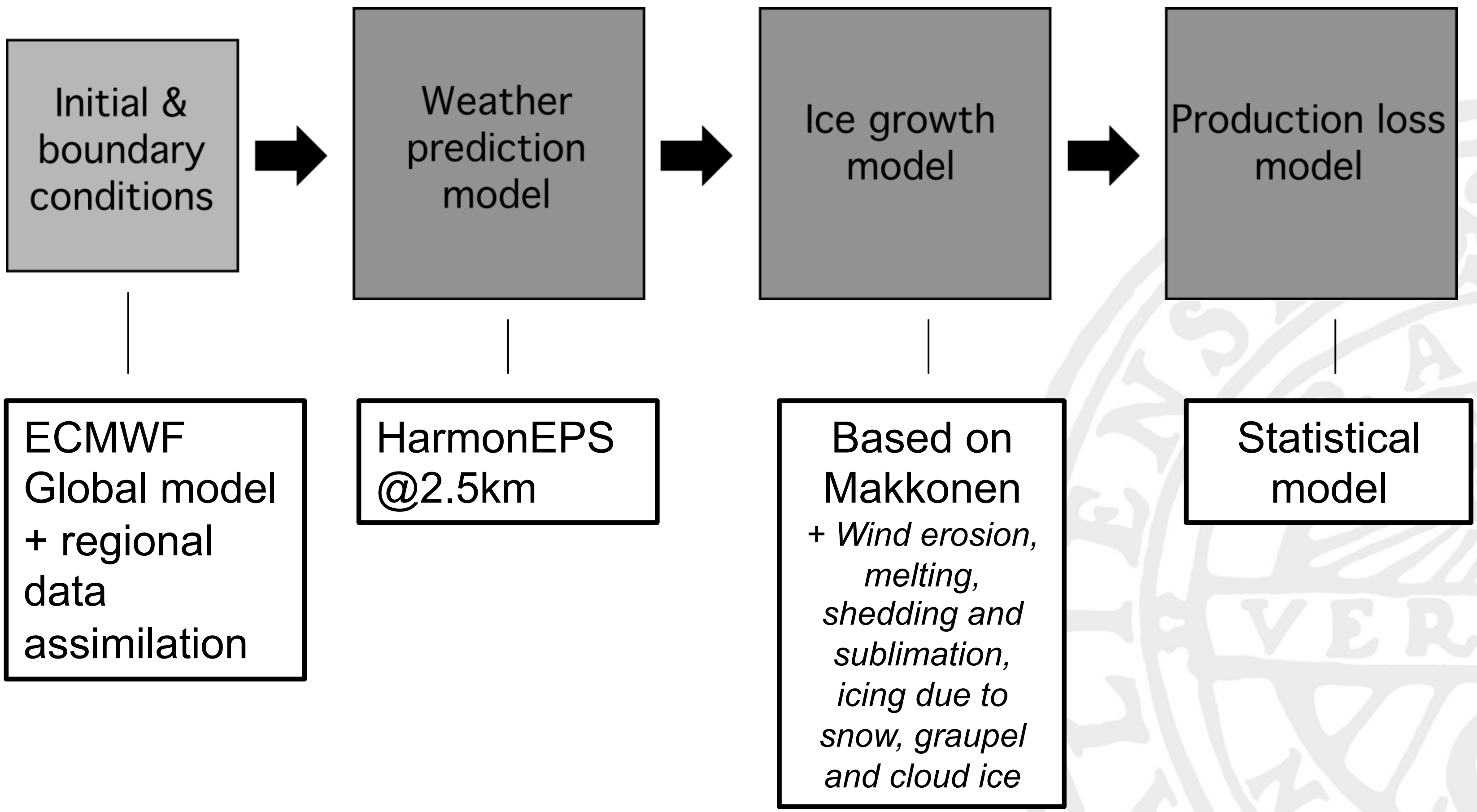
Modelling chain



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