Icing and the Humidity of Air

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***Abstract*—We analyze air humidity data from two hilltops, at which the relative humidity is frequently above 100% at sub-freezing temperatures, as indicated by frequently observed in-cloud icing events. Humidity measurements were made at these two sites by the commonly used Vaisala HMP35 and HMP233 capacitance probes respectively and simultaneously by the same manufacturer's HMP243 that determines the frost point by a heated capacitance sensor. Ice-detectors were also used and the system was monitored by a video camera. Our results show that in icing conditions the relative humidity is frequently well above the frost point and that the conventional humidity measurements are unable to detect these events. Furthermore, after such events, the iced sensors show too high humidity. We demonstrate that these problems can be solved by the novel solution introduced by Vaisala as the HMP243 dew point transmitter. With this device, which has a heated humidity probe, it seems possible to detect reliably the occurrence and, in particular non-occurrence, of rime icing.**

I. Introduction

THE relative humidity of air is typically very high during an icing event. Consequently, in icing models it is usually assumed that the air is saturated with respect to water. However, since an icing cloud may partially consist of ice crystals, this assumption is inaccurate. Furthermore, a cloud may be supersaturated. The humidity of air is interesting also because reliable ice detection is still a practical problem in many applications and it is tempting to think that a measurement of relative humidity could provide it for us.

The main reason for not utilizing the measured humidity of air in icing research is that it is generally considered unreliable at freezing temperatures combined with a high humidity. There is a good reason for such scepticism - the humidity probe will ice up. At supersaturation sublimation will occur on the probe, after which the reading will be fixed to the humidity corresponding to the frost point [1].

The possibility of measuring correctly the humidity of air in icing conditions and utilizing such measurements in icing modelling is addressed in this presentation. First, we outline some present methods and the specific problems related to them. The reliability of humidity measurements in cold and humid conditions has been addressed in several studies [2]-[5]. They show somewhat conflicting field data, apparently, because different sensors, with their characteristic errors and calibration problems, were used.

One method to measure RH is to optically detect the dew/frost point by a cooled mirror and then calculate RH from that and the measured air temperature. This method is generally considered accurate [6] and several humidity measurement instruments have been developed based on it, for example, MBW Elektronik DP3-D [4], General Eastern 1011B [5] and Metolabor AG "Snow White" [7]. The cooled mirror hygrometers are often used as a standard, although it has been found by laboratory experiments [8] that in humid air between 0 and -20^{o}C supercooled dew may be forming on the mirror rather than frost, making the interpretation of the measurements prone to errors. Furthermore, the concept that the temperature at the time of nucleation on a cold surface necessarily corresponds to the equilibrium frost point has recently been shown to be incorrect [9].

As discussed above, fundamental problems are related to icing on the sensor when measuring humidity at cold temperatures by conventional means. A novel solution to this problem has been introduced by Vaisala in the HMP243 and HMT337 dew point transmitters. These devices have a heated humidity probe that prevents sublimation entirely [10].

In this paper, data from simultaneous measurements by the HMP243 and the same manufacturer's commonly used conventional capacitive sensors HMP35C and HMP233 are analyzed in order to test the new method and to reveal the true humidity conditions in icing conditions as well as to consider the possibility of icing detection by humidity data.

II. The humidity probes

The HMP35C, used in our studies, is based on the Vaisala Humicap, which is a capacitive polymer film probe sensitive to the relative humidity. HMP35C is essentially the same as the HMP35A used in [2] and the HMP35CF used in [4]. The HMP233, also used by us, is based on the Vaisala Humicap as well, and is essentially the same as the HMP235 used in [5]. The other hygrometers, used in [5], HMP50Y and HMP50U utilize Vaisala Intercap, an interchangeable capacitance sensor based on the Humicap method. Because of the same measurement principle and very similar sensors, the results of all the above mentioned HMP devices should be comparable.

The HMP243, on the other hand, uses a different measurement principle. While the humidity sensor element is a capacitive polymer film based on the Humicap, the device is fundamentally different in that the probe itself is heated a few degrees above the ambient air temperature in order to prevent condensation/sublimation. A Pt100 thermo-element is attached to the humidity sensor head for measuring its temperature T_s. The device includes a separate unheated thermometer installed far away from the heated probe. The unheated thermometer measures the ambient air temperature T_a which makes it possible to calculate the relative humidity RH. Following [10], the principle of HMP243 is as follows.

