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# Icing Indices: a good solution?

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***Abstract*—Four Icing Indices composed of restricted meteorological parameters were confronted to the output signal of icing monitors. Problems were encountered because of the icing sensitivity of the monitors. However one or two indices seem to predict satisfyingly the occurrence of icing, and further work will be necessary to achieve an operational success rate of 95 %.**

## I. Introduction

The occurrence of icing has important consequences in a great variety of domains: civil and military aviation, road operation, wind energy production, electrical energy transport etc. It is therefore for both security and economical reasons important to know the expected icing situation of a chosen place before engaging great financial resources in a project.

In a very simplified manner on can admit that icing occurs when liquid or solid water particles impact against an object. In general, the accretion rate per surface unit will be proportional to the relative normal velocity between particles and structure, and to the water concentration of air. Except for the aviation where the relative velocity is given by the aircraft speed, the wind plays an important role in icing. Thereafter a number of other parameters (see [1]) will degrade this maximal accretion rate: collision efficiency, mainly determined by the size distribution of particles, sticking efficiency ($\cong$ 1 for water droplets or wet snow, and $\cong$ 0 for dry snow) and accretion efficiency. All the combinations lead to a great variety of icing phenomena known under the names of rime, glaze, wet snow, freezing rain etc.

Reduced interest (except in the aviation sector, where the consequences can be humanly and financially important) is dedicated to icing sensors by the manufacturers of weather instruments. The actors presently on the market come understandably from the aircraft industry: SAAB, Goodrich, Vibrometer etc. This situation is slowly evolving, but the available icing sensors for terrestrial applications are still mainly prototypes. Therefore, as alternative to icing monitors, it is attempted to select a minimal set of restricted meteorological parameters (input parameters) defining a multidimensional space where a subspace can be found in which icing always occurs. With such "Icing Indices", a simple icing climatology at any meteorological station site could be computed. This is the aim of this work.

The selected input parameters are air temperature $T_{re}$, dew point temperature $T_{mi}$ (or relative humidity RH), sky temperature $T_{sky}$ (derived from downward long wave radiation), lower cloud layer given by a ceilometer and wind velocity $F_{kl}$. These parameters qualify the meteorological situation. They are combined in qualitative (yes, no) or quantitative Icing Indices.

The validation parameters are the output signal from the icing sensors, as well as the camera pictures. These parameters qualify the icing situation.

Finally the indices should be confronted with the icing situation (output of icing monitors) and the restrictive conditions (air temperature less than xxx, relative humidity greater than yyy etc.) adapted in order to maximize the coincidence.

## II. Technique

### A. Site description and meteorological instruments

The method was tested on the data of the test site Guetsch from MeteoSwiss. The Guetsch station (46.65 °N, 8.62 °E) is located in the middle of the Swiss Alps, at an altitude of 2300 m in the Gotthard region above the village of Andermatt. Picture 1 shows the general setup of the test facility, with the meteorological test station in the front, and the wind turbine facility in the background, at around 200 meters from the test station. Two 10 meters wind masts may be seen, the one at the back belonging to the official meteorological station of the Guetsch which is located about 100 meters downward on the slope, while the second one at the front is connected to the test station and equipped with a rugged Goodrich/Rosemount Pitot tube.

Picture 1: Alpine Test Site Guetsch.

On the measurement field 2 measurement bridges are available: the first one supports the instruments which are to be tested while the second one holds the standard reference meteorological instruments: thermo-hygrometers (Meteolabor, THYGAN or Rotronic, Hygroclip), pyranometer (K&Z, CM21), pyrgeometer (K&Z, CG4). A ceilometer (Vaisala, CT25K) is visible in the middle of the field. The Data Acquisition System is located together with a barometer (Vaisala, PTB220A) in the enclosure which can be seen on the north side of the measurement bridges. Most of the sensors are sampled at 1 s, average and standard deviation are calculated for 10 minutes intervals.

Table 1 shows the climatic monthly averages (30 years avg.) and monthly averages experienced during the test period.

