Innovations in F-LOWICE Real-Time Forecasts of Wind Power and Icing Effects

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***Abstract*: Recent enhancements to F-LOWICE have been made to improve real-time, HIRLAM-based forecasts of temperature and wind speed at wind farms, as well as the downstream effects on both "clean" and "iced" power estimations from the F-LOWICE algorithms. A method to communicate the uncertainties in wind power forecasts and the effects of icing upon them is also described.**

Keywords: icing, wind power, models, probability

LEGEND AND ABBREVIATIONS

FMI	*Finnish Meteorological Institute*
LAPS	*Local Analysis and Prediction System*
LWC	*Liquid Water Content (TNR 8 pt)*
MVD	*Median Volume Diameter*
T	*Temperature*
U	*Wind Speed*

INTRODUCTION

In recent years, numerous systems have been developed for the diagnosis and prediction of wind power and the effects of icing conditions thereon. These include two systems developed in partnership between Leading Edge Atmospherics ("LEA") and the Finnish Meteorological Institute ("FMI") called "LOWICE" and "F-LOWICE". Respectively, these systems produce diagnoses and forecasts of icing and wind power. As part of the Swedish Energy Agency's Wind Pilot Program, LOWICE, F-LOWICE and forecast systems from several other agencies were run over Sweden for several icing seasons.

Output from these systems have been compared with observations of temperature, wind speed, power and icing at wind farms and the results have proven that these systems provide reasonably realistic information. Of course, the systems are not perfect and errors and biases have been identified. Among the LEA-FMI systems, the LAPS analysis-based diagnostic system LOWICE clearly outperformed the HIRLAM-forecast based F-LOWICE system, especially in terms of temperature and wind speed. Model forecast errors promulgated downstream causing errors in icing presence, and both "clean" and "iced" power predictions. Additional errors inherent in models include mis-timing of weather features, such as fronts, wind maxima/minima, presence and strength of inversions, structure of wind profiles, plus natural variability of meteorological phenomena, especially in complex terrain.

In an effort to improve real-time F-LOWICE forecasts for the final seasons of the Wind Pilot Program, two improvements to the system were put in place. The first was an attempt to identify errors and biases in the first six hours of HIRLAM model forecasts of temperature (T) and wind speed (U) at wind farms via comparison with wind farm observations and high-quality diagnostics from the LAPS model, then apply those corrections to the remainder of the forecast run.

The second approach was to communicate to users some of the uncertainties in power forecasts that are associated with local variability as well as mis-forecasting of meteorological features that are relevant to wind turbine icing and power.

I. DIAGNOSITCS, FORECASTS AND OBSERVATIONS

LEA and FMI have been running two real-time systems to assess the potential for wind turbine icing across Scandinavia for several years. The longest running system is "LOWICE", which provides hourly diagnoses, while the newer "F-LOWICE" system (forecast version of LOWICE) has been providing forecasts out to +48 hours for the last two years.

A. LAPS-based LOWICE

Beyond the direct measurement of icing at a given location, there are numerous sources of meteorological data that can be used to estimate near-surface icing conditions indirectly. In particular, observations from satellites, surface stations and radars provide a great deal of useful information, especially when paired with forecasts from numerical weather models. Each of these data sources has its strengths and weaknesses for the diagnosis and forecasting of icing, and the information from each must be considered carefully in the context of the meteorological environment in order to use them effectively. For example, significant radar reflectivity can be a strong indicator of glaze icing when freezing rain is occurring, but it can also be a strong indicator of the depletion of liquid water in icing clouds when snow is occurring.

It is with these concepts in mind that a real-time version of the "LOWICE" system was developed using the Finnish Meteorological Institute's Local Analysis and Prediction System (LAPS) model to produce hourly assessments of the likelihood and severity of icing over Scandinavia [1,2]. LAPS-Scandinavia combines ECMWF model forecast grids with Meteosat geostationary satellite data, reflectivity from a network of radars, and surface observations across the domain to create hourly, 3-D analyses of the state of the atmosphere in the domain. LAPS grids of pressure, temperature, winds, relative humidity, cloud fields and precipitation provide essential input fields to the LOWICE system. A map of the LAPS domain and the model's representation of terrain of Scandinavia are given in Fig. 1.

