A field study of atmospheric icing analysis in a complex terrain of the high north

by

Taimur Rashid, Umair N. Mughal, Mohamed Y. Mustafa and Muhammad S. Virk

Reprinted from

International Journal of
Ocean and Climate Systems

Volume 5 · Number 4 · December 2014

Multi-Science Publishing
ISSN 1759-3131

A field study of atmospheric icing analysis in a complex terrain of the high north

Taimur Rashid, Umair N. Mughal, Mohamed Y. Mustafa and Muhammad S. Virk*
Atmospheric Icing Research Team Faculty of Technology, Narvik University College, Norway
*E-mail: msv@hin.no

Abstract

Analyses of atmospheric icing events hold the key for computing the significant parameters leading to icing load calculations. In the cold regions of the high north, atmospheric icing loads on structures become important when it comes to design and safety of infrastructures. Furthermore, icing load calculations over a certain period of time provide a vital input for designers to improve the safety of structures. Patterns of icing events can be evaluated in correlation with other meteorological parameters such as atmospheric temperature, relative humidity and wind speed to better estimate icing loads. A field study has been performed in the complex terrain of northern Norway, by the atmospheric icing research team of Narvik University College, where customized meteorological atmospheric ice monitoring stations were installed to study atmospheric icing events in relation with the associated weather parameters. The meteorological parameters of three different sites in the vicinity of Narvik (*68°25′14′ N17°33′36′ E*) were collected, sorted, averaged to standardized timeline and further validated with recordings of weathers parameters obtained from the national weather forecasts, where a good agreement was found. Analyses were mainly performed between accreted ice loads and associated meteorological parameters. The results presented can be used as base for the development of more detailed mathematical models for the better prediction of atmospheric icing events in complex terrains.

Keywords: Atmospheric icing load, Meteorological parameters, Instrumentation, Complex terrain, High north.

1. INTRODUCTION

There can be many forms of atmospheric icing events such as in-cloud, which is most common and occurs as a result of the collision of super-cooled suspended water droplets and ice crystals with the exposed surfaces of structures in cold regions. Generally an icing event is defined as periods of time where the temperature is below 0 ºC and the relative humidity is above 95%. According to ISO (2000) standard -12494, ice accretion can be defined as, *'Any process of ice build-up and snow accretion on the surface of the object exposed to the atmosphere'*. Efforts to understand the meteorological conditions leading to atmospheric icing events, especially in mountainous areas, have been going on for a long time and it was concluded by Fikke et al. (2006) that the need for reliable measurements of icing events complying with the required standards are inevitable. Atmospheric icing load is an important parameter in this regard, whichis critical for better and safe structural designs in cold regions. Yundongand Jinying (2010) found that prediction of icing loads can be improved significantly depending upon correlation between meteorological factors and icing events. Fikke et al. (2008) were amongst the first to establish an atmospheric model for prediction of icing events in remote areas.

Ice accretion on structural parts is closely related to meteorological parameters causing alarming problems on elevated structures. Nygaard et al. (2011) described that theories and statistics related to this phenomenon are limited for ice prediction and ice accretion influence to assert geographical distribution of its intensity. Due to the high cost of ice monitoring and prediction equipment, and taking into consideration that they are needed at each location, where icing has to be monitored, implies more complex logistic problems. A reasonable approach is needed to implement icing prediction using meteorological results from a weather station not at the site. In this case weather parameters are measured at a nearby site which is more easily accessible and then mathematical formulae are used to predict icing at the desired remote location. In many implications like wind energy, icing frequency evaluation is exceedingly vital, as many of the prospective onshore wind farm locations in the Nordic countries are on hilltops and elevated areas. The unpredictability elements in such situations could easily cause extensive ice loading on equipment and structures within no time. The diversity in the nature of intensive cold environment makes it all important to evaluate icing events and loads in perspective of other meteorological parameters. This requires efficient and reliable data collection and evaluation through appropriate sensors, which are able to withstand the harsh conditions of cold environments. Careful observations and analysis can be instrumental in providing the break through of formulating predictable components of such analytical correlations.

In this research work, customized meteorological equipment setup was designed and installed in the complex terrain of Narvik, Norway to monitor the icing events and resultant icing loads. A customized mechanism was adopted to ensure proper validation of the data collected through various meteorological sensors over a period of time followed by its safe collection/retrieval and analysis. Analyses were performed to get an insight of the icing events and resultant icing loads impact with respect to standard meteorological parameters such as atmospheric temperature, atmospheric pressure, relative humidity and wind speed. The collected data was also validated with meteorological data from Norwegian national weather forecasts, where a good agreement was found.