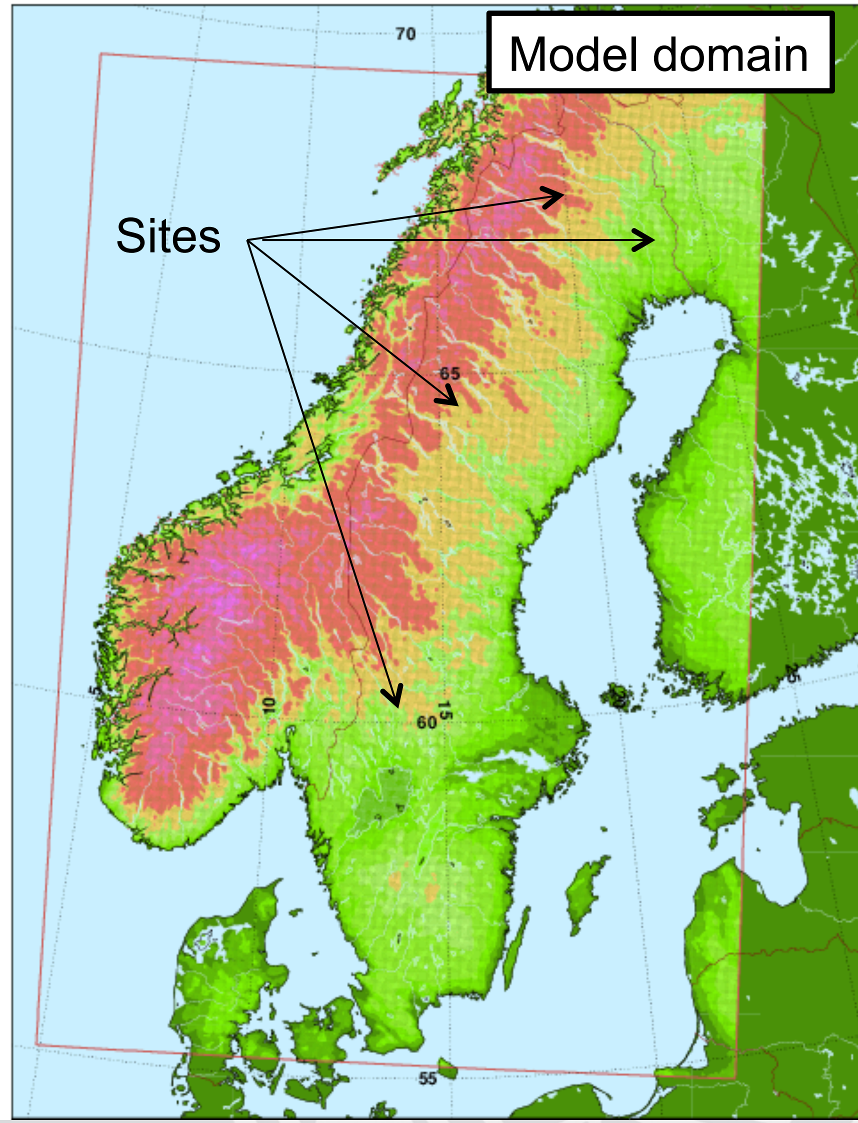
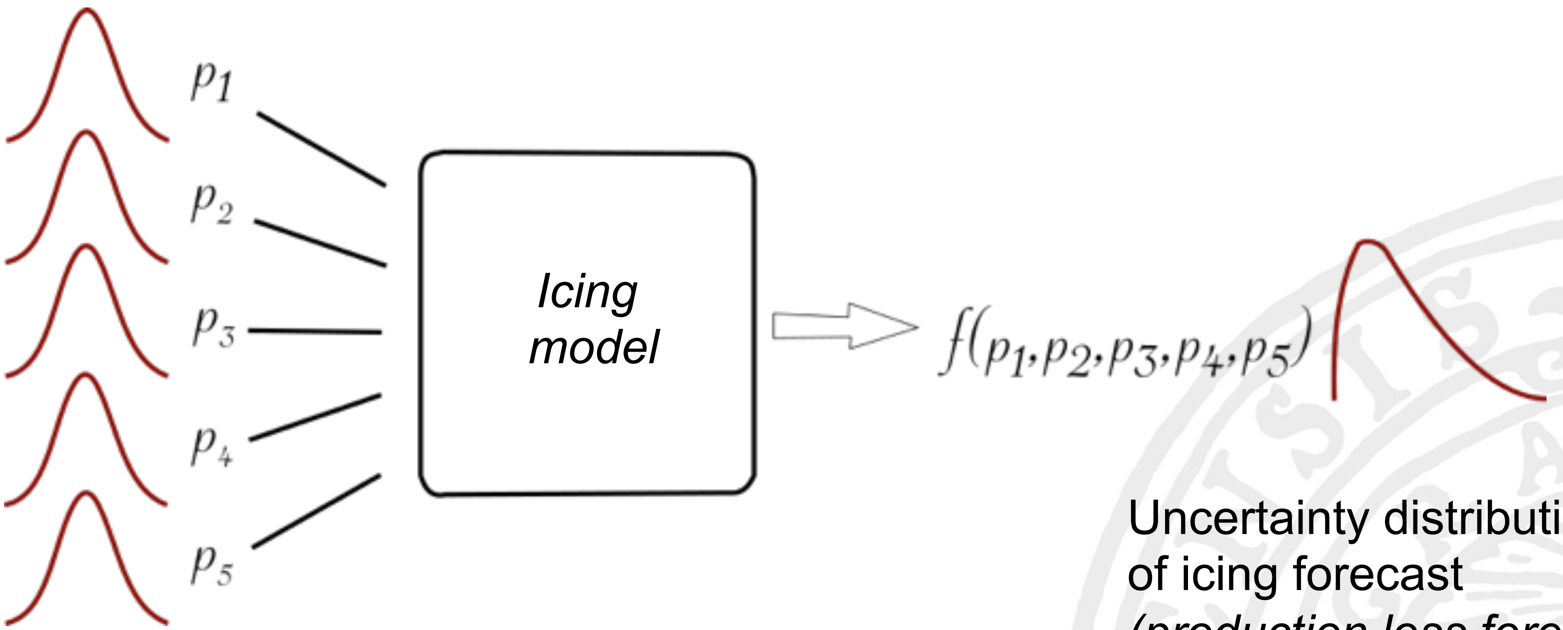
Period and verification data