At each grid point, LOWICE examines the satellite and surface observations to determine whether or not the grid point is "cloudy", and then tests to see whether the vertical level of interest (e.g. a wind farm) is vertically located within the clouds and/or within a layer of liquid precipitation. If either is the case and temperatures are suitable, then icing conditions may exist. The likelihood of icing is then assessed through examination of the physical structure present (e.g. a single layer cloud), applying fuzzy-logic interest maps to icing-relevant fields (e.g. temperature, cloud top temperature), and testing for the presence of certain precipitation types (e.g. snow, freezing rain) nearby. Using this same information, liquid water content is estimated and combined with wind speed to estimate icing rates, ice loads and most importantly, both "clean" (ice-free) and "iced" power for individual turbines and entire wind farms.

B. *HIRLAM-based F-LOWICE*

A forecast version of LOWICE, known as "F-LOWICE" was developed to produce 0-48 hour forecasts of the same fields and outputs described above, based primarily on numerical model forecasts from the HIRLAM model [3]. Of course, observations of the presence of clouds, cloud structures, cloud phase, precipitation presence, intensity and type, as well as other highly relevant fields for icing and wind power are not available for future times. However, surrogates of these fields can be derived from 4-D model forecasts of temperature, wind speed, relative humidity, explicit cloud microphysics, and precipitation. Though imperfect, these fields can be used to simulate the expected presence of relevant meteorological features in the atmosphere and passed through algorithms similar to those applied in LOWICE to estimate icing- and wind-power in the future. A map of the HIRLAM sub-domain used by F-LOWICE and the model's representation of terrain of region are given in Fig. 1.

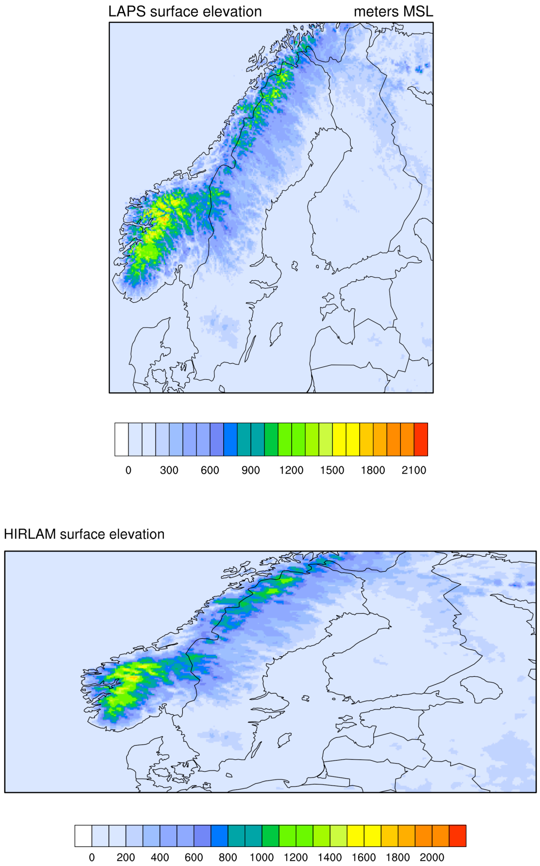

Figure 1: LAPS (top) and HIRLAM subset (bottom) grids used by LOWICE and F-LOWICE, respectively. The height of the model terrain is shown here.

C. *"GROUND TRUTH"OBSERVATIONS*

Real-time data from wind turbines and co-located meteorological and icing instruments provided "ground truth" observations for comparison with LOWICE and F-LOWICE system output. Turbine data included temperature, winds, and measured power production, while the meteorological instruments provided independent measurements of temperature, winds, and in some cases ice load, visibility and/or ceiling height. Webcam images were also available at some sites (Fig. 2). Such imagery proved very helpful for documenting events and corroborating instrumentation measurements with things like visible ice growth or depletion over time.

Figure 2: Example of iced instrumentation package on top of a wind turbine. Another turbine and some low-altitude icing clouds are evident in the background.

II. ADJUSTMENTS TO RAW HIRLAM MODEL FORECASTS

In an effort to correct for systematic over-forecasts of wind speed (U) and under-forecasts of temperature (T) coming from raw, interpolated HIRLAM model grids, a rudimentary correction scheme was developed. It was based on comparison of the first six hours of each HIRLAM model run with both a) turbine-observations and b) LAPS gridded diagnoses of T and U. Differences and ratios were calculated then weighted to estimate appropriate corrections to raw HIRLAM forecasts for hours 1-6, then those same corrections were applied to forecast hours 7-48, covering the remainder of the forecast run. Comparisons between observations and both the original and adjusted output at longer forecast times (12+ hours) have been made. Although statistics have not yet been calculated, visual inspection of daily output have indicated that predictions of T, U, icing and iced power have improved.