2. MECHANISM OF ICE FORMATION

Drage (2005) described that mostly it is freezing fog, which is a major cause of ice accretion on structures. This type of icing is known as in-cloud icing which has been found to be the type of icing giving the highest accumulated loads. Clouds are formed of visible moisture in the atmosphere which can be in the form of liquid water droplets or ice crystal. Czernkovich (2004) found that these can form through various processes, but in all cases the air must be cooled to saturation for visible moisture to develop. As the air parcel is lifted upwards, air pressure drops and the parcel expands adiabatically, which causes its temperature to drop with increased elevation. Such ambient temperature lapse rate can be defined as follows:

$$-\left(\frac{\partial T}{\partial z}\right) = \gamma \tag{1}$$

This temperature lapse rate describes how air at higher elevations is typically cooler than at lower elevations. Rising air cools approximately following the ideal gas low because the ambient pressure decreases with altitude and thereby the air expands causing cooling. The rate of cooling can be calculated based on the decrease in pressure using the following correlation:

$$\left(\frac{T}{T_o}\right) = \left(\frac{P}{P_o}\right)^{K} \tag{2}$$

Once air is lifted to the 0 °C isotherm (freezing level) and visible moisture is present, there is a possibility of forming ice particles. Ice particles must form on some sort of nucleus, which are called *ice* or *freezing nuclei* (*IN*/*FN*), but as we find in the atmosphere that *FN* are far less abundant than cold cloud nuclei (*CCN*) which are responsible for the formation of rain droplets. Thus, even though liquid droplets may be lifted well above the freezing level, they are not guaranteed to freeze unless they come into

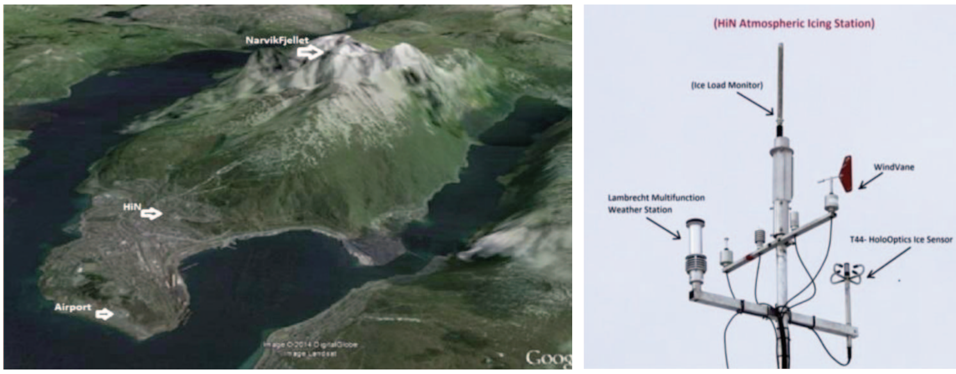

Figure 1. Overview of Narvik area terrain & ice monitoring station components used for this field study

contact with a *FN,* where at 0 °C only about one *FN* in every one million *CCN* is found to exist (which is a very low percentage). Generally, it is observed that only negligible concentrations of *FN* exist at temperatures above –15 °C. This is why observations have shown that ice accretion on structures is most hazardous and most common when cloud temperatures are warmer than about –15 °C.

3. FIELD STUDY SETUP

In this study, meteorological data was collected from two ice monitoring stations; one of them was installed at Narvik University College (*altitude 140 m a.s.l*), while the other was installed at Narvikfjellet (*altitude 1007 m a.s.l*), respectively (Figure 1). Narvikfjellet lies towards the east from the Ofotfjorden and towards the North West from Beisfjorden on the western coast of Norway. The installation sites were selected mainly based on*, a) altitude, b) ease of access & c) coverage of key locations within the area of interest (weather conditions)*. It is pertinent to mention that data form the national weather station at *Narvik Airport* was also used in the analysis phase of the work for validation. Narvik area is having complex mountainous terrain and is located on the shores of the Ofotfjorden. The municipality is part of the traditional district of Ofoten of Northern Norway, within the Arctic Circle, towards the Swedish national border.