- Two winter periods:
    - December 2013 to February 2014
    - September 2014 to December 2014 (February 2015)

- Four observation sites, wind parks without ice protection systems:
    - Wind speed (from the nacelle)
    - Temperature (from the nacelle)
    - Production data
    - (Icing observations)
- Forecasts 06 UTC +42h (+18-42h for next day)



Icing model ensemble

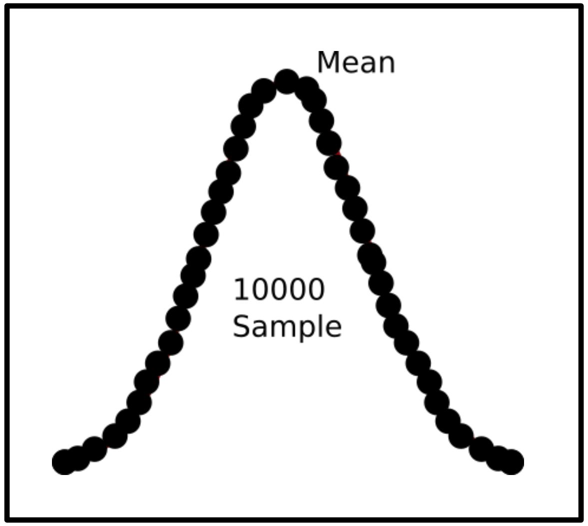


Uncertainty distribution
of icing forecast
(production loss forecast)