TABLE I
SITE CLIMATOLOGY: 30 YEAR AVERAGE AND WINTER 08/09. T IS AIR TEMPERATURE, FKL IS WIND SPEED, GR IS GLOBAL RADIATION AND N IS THE NUMBER OF ICING DAYS (NUMBER OF DAYS WITH TMIN < 0 °C).

| VALUE | Oct | Nov | Dec | Jan | Feb | Mar | Apr |
|---|---|---|---|---|---|---|---|
| T | 2.1 | -3.1 | -5.5 | -6.5 | -6.9 | -6.0 | 3.7 |
| Test T | 2.4 | -3.9 | -6.3 | -7.4 | -8.6 | -5.7 | -0.8 |
| Tmin | -0.5 | -5.6 | -8.1 | -9.3 | -9.5 | -8.2 | -5.7 |
| Test Tmin | -0.5 | -6.1 | -8.7 | -9.7 | -10.8 | -8.4 | -2.5 |
| Tmax | 6.0 | 0.1 | -2.4 | -3.8 | -4.2 | -3.3 | -1.1 |
| Test Tmax | 6.1 | -1.7 | -3.9 | -5.2 | -6.4 | -3.2 | 1.0 |
| RH | 66.8 | 67.2 | 63.4 | 66.0 | 68.3 | 72.2 | 78.1 |
| Test RH | 77.4 | 82.0 | 72.7 | 59.5 | 80.8 | 74.1 | 80.5 |
| Fkl | 6.5 | 6.4 | 6.8 | 6.5 | 6.0 | 6.2 | 6.6 |
| Test Fkl | 5.0 | 6.5 | 6.9 | 5.2 | 7.6 | 7.2 | 6.6 |
| GR | 112 | 78 | 61 | 74 | 119 | 180 | 229 |
| Test GR | 115 | 66 | 56 | 78 | 113 | 183 | 219 |
| N | 14.7 | 26.3 | 29.5 | 30.8 | 27.9 | 30.3 | 28.1 |
| Test N | 12 | 29 | 31 | 31 | 28 | 31 | 28 |

## B. *Icing sensors*

Two icing sensors have been selected for the evaluation. The first one is the icing detector 0872J1 developed by Goodrich. It consists of a vibrating finger whose frequency is monitored. When ice accretion occurs, the resonance frequency decreases, and as soon as a threshold value corresponding to an accretion of 0.5 mm is reached, the sensor heats and sends an output signal every minute. Assuming an ice density of 1000 $kgm^{-3}$, each cycle corresponds to an accretion of 0.5 $kgm^{-2}$.

The second sensor is the SAAB Combitech IceMonitor MKI. An upright mounted rod is placed on a load cell for weighing. The cylinder should freely rotate when ice builds up to obtain a cylindrical ice build up which is detected by the load cell as a vertical force. The bearing for the rod is heated (via a thermostat) to secure the weighing function. The result is expressed in kg (maximal 10 in our case). An output of 0.05 kg (accuracy of the instrument) corresponds to an accretion of 3.3 $kgm^{-2}$, which is 7 times higher that the Goodrich increment.

A rugged camera system (special heating) is installed on one of the wind masts and allows for panorama views of the surrounding as well as zoomed pictures of the instruments providing valuable information on the icing rates. Pictures taken in specific directions are further used for monitoring the visibility by aiming at specific targets located at different distances. A complete picture set is taken every 10 minutes, but the camera is moved constantly to avoid ice accretions on the rotating parts.

## C. *Availability of instruments*

The observation period lasts from October 1st 2008 to Mai 3rd 2009. This represents 5160 hours of operation and 100% of availability.

### 1) *Meteorological instruments*

The thermo-hygrometer THYGAN suffered a 10 days breakdown, but values could be replaced by the similar instrument located at the official station. Small interruptions caused ca 3.3 % data losses for the rest of the instruments.

### 2) *Camera*

The camera suffers from two penalties. It works in the visible range, is therefore nightly blind which represents an information loss of 55% during winter. Furthermore some breakdowns occurring during bad weather conditions increased these losses so that pictures were finally available only 36% of time.

### 3) *Combitech IceMonitor*

A drift from zero was observed at the beginning of November, probably due presumably to low temperatures on the amplifier. The instrument was exchanged at the beginning of March but still showed a peculiar behavior, with strong negative excursions possibly due to a snow/ice bridge formed between the rotating rod and the static housing (see Figure 1, Pictures 2 to 4) leading to an asymmetrical accretion and to erroneous weighting. We therefore did not consider this monitor in the evaluation. However we used it together with the camera in order to estimate the icing type and the icing severity.