An example of the difference between the original (left) and adjusted wind speeds (right) and their effect on power forecasts is shown in Fig. 3. It is clear that for this case, wind speed and power estimates were far too high in the original version. These are greatly improved in this adjusted version for this case, with the over-estimation of wind speed and power essentially eliminated. However, due to some issues with the handling of air density effects on the power curve (January application of September-derived power curve), the adjusted result now gives a slight under-estimate of power production.

In the absence of a correction to the air density issue (which should be easy), adjusted values of ice power only resulted in a slight improvement in the power estimation for this case. Still, the adjustments to both wind speed and power have put the latest version of F-LOWICE in a better position to accurately predict the presence of icing, ice growth and decay, the clean power and the effects of icing on power production (power loss due to ice), once issues like the air density have been resolved.

It is important to note, however, that differences found between observations and forecasts over the first six hours are not always representative of the differences that will occur in the hours that follow, especially at times well beyond +6 h. To this end, climatological biases are also being considered as an additional ingredient to the HIRLAM adjustment scheme. In concept, differences between the 1-6 hour forecasts and recent observations should be more meaningful for forecast times that immediately follow (e.g. 7-12 hours), but should become less meaningful with forecast length. In contrast, long-term errors (e.g. a persistent cold bias) may become more meaningful with forecast length. Thus, we are considering applying a gradual transition from the observation-based adjustments to the climatological adjustments with forecast length. This would be handled by applying time-adjusted weight to the different adjustment parameters.

Though visual inspection of daily HIRLAM/F-LOWICE forecasts and corresponding observations from wind farm appears to indicate that the method described above has yielded improvements in forecast quality, the adjusted forecasts have yet to be verified. A head-to-head comparison of original and adjusted T, U and power forecasts is planned in the coming months.

III. Probabilistic forecast information

It is well understood that numerical model forecasts of even basic parameters such as temperature and wind speed are prone to errors and that those errors tend to increase with increasing forecast length. Mis-timing of fronts, wind maxima/minima, the presence and strength of wintertime inversions and complex vertical wind profiles can make even the simple aspects of forecasting wind power quite difficult at times. Moisture parameters, especially forecasts of microphysical fields, take these challenges a step further, as the prediction of relative humidity, let alone saturation, cloud phase, liquid water content and drop size are far more difficult, especially as forecast length increases.

Thus, there is inherent uncertainty in not only the basic parameters of T and U, which are pivotal to wind power production forecasts, but quite significant uncertainty in forecasts of the presence, intensity and downstream effects of icing on power production. Despite this, single values of all of these parameters are typically provided to wind power forecast users, such as power traders. These values are considered to be representative of the icing at a particular wind turbine, both in 3-D space and in time (e.g. for a given hour).

In an effort to convey a sense of the uncertainty that is inherent in such forecasts, LEA-FMI began to experimentally provide wind power trading companies with graphics showing not only the baseline, single-point forecasts of clean power and three unique estimates of iced power for specific wind farms, but also a "cloud" of clean and iced power forecasts for data points immediately surrounding the wind farms in 3-D space. With these data presented in time series (e.g. Fig. 4), it is possible to get an indication of the level of uncertainty in both space and time.

During the 2014-15 icing season, the probabilistic plots began to include the adjustments that were described in the previous section, helping to improve upon over-forecasts of power production that were present in earlier versions of both standard and "probabilistic" output from F-LOWICE.

IV. Future work

The methods described above represent improvements in both the quality of F-LOWICE forecasts of icing and power and the communication of the inherent uncertainties in such forecasts to highly sensitive users such as power traders. Though these are steps in the right direction, there is a great deal of work left to be done. One of the most important items for the advancement of LOWICE and F-LOWICE is the adjustment of power curves to include air density. Currently, their power curves are derived during ice-free periods of early autumn, and they have been held constant throughout the icing season. This approach ignores the fact that greater air density during colder periods causes power curves to change, generally becoming steeper and shifting slightly to the left, allowing greater power generated at the same wind speed. If this were corrected, the underproduction of power shown in Fig. 3 should be improved upon. Further improvements to the linear approximations of the power curves may also help.

