LAPS-LOWICE: A REAL-TIME SYSTEM FOR THE ASSESSMENT OF NEAR-SURFACE ICING CONDITIONS

Ben C. Bernstein*[1], Ian Wittmeyer[1], Erik Gregow[2] and Jarkko Hirvonen[3]
[1]Leading Edge Atmospherics, Longmont, Colorado USA
[2]Finnish Meteorological Institute, Helsinki, Finland
[3]Finnish Meteorological Institute, Kuopio, Finland
*Corresponding author email: icingweather@gmail.com

***Abstract**:* The LAPS-LOWICE system combines observations from satellite, radar and surface stations with 3-D numerical model grids to assess the likelihood and severity of icing, as well as ice loads over Scandinavia. In this paper, the LAPS-LOWICE system and methodology will be described.

1. INTRODUCTION

It is well known that icing can seriously affect wind turbines, causing them to temporarily lose efficiency, shut down, and even sustain significant damage. This is true both for icing associated with clouds and precipitation (e.g. freezing rain). Estimation of the likelihood and intensity of near-surface icing conditions is a challenging problem for meteorologists and those affected by this phenomenon, including the power industry.

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 conditions, 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 is being 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.

2. LAPS AND LOWICE

LAPS-Scandinavia combines ECMWF model forecast grids with Meteosat-9 geostationary satellite fields, 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 (Fig. 1). LAPS grids of pressure, temperature, winds, relative humidity, cloud fields and precipitation provide essential input fields to the LOWICE system.

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 turbine site) is vertically located within the clouds and/or within a layer of liquid precipitation (e.g. drizzle). 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 and ice loads.

3. CONCLUSION

By intelligently blending 3-D numerical model fields and observations from satellite, radar, surface stations, etc., LAPS-LOWICE produces high-resolution grids of icing probability, severity (rate) and ice load across Scandinavia. This method is physically based, following proven methods for the diagnosis of icing aloft and applying it to the near-surface environment. By Spring 2011, this system will begin producing these fields in real-time.

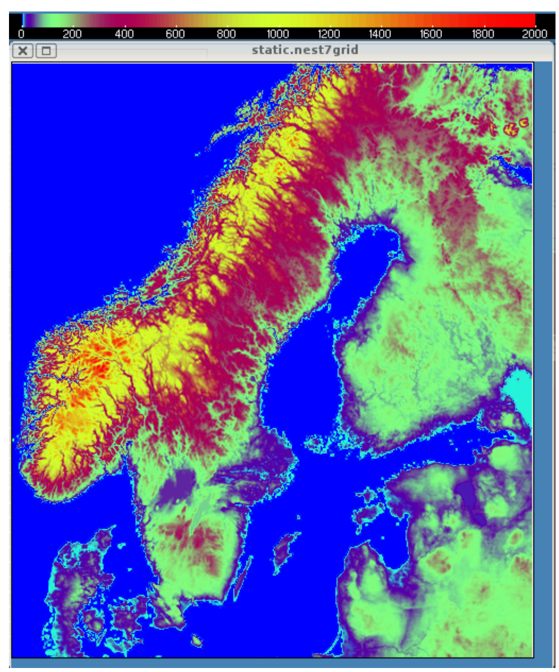

Figure 1. FMI-LAPS "Scandinavia" domain and model topography (m).

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Longmont, Colorado, USA
**icingweather@gmail.com*

Erik Gregow and Jarkko Hirvonen
Finnish Meteorological Institute
Helsinki, Finland and Kuopio, Finland

***Abstract*—The LAPS-LOWICE system combines observations from satellite, radar and surface stations with 3-D numerical model grids over Scandinavia to assess the likelihood and severity of icing, as well as ice loads. In this paper, the LAPS-LOWICE system and methodology will be described.**

Keywords - icing severity, icing rate, ice load, algorithm

I. Introduction

It is well known that icing can seriously affect wind turbines, causing them to temporarily lose efficiency, shut down, and even sustain significant damage. This is true both for icing associated with clouds and precipitation (e.g. freezing rain). Estimation of the likelihood and intensity of near-surface icing conditions is a challenging problem for meteorologists and those affected by this phenomenon, including the power industry.

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 conditions, 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 is being developed using the Finnish Meteorological Institute’s Local Analysis and Prediction System (FMI-LAPS) model to produce hourly assessments of the likelihood and severity of icing over Scandinavia.

II. LAPS Model Analysis

As described above, this version of the LOWICE system is being run using gridded output from the LAPS model [1]. In this case, LAPS has been configured to run over the Scandinavian domain, including most of Finland, Sweden and Norway, as well as nearby water and land areas (Fig. 1). FMI-LAPS combines short-term ECMWF model forecast grids with scans of standard satellite fields (e.g. visible and infrared channels) from the Meteosat-9 geostationary satellite, reflectivity from a network of radars, as well as surface observations from airports, meso-networks, Finnish road-weather observations, oil platforms, buoys and other stations across the domain. Additional information is gleaned from balloon borne soundings and aircraft observations [2].