The relative humidity RH (in percent) is defined by WMO with respect to water, i.e.

$$RH(T_a) = [e_w / e_{sat,w}(T_a)]\ 100 \qquad (1)$$

where e_w is the water vapor pressure in air and $e_{sat,w}(T_a)$ is the saturation water vapor pressure with respect to water at the temperature T_a. From (1), the ambient water vapor pressure is

$$e_w = [RH(T_a)/100]\ e_{sat,w}(T_a) \qquad (2)$$

On the other hand, because (1) is valid at any T, it may be applied at the temperature T_s of the heated polymer sensor as well, so that

$$e_w = [RH(T_s)/100]\ e_{sat,w}(T_s) \qquad (3)$$

From (2) and (3) it follows that

$$RH(T_a) = [e_{sat,w}(T_s)/e_{sat,w}(T_a)]\ RH(T_s) \qquad (4)$$

The HMP243 probe determines $RH(T_s)$, since it measures the heated sensor's capacitance C and temperature T_s directly and the response function $C(RH,T_s)$ for the sensor is well known from experiments. Using the measured T_a and T_s the saturation water vapor pressures in (4) can be determined since the function $e_{sat,w}(T)$ is known. Thus, the ambient relative humidity $RH(T_a)$ can be calculated from (4).

The ingenious use of (4) as the measurement principle of HMP243 avoids the problems of sublimation because (4) is valid at any temperature of the sensor head. Consequently, the humidity probe, as a whole, can be heated sufficiently to keep T_s well above T_a, so that the probe is ice-free at all times, and yet obtain an accurate RH value for the undisturbed ambient air.

III. The measurements

The measurements analyzed here were made in two parts. The first consisted of two winter periods in 1998-2000 at the top of Pyhätunturi hill, where HMP35C and HMP243 were simultaneously used. Pyhätunturi is located in central northern Finland at 67.01 ^{o}N, 27.13 ^{o}E and its elevation is 477 m above sea level. The data were collected automatically with little human intervention, but the measurement system was monitored by a video camera and two ice-detectors, Labko LID-2000 [11] and Instrumar IM101 V2.4 [12].

The second measurement period was in the winter of 2003-2004 at the top of Olostunturi hill, where HMP233 and HMP243 were simultaneously used. Olostunturi is also located in northern Finland, 180 km to the north-west of Pyhätunturi. Both hills are inland about 200 km from the nearest coast. The top of Olostunturi is 508 m above sea level and it is located at 67.55 ^{o}N, 23.46 ^{o}E. This site was mostly manned during the measurements, so that the instruments could be carefully monitored and the radiation shields of the hygrometers cleaned from rime ice. Manual observations were also made e.g. on the liquid water content and droplet size of the icing clouds using the rotating multicylinder method [13], which made it possible to objectively detect rime icing, i.e., situations where the air was saturated with respect to water. In addition, an ice detector, Labko LID-3200, was used.

The hygrometers were installed on the roof of a measurement hut at the height of 4m from the ground in their original unventilated shields. The instruments were connected to a measurement computer via a serial port. The measurement frequency was 1 Hz, but ten minute mean values are presented and analyzed in this paper. There were 34934 such ten minute mean values measured on Pyhätunturi and 17490 on Olostunturi.

The hygrometers used in this study were calibrated as follows. The particular HMP35C device used on Pyhätunturi had been in routine use by the Finnish Meteorological Institute for several years. The HMP243, when used on Pyhätunturi, was new. Both instruments had been calibrated on the production line at the factory. Because of such calibrations and the unmanned site, the instrument calibration and control on Pyhätunturi represent a situation that is rather characteristic to the automated weather stations, from which e.g. the data of [4] originate from.

The calibrations of HMP233 and HMP243 for the well controlled measurements of the manned station, Olostunturi, were done more carefully in an attempt to minimize all uncertainties. The devices were specially calibrated for this purpose at the manufacturer's laboratory both prior and after the measurement period. The calibration was done at three calibration points, RH of 0%, 75% and 97.5% at room temperature. The shift in the calibrations of these two probes during the measurement periods was below the nominal measurement accuracy.