Acknowledgment

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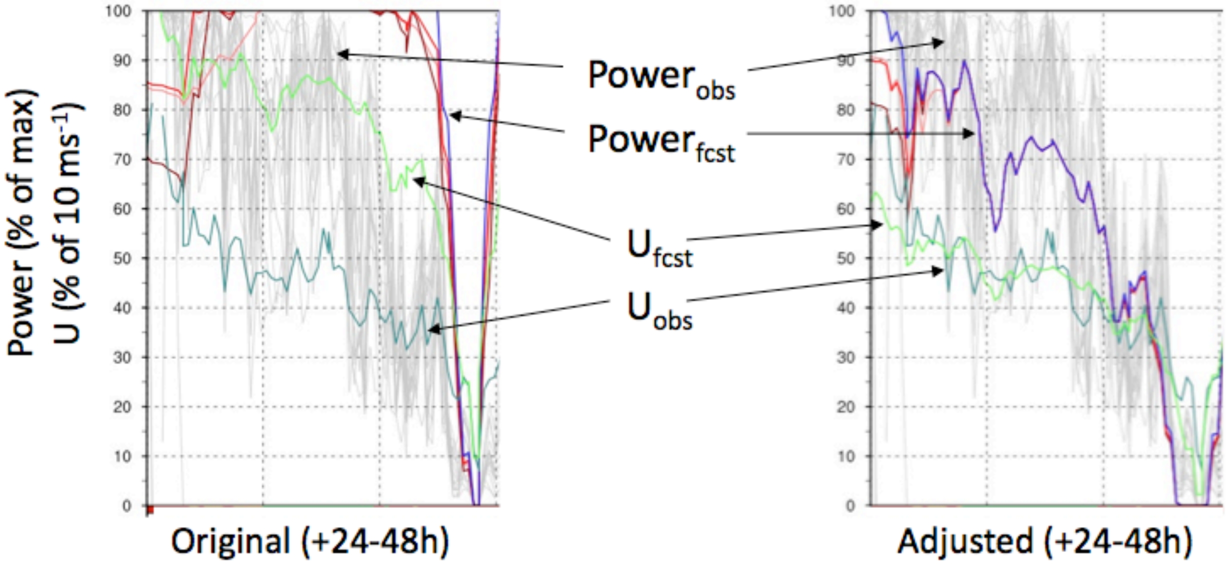

Figure 3: Wind speed and power data for 3-day period in January. Observed power production (grey) and median observed wind speeds (dark green) from multiple turbines are shown in both panels. In the left panel, the original HIRLAM forecast wind speeds (light green) and associated F-LOWICE "clean" (blue) and "iced" (red and tan) power are shown. In the right panel, adjusted HIRLAM wind speeds and F-LOWICE power are shown. All forecasts are from forecast times +24 to +48 h.

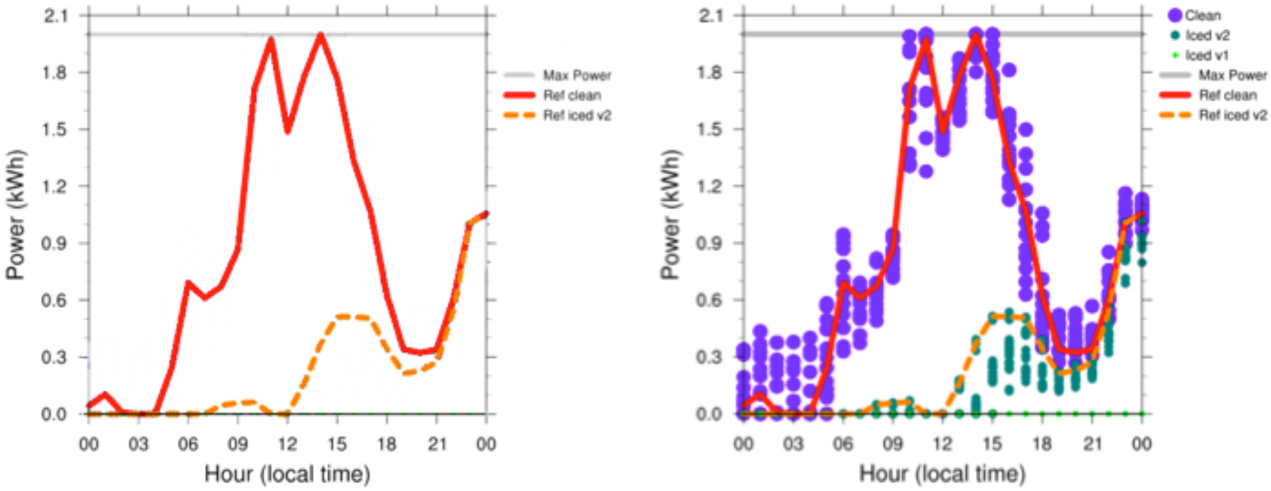

Figure 4: Standard (left) and "probabilistic" (right) plots of forecast clean and iced power from F-LOWICE for an example 24-hour period. The original clean (red) and iced (dashed tan) lines are included in both panels. Forecasts shown are for one wind turbine based on forecast times from +24 to +48 h.