LAPS combines this information to create hourly, 3-D analyses of the state of the atmosphere across the domain. Of particular importance for icing, this version of LAPS provides grids of pressure, temperature, winds, relative humidity, model condensate, 2-D and 3-D cloud fields (e.g. cloud top temperature, cloud top and base height, fractional cloud cover, cloud layering), and precipitation (occurrence, type and reflectivity). These grids provide essential input fields to the LOWICE system.

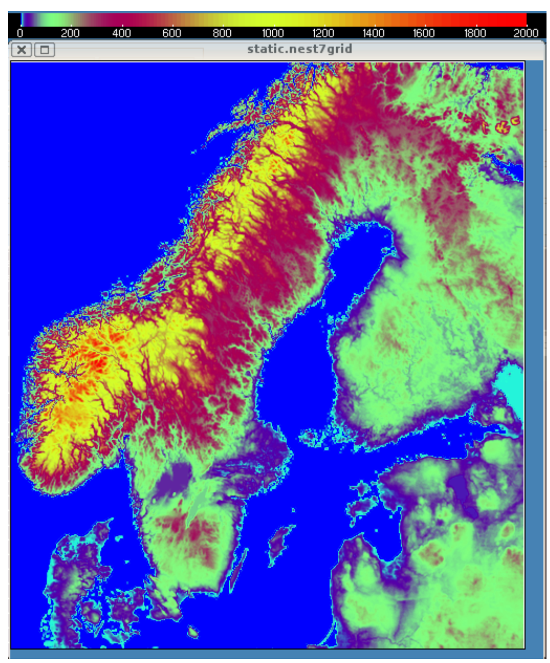

Figure 2. FMI-LAPS “Scandinavia” domain. Model topography (m) is shown here.

III. The LOWICE System

A. From Aicraft Icing to Near-Surface Icing

The basic concepts behind LOWICE were derived from the Current Icing Product (CIP), which combines numerical model output with observations from satellite, radar, surface stations, pilot reports and a lightning detection network to produce 3-D diagnoses of the probability and severity of icing conditions aloft over the contiguous United States and southern Canada for the aviation community [3,4]. LOWICE applies numerous CIP concepts, but also includes a great deal of unique concepts and code that are specific to the near-surface icing environment.

B. Initial Decisions

Using the fields described above, LOWICE examines the data for each vertical column within the LAPS grid. First, satellite and surface observations are used in concert with LAPS cloud and temperature fields to determine if the grid point is "cloudy". If clouds are present, then the vertical profile of LAPS cloud and RH fields are examined along with observations of precipitation (and its type) from surface observations and radar to determine whether the following features appear to be present: single-layer clouds, multiple cloud layers, a classical freezing rain structure, a non-classical freezing drizzle structure and/or a snow-dominated sub-freezing layer. Each of these environments must be examined differently to correctly assess the expected likelihood and severity of icing.

C. Icing Likelihood

The icing likelihood field closely mimics the "icing potential" field in CIP [3]. Thus, it will only be discussed in brief here. Icing is only considered possible at a given vertical level if it is located somewhere between the highest cloud top and the lowest cloud base. Levels just below cloud base are also considered for icing due to uncertainty in ceiling height observations, especially in complex terrain. In addition, icing is considered possible at all levels below cloud when liquid precipitation is observed, since freezing precipitation is possible when certain meteorological environments/structures are present.

The icing likelihood is then initially assessed using a combination of temperature (T) and relative humidity (RH) at the level of interest, combined with the cloud top temperature for the cloud layer that is immediately affecting that level (CTT). T, CTT and RH are all passed through fuzzy-logic membership functions to estimate the meaning of each value for icing. These functions are designed to account for some of the uncertainty that is inherent in the observations and model forecast fields being used, as well as the physical characteristics of supercooled liquid water in the atmosphere (e.g. it is much more likely to exist at -5^{o}C than it is at -20^{o}C; see Fig. 2 and Ref. [3]).

The initial icing likelihood value is then enhanced and depleted when certain observations of present weather were found near the grid point (e.g. freezing drizzle, freezing fog, snow). Because the nearness of such observations implies a great deal about their relevance, the impact that they should have on the icing likelihood (and later, severity) at the location in question is dependent on the distance to the stations that supplied these reports. Nearby observations have a much greater impact than those that are more distant.