The field ice monitoring stations used for this study were comprised of a multifunctional weather sensor along with two different atmospheric icing sensors. The multifunctional weather sensor determines wind speed and direction, temperature, humidity, pressure and dew point. The ice load monitor is capable of measuring accreted ice mass, whereas the icing rate monitor detects icing events and gives icing rate. All these parameters were recorded by the industrial scale embedded data-logging system. The overall acquisition system was housed inside a weather proof cabinet to avoid heavy icing penetrating into the sensitive hardware circuitry. The equipment cabinet also included power converters and a portable battery to keep the logging active in case of temporary power failure. The period under consideration for this study was the heavy snow/ice months with considerable transitions. Each parameter was logged into a specific field, which were then further filtered to examine their validity.

4. RESULTS & DISCUSSION

The field study was focused on recording icing events and the resultant icing loads along with other meteorological parameters. First it was necessary to observe the change of weather parameters at different installed meteorological stations in relation to each other. The observations collected from three sites were correlated in order to confirm the integrity of the customized icing stations, which can form the basis of further analysis. The data used for this study was selected from January – March 2013. The obtained meteorological data from HiN and airport stations were super imposed upon each other for validation. The national weather station at airport was located at sea shore, whereas the HiN weather

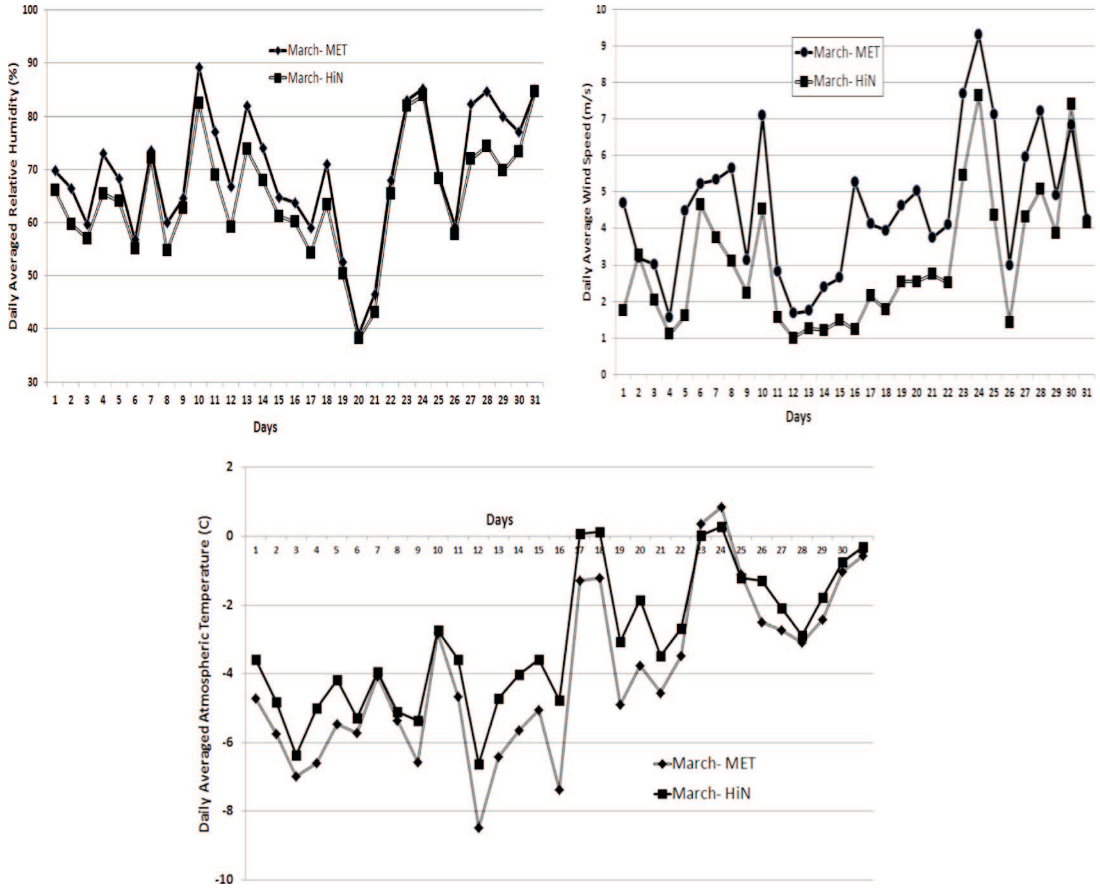

Figure 2. Comparison of daily averaged meteorological data between HiN & National weather station (MET) of Narvik

station was located at 140 m a.s.l on mid-way of a mountain (Narvikfjellet). This difference in altitude, location and terrain caused a small change in the values of the desired meteorological data. Despite of difference in the complexity of surrounding terrain and altitude, a good agreement was found between both data sets. The following figure shows a comparison of averaged daily data of wind speed, relative humidity and atmospheric temperature for two different sites (HiN and Narvik airport) for the month of March 2013.