Our measurement sites were purposely chosen so that high humidity combined with subfreezing temperature would be common. The high humidity on these hills was expected due to experiencing in-cloud conditions caused by passing low level clouds and by air uplift induced by the hill itself. Because supercooled cloud droplets occur in clouds and orographic fogs, and the hilltops are windy, severe rime icing is often related to these events. This causes an additional potential problem in measuring the air humidity because the radiation shields and other surrounding structures may be covered with ice. The ice may reduce ventilation and, at the same time, produce by sublimation an artificial environment where the air around the hygrometer sensor is saturated with respect to ice.

On Olostunturi ice was removed from the radiation shields when manually deemed necessary. This happened 15 times during the measurement period of about five months. We found no change upon ice removal in the readings of either of the hygrometers in 13 of these cases. In one case, in which the shield of HMP233 appeared to be completely blocked by ice, there was a noticeable change in its RH reading. In another case there was, upon cleaning, a significant increase of RH measured by HMP243, but not in RH measured by HMP233. The reading of HMP243 returned to its pre-cleaning value in two hours, and we suspect that the change was caused by pieces of rime adhered to the heated HMP243 sensor head during the removal of ice.

Thus, overall, the ice accumulation on the radiation shields around the hygrometers seems to have affected our humidity measurements surprisingly little, if at all. Nevertheless, it is apparent that a hygrometer cannot measure correctly in a shield, the ventilation of which is completely prevented by an ice cover. In a remote polar site a shield, once heavily iced up, may stay that way for most of the winter. Thus, attention should be paid to this problem when planning measurements and analyzing data from unmanned sites.

One way to prevent icing of the hygrometer shields would be to heat them continuously, or at least at times, similarly to what is done to anemometers [14]. This, however, requires a high heating power and heats the air flowing into the shield, thus reducing the apparent relative humidity. Note, however, that HMP243 is immune to such an effect, as shown by (4), provided that the measurement of the ambient temperature is unaffected by it.

IV. Results and discussion

The correspondence of RH as measured by HMP35C and HMP243 on Pyhätunturi is shown in Fig. 1 and that of HMP233 and HMP243 on Olostunturi in Fig. 2. There are several striking features in these figures. First, points with RH ≥ 100%, i.e. air at or above saturation with respect to water, are completely absent from the data of HMP35C and HMP 233. They are abundant, however, in the data of HMP243, particularly on Pyhätunturi. These points are largely related to the well documented rime icing events on the hills, so that we know that they are real. Thus, HMP 243 is able to detect the in-cloud conditions and the icing situations, contrary to the conventional sensors.

Second, the HMP233 and HMP243 on Olostunturi measured RH in an excellent agreement up to RH around 60%. This illustrates that the instruments measure consistently and that their calibrations, at least in this range of RH, are good. Problems arise at higher humidity and become more serious close to RH = 100%. Apparently, the points in Figures 1 and 2 where HMP243 shows a much higher RH are due to an ice cover on the sensor of the other probe. Such an ice cover may persist a long time after its formation even at low subsequent humidity, unless the air temperature rises above 0C. As a consequent of icing, a conventional capacitance probe shows too high RH when still iced up, even though the air is no more saturated with respect to ice and a too low value when being iced up in air which is actually supersaturated with respect to ice. In the latter case the reading is fixed at RH_i = 100%. Here RH_i is the relative humidity (in percent) with respect to ice, i.e.