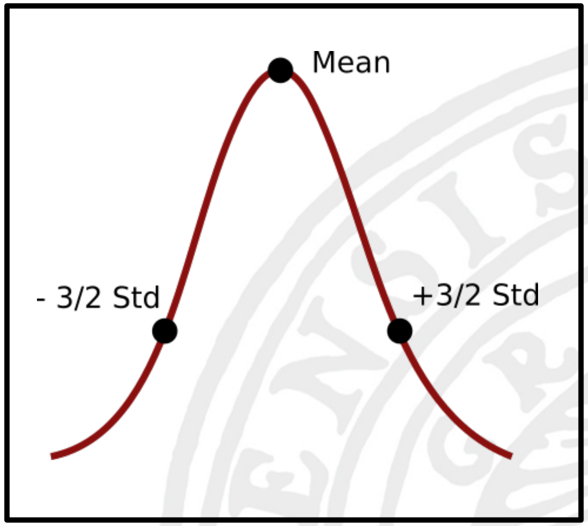
Uncertain parameters
of the model with estimated
uncertainty distribution

Sampling from the uncertainty distribution with an ensemble

Random sampling



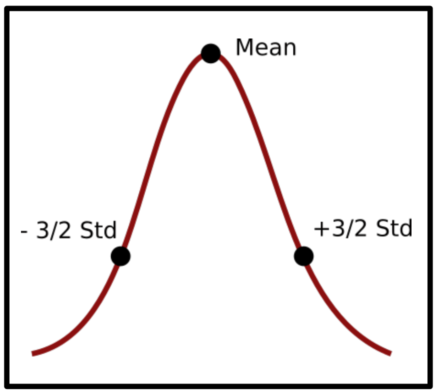
Deterministic sampling



Optimal selection of ensemble members limits the ensemble size.
⇒ Less computational time and easier uncertainty quantification.

Sampling from the uncertainty distribution of each parameter

Deterministic sampling



(No skewness)

Hadamard matrix

- 9 member ensemble (8 perturbed)
- Perturbed members weight ~1/18, control ~9/18

Uncertain parameters

	Ensemble members 1	2	3	4	5	6	7	8
P_1	+	-	+	-	+	-	+	-
P_2	+	+	-	-	+	+	-	-
P_3	+	-	-	+	+	-	-	+
P_4	+	+	+	+	-	-	-	-
P_5	+	-	+	-	-	+	-	+

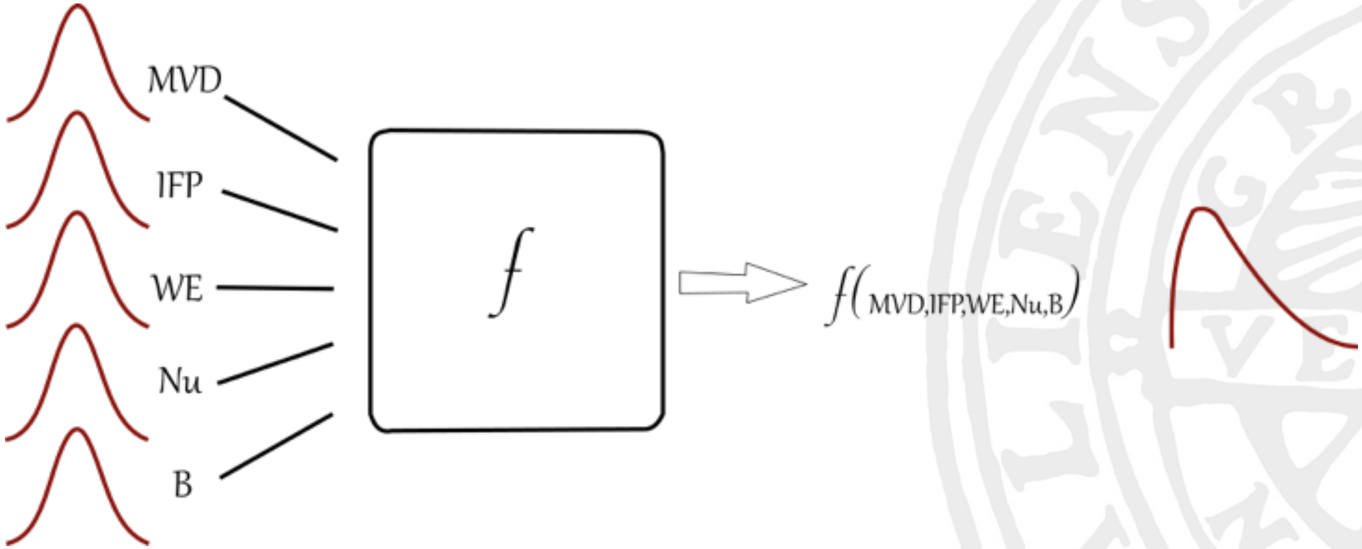
Standard deviation

Random and deterministic sampling results in similar ensemble mean and mean spread