All three meteorological sites used for this study were located along the same mountain (Narvikfjellet), which faces the open sea from the south across the SW and to the west and is affected by the gulf streams flowing through the North Atlantic Ocean. Air masses related to these streams are usually humid and have air temperatures favorable for atmospheric icing during the winter season ($-15 < T\ ºC < 0$). National weather station (airport) is located at sea shore, whereas HiN lies along the same mountain (Narvikfjellet) at 140 m a.s.l, where the weather station is mounted, hence calculations of variation in parameters with altitude are assumed to be consistent.

The atmospheric icing load sensor used for this study was installed at the Narvikfjellet meteorological station which measured instantaneous icing loads. The output values consisted of increments or decrements of the icing load with respect to previous readings. The total icing load accumulated over the measurement time period was calculated by introducing a simple accumulative algorithm, which starts with the initial value and adds the next incoming value. Zero point calibration of the sensor was erroneous at times. This undesirable error was filtered, while adding the icing load per minute. The fact that the icing load calculates the changes in the accreted load with reference to the

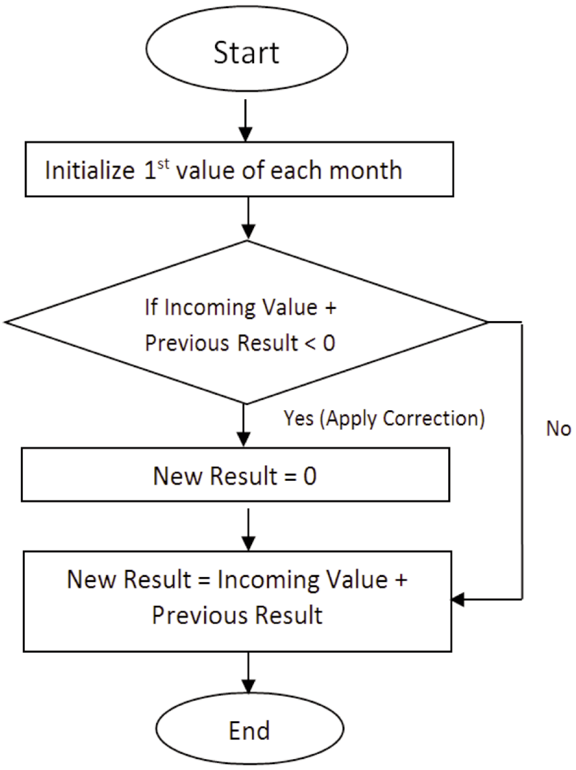

Figure 3. Simplified flow chart of the algorithm used to calculate icing load

previous reading actually leads to automatic elimination of the calculation error. Figure 3 shows a simplified flow chart which describes the algorithm used to calculate the accumulated atmospheric icing load on the rod of the ice load monitor, designed as per ISO-12494.

The icing load was recorded at each minute and then averaging was performed on hourly basis for scaling of icing load values over the desired period of time. Ice load values for the Narvikfjellet station were calculated and then averaged on a daily basis, then plotted over the period of a month. Figure 4 shows the daily average accumulated ice load on ice load monitor for the period of three months (January – March 2013). Results show high icing rates during the months of February and March, as compared to January. Ice load recorded in March-2013 reached up to 19 kg/m^2 on a vertical rod of 30 mm in diameter and 0.5 m in length. This is however expected as icing conditions become more severe during this time of the year due to the increased presence of super cooled water droplets in the air, while temperatures still drops significantly during night hours.

Keeping this in mind, attention was focused on the analysis of the data obtained in March. The following figure shows the icing load at Narvikfjellet station in comparison with the meteorological parameters recorded at HiN meteorological station. Results show that high wind speed, relative humidity and near zero atmospheric temperatures caused an increase in the resultant ice load. This is obvious from the data collected on the 22nd March, where a high ice load situation was observed.