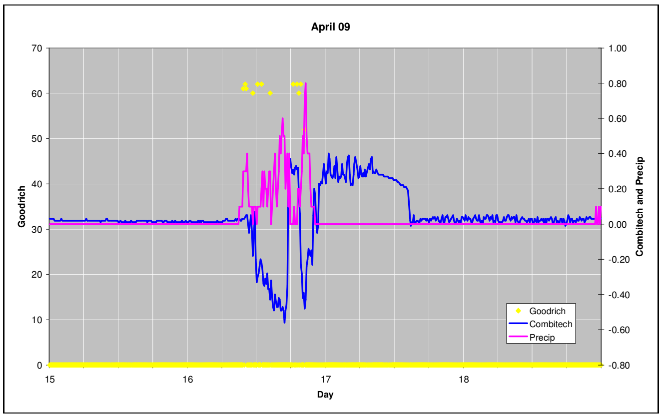
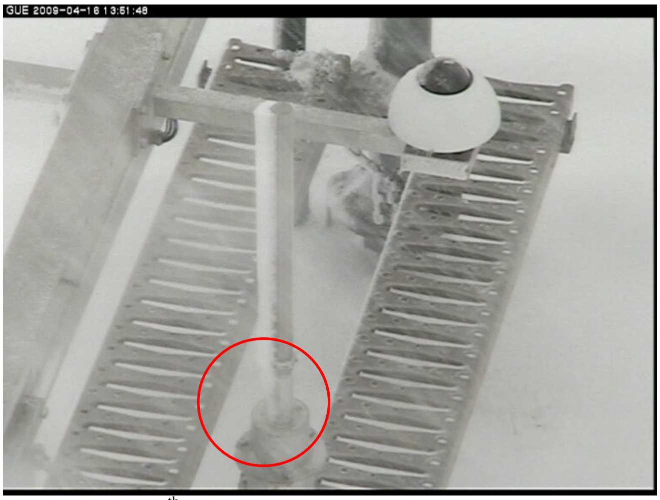



Figure 1: Icing event and bridging of Combitech IceMonitor.



Picture 2: April 16th, 15h, snow bridge prevents rod rotation of Combitech IceMonitor

Picture 3: April 17th, 8h, free rotation of Combitech IceMonitor

Picture 4: April 17th, 14h30, release of Combitech IceMonitor

### 4) *Goodrich IceMonitor*

The Goodrich monitor worked nearly (3% missing data) all the time. Camera pictures show however that under bad conditions it becomes encapsulated or at least shadowed by a snow wall (see picture 4).

Picture 5: Goodrich Ice detector encapsulated in rime ice.

## D. *Indices*

Different indices were constructed and tested against the icing. Icing occurs when the air temperature is below 0 °C. The simplified idea is that the accretion rate is proportional to the liquid/solid water content of the air and to the air velocity. The liquid water content is high when the structure is in a cloud (in cloud icing).

Within the cloud, the dew point temperature is near or even higher than the air temperature (or the relative humidity is near or even higher than 100%) and the difference between the sky temperature and the air temperature is near 0 °C. The cloud level measured with a ceilometer is near 0 m. With these hypotheses four different indices have been defined.

The first index was defined (R. Cattin, (private communication) as follows: the Icing Index $\mathbf{II_1}$ is true if

1) the air temperature $T_{re}$ is lower than 1 °C,
2) the difference $T_{re} - T_{sky}$ is lower than 2 °C and
3) the relative humidity RH is greater than 95 %.

A second index $\mathbf{II_2}$ is similar to the previous one, but with substitution of the third condition on RH (which could be thought to be equivalent with the condition on $T_{re} - T_{sky}$) by a condition on the air velocity:

1) the air temperature $T_{re}$ is lower than 1 °C,
2) the difference $T_{re} - T_{sky}$ is lower than 2 °C and
3) $Fkl > 2\ ms^{-1}$.

A third index $\mathbf{II_{ceil}}$ is defined using the output of the ceilometer CT25K. It is true if

1) the air temperature $T_{re}$ is lower than 1 °C and
2) the height of the first cloud level is less than 31 m.