Uncertain parameters in the icing model

Five parameters based on literature studies

MVD – *Median Volume Diameter*
IFP – *Ice shedding factor*
WE – *Wind erosion*
Nu – *Nusselt number*
β – *Sticking efficiency for snow and graupel*



Uncertain parameters in the icing model

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Perturbations for the ice growth

MVD – *Median Volume Diameter*

- f(LWC,Nd)
- Effects the collision and accretion efficiency
- Is done for all hydrometeors: Cloud ice/water, rain, snow, graupel
- Is perturbed with a constant +/- 0.5 (50%)
- Previous studies (eg. Davis2014) show large effect on the ice load

Davis, N., Hahmann, A. N., Clausen, N. E., and Žagar, M.: Forecast of icing events at a wind farm in Sweden, Journal of Applied Meteorology and Climatology, 53, 262–281, https://doi.org/10.1175/ JAMC-D-13-09.1, 2014

Nu – *Nusselt number*

- Effects accreation efficiency and sublimation
- Depend on the ”angle of attack”
- Is perturbed with constant (NuC) 0.03+/-0.015
- Based on Makkonen2000 and Wang2008

Wang, Xin: Convective heat transfer and experimental icing aerodynamics of wind turbine blades, http://hdl.handle.net/1993/3082, 2008

Makkonen, L.: Models for the growth of rime, glaze icicles and wet snow on structures, Philosophical Transactions of The Royal Society Lond., 358, 2913–2039, https://doi.org/10.1098/rsta.2000.0690, 2000.

Uncertain parameters in the icing model

Perturbations for the ice <u>growth</u>

β – *Sticking efficiency for snow and graupel (α_2)*

- $\beta = 1/v^{bC}$ (v=wind speed)
- bC is perturbed with 0.75 +/-0.22
- Based on Nygaard et al (2013) and ISO2001standard for ice modelling where it is stated as very uncertain

Sensitivity of the "ice growth perturbations":

$$\frac{\partial ploss}{\partial STD} \approx \pm 0.1 MW$$

Nygaard, B. E. K., Àgústsson, H., and Somfalvi-Tóth, K.: Modeling Wet Snow Accretion on Power Lines : Improvements to Previous Methods Using 50 Years of Observations, Journal of Applied Meteorology and Climatology, 52, 2189–2203, https://doi.org/10.1175/JAMC-D-12-0332.1, 2013

Uncertain parameters in the icing model

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Perturbations for ice loss

IFP – *Ice falls of during melting* (Björn Egil Nygaard)

- Constant in the equation for melting = 8
- Perturbed with 8+/- 3.5
- Is estimated for ice on power lines

(+ Nusselt number for sublimation)