Analysis of meteorological data of 22nd March at HiN meteorological station (140 m a.s.l) shows a significant increase in wind speed and relative humidity that led to a significant increase in the resultant ice load at Narvikfjellet station. It is worth mentioning that wind speed is a major factor in ice occurrence due to the fact that it increases air lifting specially in mountainous terrain. In this case an increase in wind speed observed at HiN station (bottom of Narvikfjellet) increased air lifting and raised the availability of super cooled droplets at the top of Narvikfjellet (1007m a.s.l), especially as this is usually combined with increased chilling of the air. An increase in wind speed also increases

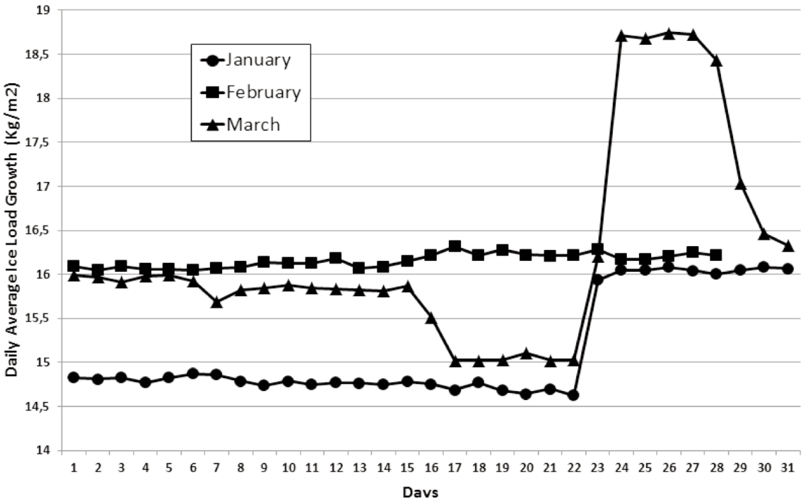

Figure 4. Icing load situation at Narvikfjellet-Narvik

the collision efficiency of icing accretion, which leads to increased icing loads on structures, and also increases liquid water content (*LWC*). Measurements of the relative humidity, during this time period indicate an increase in humidity levels. At the level of the HiN measurement station, humidity levels reached 80%, which are not sufficient for atmospheric icing to occur, but as air was lifted up, humidity of the air was expected to increase at Narvikfjellet station. Drage (2005) described that for icing to occur, humidity of the air must increase above 95%, which was expected to occur at the level where icing was observed, as there was a difference of height of about 850 m between the two stations.

During this study, temperature measurements were carried out at HiN station, and no temperature data was recorded at the Narvikfjellet icing station. Therefore, making reliable estimates of air temperature at Narvikfjellet station was crucially important. A lifted volume of air close to the slope of the Narvikfjellet Mountain is mixed with ambient air. However, this process was assumed to be near adiabatic.

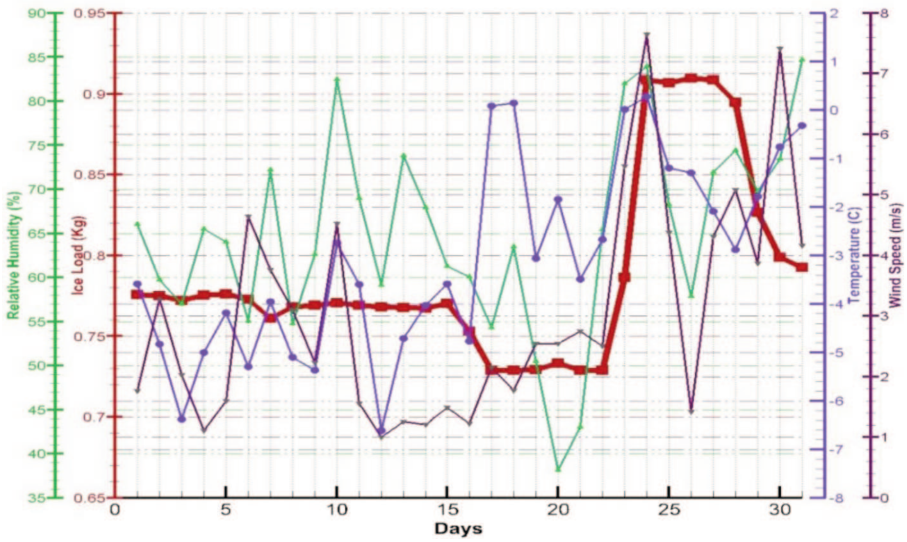

Figure 5. Ice load conditions at Narvikfjellet in comparison with standard meteorological parameters for March at HiN meteorological station