A last index $\mathbf{II_{ngwc}}$ is using a specificity of the THYGAN. This thermo-hygrometer **measures** the dew point temperature of the air. If the air contains some liquid droplets or solid particles, the instrument can detect a dew point temperature higher than the temperature of the air (or a relative humidity higher than 100%). These temperatures can be used to determine a non gaseous water content $\rho_{ngwc}$ (see Appendix). To build the index $\mathbf{II_{ngwc}}$, this value is multiplied by the air velocity $F_{kl}$ and by 600 s to get an accretion in $kgm^{-2}$ per 10' interval if the air temperature is < 1 °C and lower than the dew point temperature.

## III. Results

A signal output from the Goodrich IceMonitor is defined as a hit. A true value from any icing index is also defined as a hit. The task consists now in measuring the coincidence between monitor hits and index hits.

As mentioned before we used icing data only from the Goodrich icing monitor (thereafter the monitor). Its breakdown periods were not considered in the evaluation. Another difficulty comes from its sensitivity to encapsulation, which is only detectable by camera pictures (see Picture 4). Instead of looking at the monitor status when an index is true, we looked at the index status when the monitor signal is true.

Table 2 shows the result for the four defined icing indices. We recorded 631 hits from the monitor during the evaluation period. For each icing index, the values indicate the number of hits and the percentage of monitor hits coincident with at least one index hit within the coincident window.

The second line gives the values if we extend the coincidence window to the 2 intervals (20 minutes) preceding a hit from Goodrich monitor, in order to damp the short term variations of the indices. The percentages are computed relatively to the 631 Goodrich hits.

TABLE 2
HITS AND RELATIVE COINCIDENCE TO THE GOODRICH ICE DETECTOR HITS.

| | Goodrich | $II_1$ | $II_2$ | $II_{ceil}$ | $II_{ngwc}$ |
|---|---|---|---|---|---|
| Hits | 631 | 2907 | 5514 | 1965 | 1708 |
| Coincidence [%] | - | 36.3 | 47.2 | 36.1 | 30.1 |
| Coincidence 2 intervals [%] | - | 67.2 | 78.9 | 46.4 | 37.4 |

The (relatively) best result is obtained with $II_2$, built up with data from a thermometer, an anemometer and a pyrgeometer. However $II_1$ shows comparable results. It seems that a condition on the relative humidity is not essential, as estimated in Chapter II D, Figure 2 shows the temperature - wind velocity distribution when the Goodrich monitor had a hit. One observes a non negligible amount (6.7 %) of hits with a positive air temperature indicating a sensitivity of the Goodrich to wet snow.

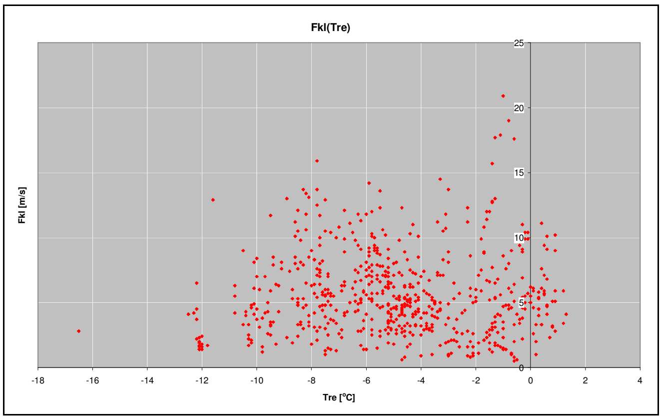



Figure 2: Temperature – wind velocity distribution when the Goodrich Ice detector had a hit.

Figure 3 gives an overview of the data between January and March 2009. The precipitation is displayed in blue, the air temperature in cyan, the hits from the index II2 in magenta and the hits from the Goodrich Ice Detector in yellow. The orange line signalize a breakdown (camera or Goodrich), making the analysis impossible.

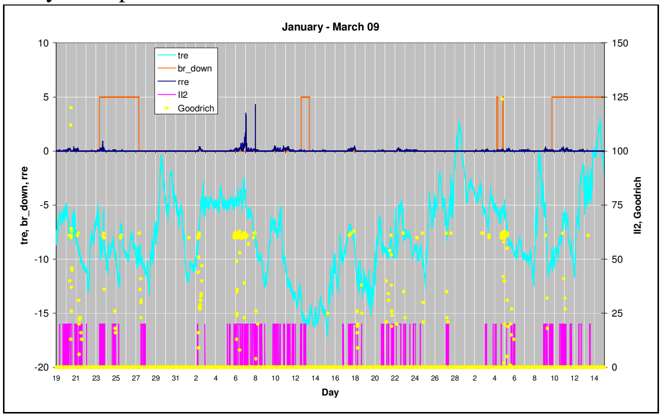



Figure 3: Overview of the data between January and March 2009.