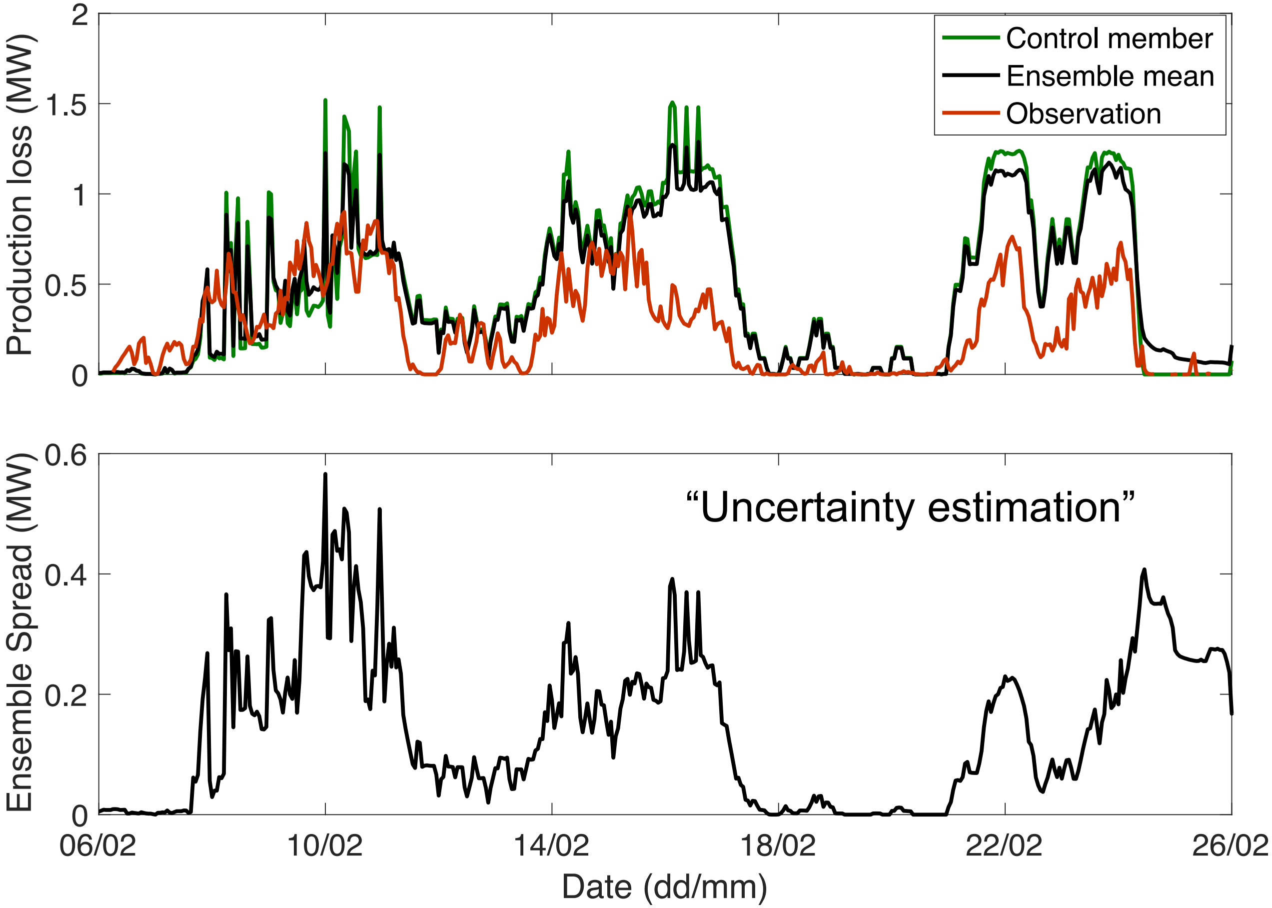
WE – *Wind erosion*

- $g/m^2/(ms^{-1})$ after 5 ms^{-1}
- Is perturbed with 10+/- 4.4
- Has been shown to be important in the icing model, but in eg. Davis2016 it is not very sensitive.
- Perturb more?

Sensitivity of the "ice loss perturbations":
Low on average, high occasionally

Davis, N. N., Pinson, P., Hahmann, A. N., Clausen, N.-e., and Žagar, M.: Identifying and characterizing the impact of turbine icing on wind farm power generation, Wind Energy, 16, 1503–1518, https://doi.org/10.1002/we, 2016

Results – Example



Verification

- The ensemble forecast is compared with the control member which has no perturbations

Uncertainty estimation

- Mean spread of ensemble members

Results – Reduced forecast error

RMSE production loss (MW)

2013-2014

Site	A	B	C	D
CM	0.54	0.49	0.33	0.48
Det. sampling (Ensemble mean)	0.45	0.45	0.29	0.45