Air temperature at different heights along the Narvikfjellet Mountainfor the volume of air that was lifted was assumed to follow the following function;

$$T_z = T_1 - \gamma_d .(z - z_1); \qquad z \le z_c \tag{3}$$

$$T_z = T_1 - \gamma_d .(z_c - z_1) - \gamma_w .(z - z_c); \qquad z > z_c \tag{4}$$

Where T_1 is the temperature at the HiN weather station, z_1 and z_c are the heights of the HiN weather station and the cloud base, respectively. Drage and Thiis (2012) defined γ by equation (1) above as $-dT/dz$, where γ_d is the temperature gradient for unsaturated conditions (below cloud base) and γ_w is the temperature gradient for saturated conditions (inside the cloud). Rearranging the second equation, the cloud base can be calculated using the following equation:

$$z_c = \frac{T_z - T_1 - \gamma_d z_1 + \gamma_w z}{\gamma_w - \gamma_d} \tag{5}$$

Earlier work by Harstveit (2005) suggested that $\gamma_w = 0.54$ ºC/100 m and $\gamma_d = 0.85$ ºC/100 m. Estimates by Drage (2005) from measurements at Brosviksåta suggested $\gamma_w = 0.62$ ºC/100 m and $\gamma_d = 0.92$ ºC/100 m, with standard deviations of 0.07 and 0.08, respectively. The later values suggested by Drage (2005) are used for this study, together with meteorological data obtained at the meteorological station at the HiN station. Figure 6 shows a comparison of the recorded atmospheric temperature at HiN station with the calculated temperature at Narvikfjellet station. Results show an approximately 1 ºC decrease in temperature with every 100 m increase in altitude along Narvikfjellet Mountain between both stations.

Further analysis were also performed to compare the icing events indications at HiN and Narvikfjellet stations, as there was a difference of altitude of around 850 m, the HiN icing station was installed at the bottom of Narvikfjellet, whereas the Narvikfjellet station was installed at the top of the mountain. Results show high occurrence of icing events at HiN during the last quarter of March, this was similar to data obtained from the Narvikfjellet station. The following figure shows the icing events indications at HiN icing station. 1 stands for the occurrence of an icing event, whereas 0 stands for no icing event.

Results from the last quarter of March were further analysed to study the occurrence of icing events. A comparison was made between the numbers of icing events indications at HiN icing station in comparison with the icing occurrence rate at Narvikfjellet.

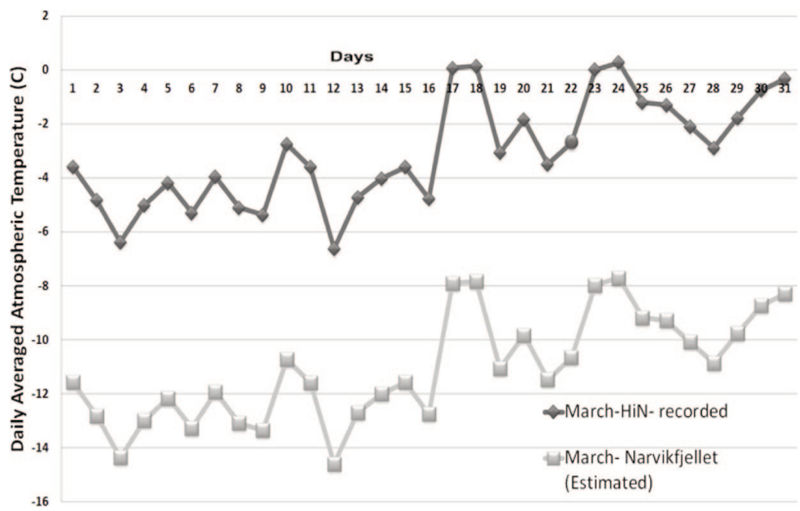

Figure 6. Actual temperature at the HiN weather station and calculated temperature at Narvikfjellet

Figure 7. Recorded icing events indications from HoloOptics-T44, installed at HiN