From Figure 3 (or equivalent Figure from another period), three specific cases have been selected as example of good coincidence, hit from index without hit from monitor and hit from monitor without hit from index. The next series of pictures illustrate the two first cases. Figure 4 is an enlargement of Figure 3 and describes the situation between February 5th and 8th.

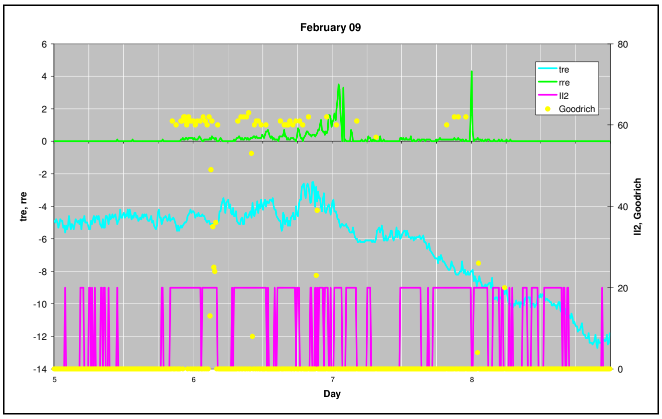
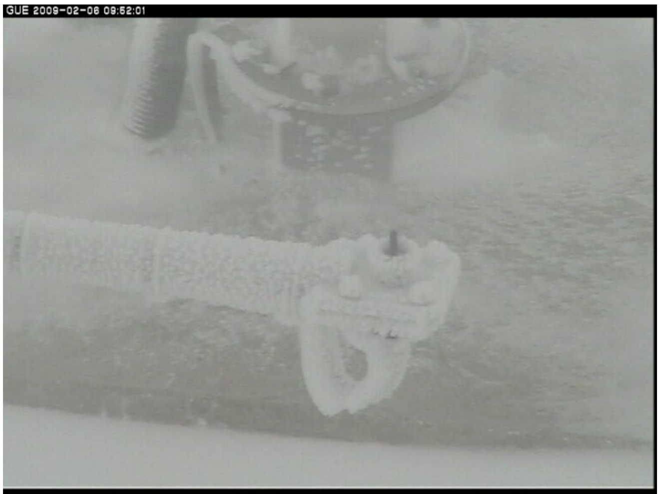



Figure 4: Enlargement of Figure 3 and description of the situation between February 5th and 8th.

The Pictures 6 to 8 are taken at about noon the 5th, 6th, and 7th February. At the beginning the Goodrich Ice Detector is free and the visual coincidence between monitor and index is good. But during the night to the 7$^{th}$ the Goodrich Ice Detector becomes encapsulated and gives no longer signs of life (hit from index without hit from Goodrich Ice Detector).


Picture 6: Goodrich Ice Detector on February 5$^{th}$.




Picture 7: Goodrich Ice Detector on February 6$^{th}$.


Picture 8: Goodrich Ice Detector on February 7$^{th}$.

Figure 5 illustrates the third case (hit from Goodrich Ice Detector without hit from index): the Goodrich Ice Detector had some hits in the in the night from October 16$^{th}$ to 17$^{th}$ without any hit from the index $II_2$ (in magenta). Snowfall occurred during night and the validity of the Goodrich Ice Detector hits was confirmed by pictures (see Picture 9). On the other hand for that special case the index $II_1$ (in red) seems to be more appropriate.

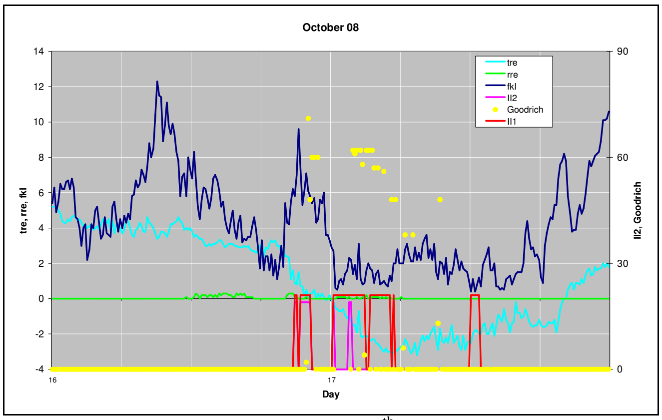



Figure 5: Goodrich Ice Detector on October 8$^{th}$.