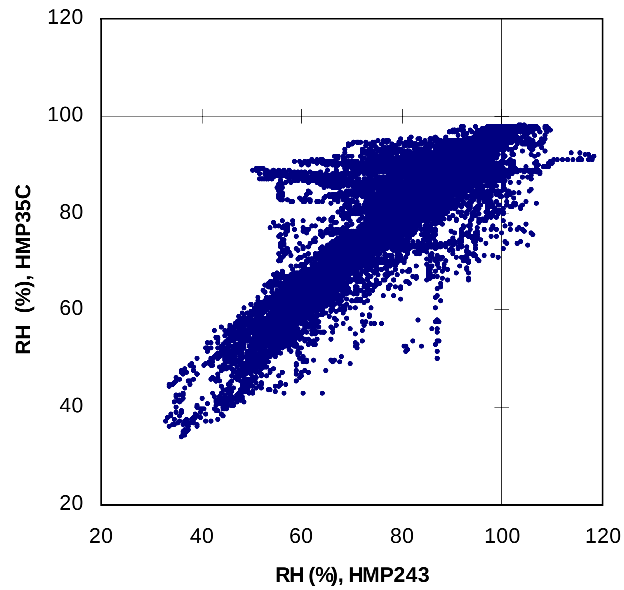

Fig.1. Correspondence of the relative humidity RH as measured by HMP243 and HMP35C (Pyhätunturi). The linear correlation coefficient is 0.908.

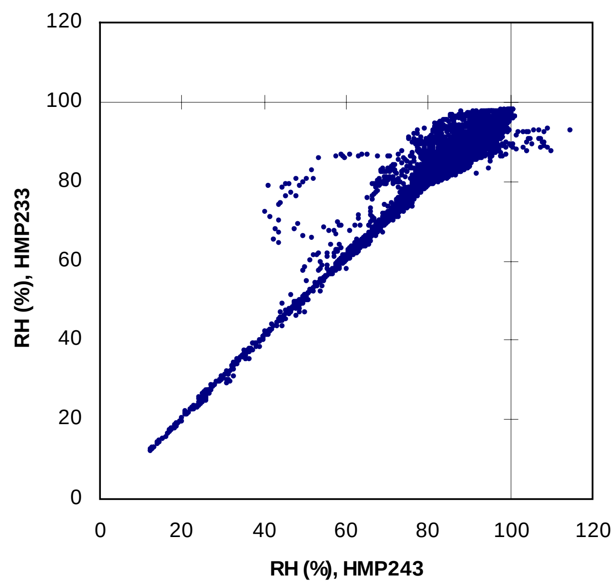

Fig. 2. Correspondence of the relative humidity RH as measured by HMP243 and HMP233 (Olostunturi). The linear correlation coefficient is 0.967.

$$RH_i(T_a) = [e_w / e_{sat,i}(T_a)]\ 100 \tag{5}$$

where $e_{sat,i}(T_a)$ is the saturation water vapor pressure with respect to ice at the temperature T_a. As a result, the error of a conventional hygrometer at high humidity may be in both ways, and the data points spread on both sides of the one-to-one line, as seen in Figures 1 and 2.

The third interesting feature in Figs. 1 and 2 is their difference in that the data from Pyhätunturi, at which

HMP35C probe was compared to HMP 243, show significant scatter even at low humidity. This may have been caused by calibration shifts or because the instrument shield has been heavily iced up for long periods. Also here however, the biggest error source is probably that, due to sublimation, the HMP35C sensor head itself has been iced up for long periods during which RH has been low. This is supported by the observation that this measurement period was colder and included more frequent supersaturated conditions than the measurement period of Olostunturi

Figures 3 and 4 show the relative humidity with respect to ice, RH_i versus air temperature T_a as measured by the HMP35C and HMP243, respectively. Figure 3 shows that, given allowance to the small calibration error and the nominal measurement accuracy, all the humidity observations below an air temperature about -13^oC fall on the ice saturation curve. Figure 3 clearly illustrates the icing problem of the probe in supersaturated conditions.

The data measured by HMP243, presented in Figure 4, reveals a picture very different from Fig. 3. Because of the measurement principle that prevents sublimation on the probe, HMP243 measures properly, both in supersaturated conditions, as well as in dry air that follows such conditions. Consequently, Figure 4 shows e.g. thousands of data points where $RH_i > 100\%$, whereas there are only a few such points measured at any temperature by HMP233 (Fig. 3).

The data that correspond to Figures 3 and 4, but as measured by HMP233 and HMP243 on Olostunturi, are shown in Figures 5 and 6. Figure 5 is similar to Figure 3 except that the points concentrate entirely on the saturation point with respect to ice at a lower temperature and that the range of air temperature is narrower. Figure 5 illustrates that, when carefully calibrated, HMP233 shows saturation exactly at $RH_i = 100\%$ within the whole temperature range. This confirms that the trends of RH_i with T_a in the data in [2], [4] and [5] are artifacts that are caused by calibration problems. Such problems may be present, for example, due to aging of the sensors, i.e., reduced polymer sensitivity to water vapor, which is more rapid in a moist environment [7].