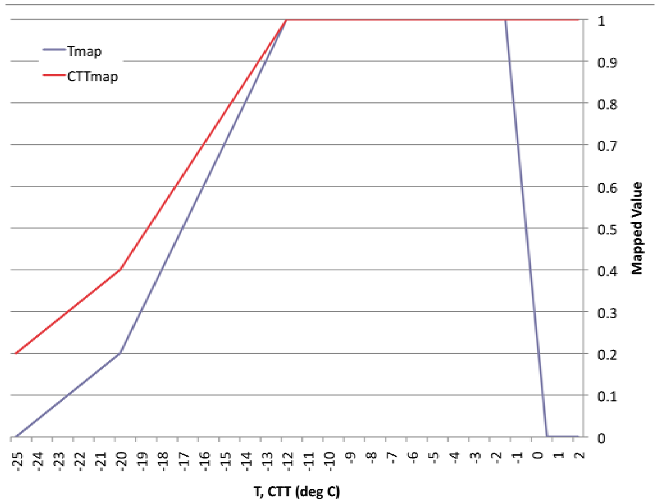

Figure 3. Membersip functions for temperature (Tmap) and cloud top temperature (CTTmap).

D. Estimating Liquid Water Content

To calculate an icing intensity, it is necessary to estimate the liquid water content (LWC; gm^{-3}), the temperature and the wind speed at the site. Temperature and wind speed are taken directly from LAPS, but LOWICE creates its own estimate of LWC using the cloud and precipitation fields described above in combination with LAPS profiles of P, T and RH.

If the level of interest is located at or above the estimated cloud base height (CBZ), then the LWC is approximated by 1) assuming a moist adiabatic lapse rate from the level down to CBZ, 2) estimating the saturated-mixing ratio at CBZ and 3) taking the difference between the mixing ratios at cloud base and the site, then 4) compensating for density. While using the adiabatic assumption is not ideal, it is reasonable for lapse rates to be at or near moist adiabatic over the shallow layer between the level of interest and CBZ.

As noted earlier, because of the potential for local variability in cloud base height between the site and the nearest reported ceiling height, LOWICE also allows for the possibility for icing at elevations slightly below cloud base. The allowable distance beneath the cloud base (dZ) changes with the distance between the site and the ceiling report. It is minimized when the ceiling report was made right at the location of the column and increases linearly when the ceiling report was made at the maximum allowable distance of 160 km. LWCs are set to nominal values between 0.1 and 0.0 gm^{-3} as dZ increases from zero to the maximum allowable value.

One important aspect of the adiabatic assumption is that all condensate remains within the cloud. Of course, many icing clouds produce precipitation, which depletes the LWC within them. The closer the observation of precipitation is to the site, the greater the likelihood that depletion is occurring at the site. To address this process, LOWICE examines all observations within the 160 km radius of influence for the occurrence of precipitation. If precipitation was observed, then a depletion factor is calculated based on the distance between the site and the precipitation report. The initial estimate of LWC can be depleted by as much as 50% of its original value, depending on the distance to the report. This approach is aggressive, but reasonably consistent with evidence from flights made in precipitating, well-mixed icing clouds sampled during natural icing flight programs (e.g. [5,6]).

E. Icing Rate and Ice Load

Once the atmospheric icing conditions have been estimated, the next step is to calculate the icing rate. This is done using a standard icing rate equation dm/dt = w * A * v, where w is the LWC, A is the cross-sectional area of the object, v is the wind velocity [7,8]. For the sake of simplicity, the collision, sticking and accretion efficiencies normally multiplied by the right side of the equation are assumed to be equal to 1.0. This may be upgraded in a future version of the code. The cross-section area (A) is set equal to 0.015 m^2, based on the ISO 12494 standard of a 0.5 m-long, 30 mm-diameter cylinder, but it could be changed to accommodate other objects. The wind speed (v; ms^{-1}) is taken directly from LAPS.

Using the hourly icing rate and accumulating ice when temperatures are in a suitable range (see Fig. 2), an ice load is estimated for the reference cylinder. This load will build during periods of active icing and can be depleted by melting and sublimation during periods when icing is not active. The melting scheme is currently based purely on temperature, but future versions may also include the presence and strength of sunlight at the location of interest. The sublimation scheme is based on a combination of wind speed and relative humidity.

IV. Climatological Version

At of this writing, the real-time LOWICE system is under development and should be complete by Spring 2011. Examples from the real-time system will be presented at the conference.

A climatological version of LOWICE based on historical 3-D model grids from NOAA-GFS model grids and observations from Meteosat and surface stations has been run on a large database from 2005 through 2010. Its estimates of the frequency of the monthly frequency of occurrence of icing were compared to coincident observations of temperature and visibility taken atop the Puijo tower in Kuopio, Finland [9], which have been shown to serve well as a surrogate for the presence of icing [10]. Comparisons were quite favorable and demonstrated that LOWICE methods are robust [11].

V. Summary

By intelligently blending 3-D numerical model fields and observations from satellite, radar, surface stations, etc., LAPS-LOWICE produces high-resolution grids of icing probability, severity (rate) and ice load across Scandinavia. This method is physically based, following proven methods for the diagnosis of icing aloft and applying it to the near-surface environment. It has the potential to be run over other parts of the world and could be applied to other near-surface structures such as towers and power lines. By Spring 2011, this system will begin producing these fields in real-time. Output from these runs will be compared with observations from the Puijo tower and other sites across Scandinavia.

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