Picture 9: Combitech IceMonitor on October 17$^{th}$, 9h30.

## IV. Conclusion, Further work and recommendations

### A. Conclusion

The information given by four different indices based on basic meteorological measurements has been compared with the output signal of the Goodrich IceMonitor in order to be able to perform icing climatology with simple meteorological measurements. We were confronted to the fact that icing sensors are also sensitive to icing! One index could be identified which described better, but far from ideally, the icing reality. They are however cases where another index performs better. Therefore a more sophisticated index needs to be developed, whose definition could vary with the atmospheric conditions (air temperature, wind, precipitation etc.).

### B. Further work and recommendations

First of all the confidence in the meteorological and icing measurements under icing conditions has to be increased.

The camera offers a good, even when only qualitative, redundancy to the Combitech or Goodrich monitor. Nevertheless, as some icing events occur over night, it seems adequate to (shortly) illuminate (LED) the monitors and/or to use an infrared camera. Though the used instruments (THYGAN, CG4) are relatively robust again icing, the EUMETNET SWS II experiment [2, 3] showed that they may suffer from icing under very severe conditions. A camera monitoring of both THYGAN and CG4 were therefore also useful.

The icing monitors have to be dramatically improved. Both selected instruments proved to be sensitive to icing (!), the Combitech showing negative excursions and the Goodrich being screened.

One important point is the care allocated to the sensor's daily monitoring. A test station should receive a higher level of maintenance, if possible with local manager, than an official one. Otherwise missing - or worse, unrecognized erroneous data - can induce bad conclusions.

If these prerequisites can be realized, it is suggested to carry on the experiment at the Guetsch test station during an additional winter.

Finally a finer data analysis working with situation (air temperature, wind, etc.) specific indices should allow increasing of the rate of coincidence.

## V. Appendix

$$T_{sky} = \left(\frac{Oli}{5.67e-8}\right)^{0.25} - 273.15$$

$II_1$ = true if $T_{re} < 1$ °C and $(T_{re} - T_{sky}) < 2$ °C and RH > 95%

$II_2$ = true if $T_{re} < 1$ °C and $(T_{re} - T_{sky}) < 2$ °C and Fkl > 2 $ms^{-1}$

$II_{cloud}$ = true if Tre < 1 °C and cloud layer 1 < 31 m

$II_{ngwc} = 600 * F_{kl} * \rho_{ngwc}$ if $T_{re} < 1$ °C and $T_{mi} > T_{re}$ with

$$\rho_{ngwc} = \frac{611.2*\left(\frac{e^{\frac{17.63*Tmi}{243.12+Tmi}}}{273.15+Tmi} - \frac{e^{\frac{17.63*Tre}{243.12+Tre}}}{273.15+Tre}\right)}{461.5}$$

## VI. Acknowledgment

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## VII. References

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[3] Tammelin, B., Heimo, A., Leroy, M., Rast, J., Säntti, K., Bellevaux, C., Dal Cin, Bruno, Musa, M. and Peltomaa, A., 2003. Improvements of severe weather measurements and sensors – EUMETNET SWS II project, final report. Finnish Meteorological Institute, CD-ROM, p. 167.

## VIII. Nomenclature

$T_{re}$: air temperature at 2 m [°C]

$T_{mi}$: dew point temperature [°C]

$F_{kl}$: wind velocity at 10 m [$ms^{-1}$]

Oli: downward long wave radiation [$Wm^{-2}$]

RH: relative humidity [%]

$T_{sky}$: sky temperature [°C]

$II_1$: Icing Index based on $T_{re}$, RH and Oli measurements [-]

$II_2$: Icing Index based on $T_{re}$, Oli and $F_{kl}$ measurements [-]

$II_{cloud}$: Icing Index based on $T_{re}$ and ceilometer measurements [-]

$II_{ngwc}$: Icing Index based on $T_{re}$, $T_{mi}$ and $F_{kl}$ measurements [$kgm^{-2}$]