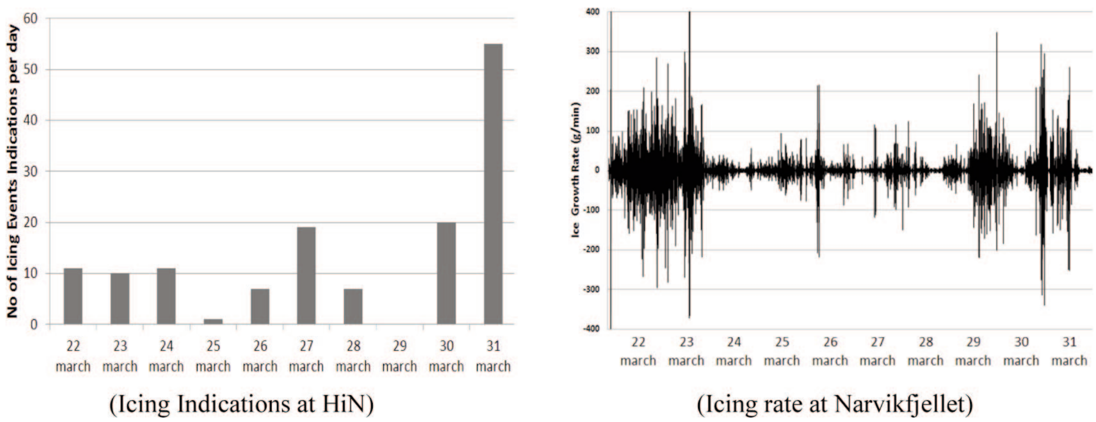

Figure 8. A comparison of icing events indications at HiN with the ice growth rate at Narvikfjellet icing station during last quarter of March 2013

5. CONCLUSION

In this paper, a field study of atmospheric icing analysis in complex terrains of northern Norway is presented. Data from three meteorological stations was analyzed to understand the icing events in correlation with the meteorological parameters. The mechanism of ice formation and the major parameters affecting icing were also discussed. Due to the high cost of ice monitoring and prediction equipment, and taking into consideration that they are needed at each location where icing has to be monitored, implies more complex logistic problems, such as power supply to the equipment, and reaching the equipment under severe weather conditions, it is a reasonable choice in such cases to implement mathematical icing prediction techniques which can be performed using data from a fairly remote or lower in altitude weather station.

ACKNOWLEDGEMENT

The work reported in this paper was partially funded by the Research Council of Norway, project no. 195153/160 and partially by the consortium of the project ColdTech- Sustainable Cold Climate Technology.

REFERENCES

Czernkovich, N. (2004) “Understanding in-flight icing”. Transport Canada Aviation Safety Seminar: 1–21.

Drage, M. A. (2005) “Atmospheric icing and meteorological variables: Full scale experiment and testing of models”. PhD Thesis, University of Bergen, p. 133.

Drage, M. A. and Thiis, T. K. (2012). “Large-scale measurements and numerical simulations of in-cloud icing around a mountain ridge.” Journal of Wnd Engineering and Industrial Aerodynamics Vol. 104, Issue 1, pp. 523–531.

Fikke, S. M. and Egill J., (2008) “Modern meteorology and atmospheric icing”, Springer, p. 381, ISBN: 978-1-4020-8530-7.

Fikke, S., G., Ronsten, A., Heimo, S., Kunz, M., Ostozlik, P. E., Pearson, J. and Chum, L. makkonen. (2006). “COST-727, Atmospheric icing on structures- measurements and data collection on icing: state of the art”, MeteoSwiss report, No. 75, p. 110.

Harstveit, K. (2005) “Using routine meteorological data from airfields to produce a map of ice risk zones in Norway”. 10th International Workshop on Atmospheric Icing of Structures –IWAI, Montréal, Québec, Canada.

ISO (2000)-12494: Atmospheric icing of structures. ISO/TC 98/SC3.

Nygaard, K., Egil B., Egill, J. and Makkonen, L. (2011). “Prediction of in-cloud icing conditions at ground level using the WRF model.” Journal of Applide Meteorology Climatology. vol. 50: pp. 2445–2459.

Yundong, X. and Jinying, L. (2010). “Study on the icing process of transmission lines and the local meteorological parameter”. China International Conference on Electricity distribution (CICED). Nanjing, IEEE, pp. 1–4.