2014-2015

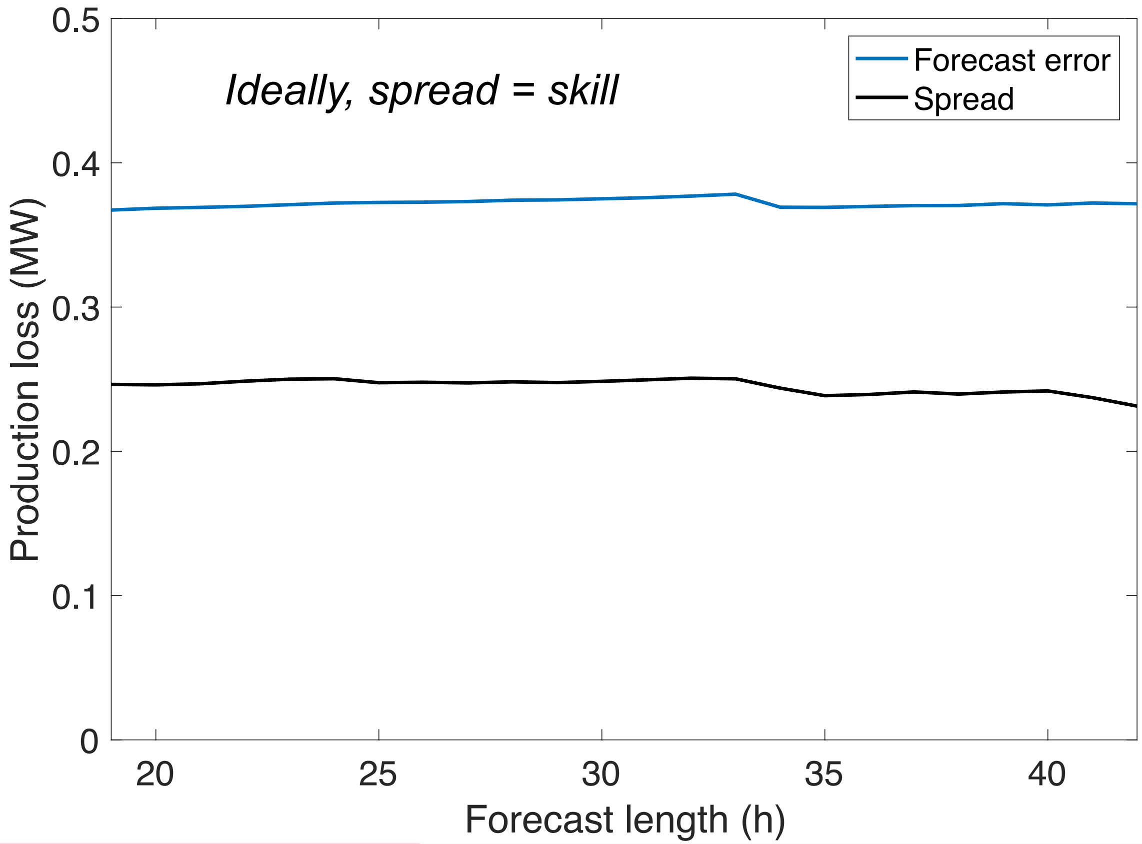
Site	A	B	C	D
CM	0.38	0.27	0.35	0.34
Det. sampling (Ensemble mean)	0.32	0.24	0.31	0.33

Average reduction of forecast error

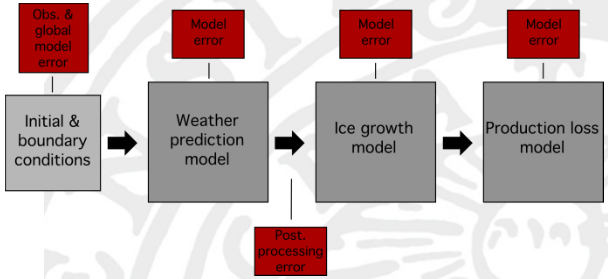
~10 %

Results – Spread/skill relationship

Averaged over the two verification periods

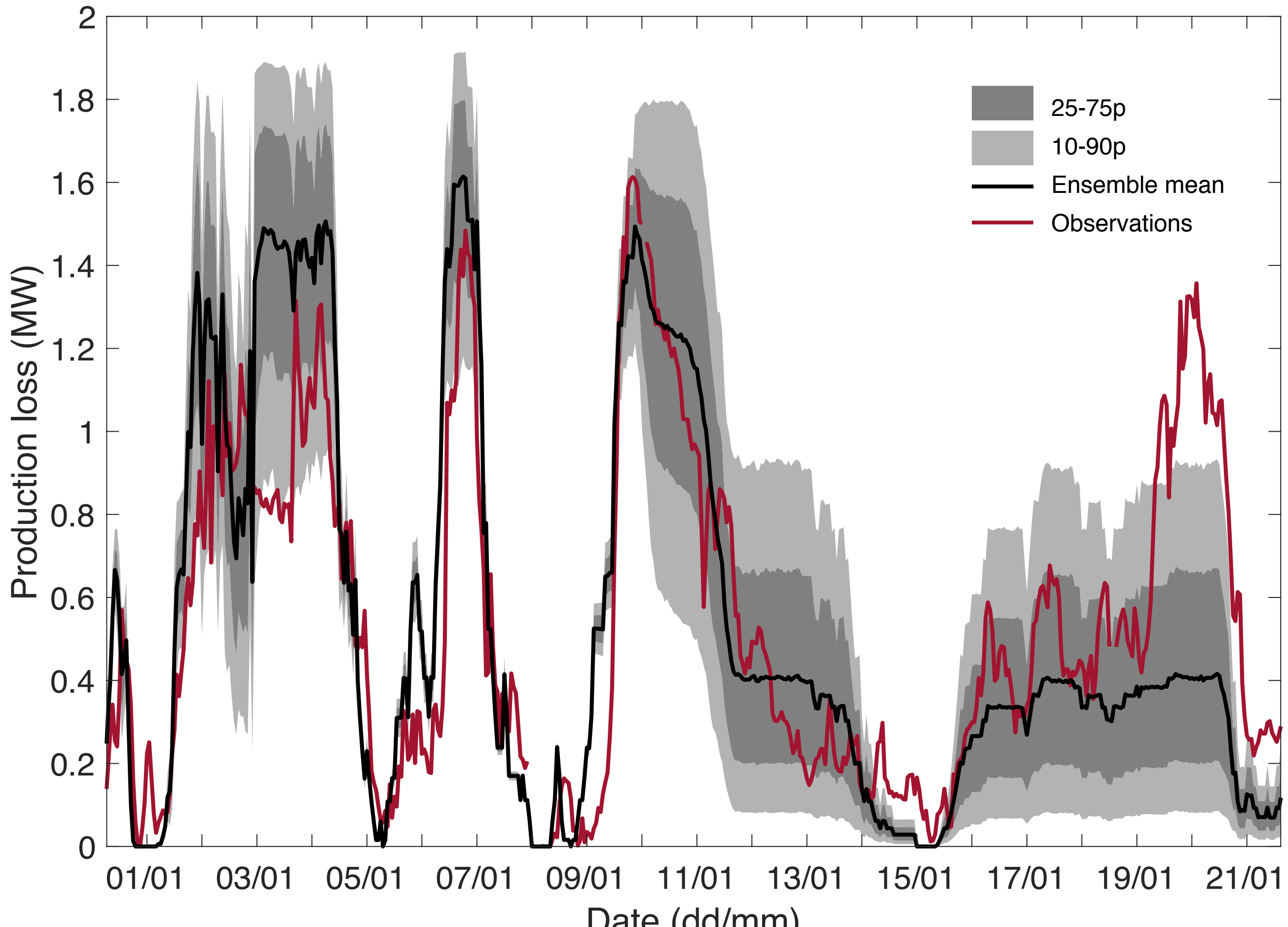


All uncertainties are not included



Results – Uncertainty distribution Probabilistic forecasting

Based on ensemble, probabilistic forecasts are created.



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Summary

- Uncertainty terms of the icing model were identified.
- Deterministic and random sampling was used to address these uncertainties in the production chain for wind power in cold climate.
- The resulting ensemble forecasts improves forecast skill.
- The spread can be used as an estimation of forecast uncertainty.
- Deterministic sampling can be used to efficiently address model uncertainties and improve the forecast. It has low computational costs and can easily be extended with new uncertain parameters.

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Thank you!