As on Pyhätunturi, Figs. 5 and 6 from Olostunturi show that HMP243 frequently measures $RH_i \geq 100\%$, whereas such points are very rarely measured by the conventional capacitance probe HMP233. From the simultaneous icing observations and measurements of cloud microphysical properties, we know that the supersaturated conditions measured by HMP243, but not by HMP233, are real (see Figs. 7 and 8). The highest ten minute mean RH values in our HMP243 data are almost 120%. Our results thus indicate that HMP243 with a heated probe is able to avoid the errors that are related to the icing on a conventional hygrometer.

As discussed above, the errors in the RH values of a conventional capacitance humidity probe may be very high in individual cases. This is crucial in some applications, such as prediction of visibility and the growth of hoarfrost, because the errors are typically related to erroneously detecting/not detecting supersaturation with respect to ice. Overall, the errors in RH are typically of the order of ±5%-units, except when RH is at or above 100% and larger errors appear.

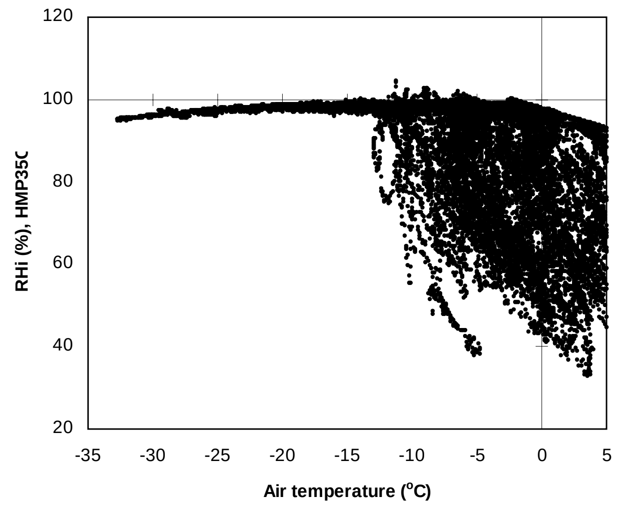

Fig. 3. Relative humidity with respect to ice RH_i as measured by HMP35C versus air temperature (Pyhätunturi).

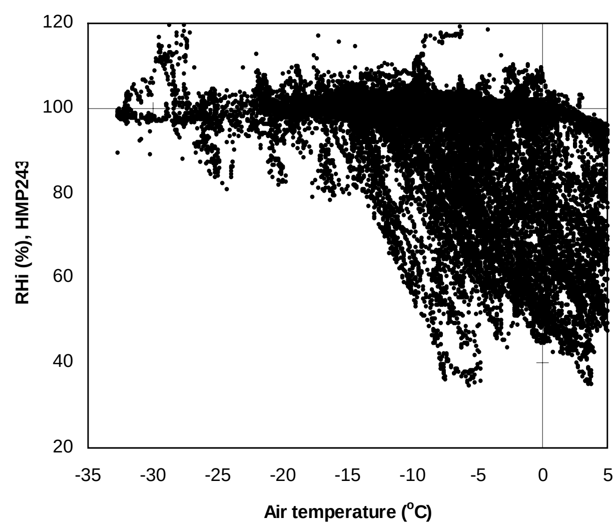

Fig. 4. Relative humidity with respect to ice RH_i as measured by HMP243 versus air temperature (Pyhätunturi).

To summarize the comparisons of the humidity probe data, we have shown that conventional instruments cannot measure at a humidity that is at or above saturation with respect to ice. Such conditions are, however, quite common as shown here using a heated capacitance humidity sensor, an ice detector and visual observations. The problems with the conventional humidity probes are due to icing of the sensor head and, in the case of an aspiration psychrometer, icing of the dry bulb thermometer. These problems have seriously hampered all meteorological studies in cold and humid environments, in which humidity data based on aspiration psychrometers, hair hygrometers, dew cells, mirror dew point probes and capacitance hygrometers have been used. Critical reevaluation of the conclusions from such studies is, therefore, necessary.

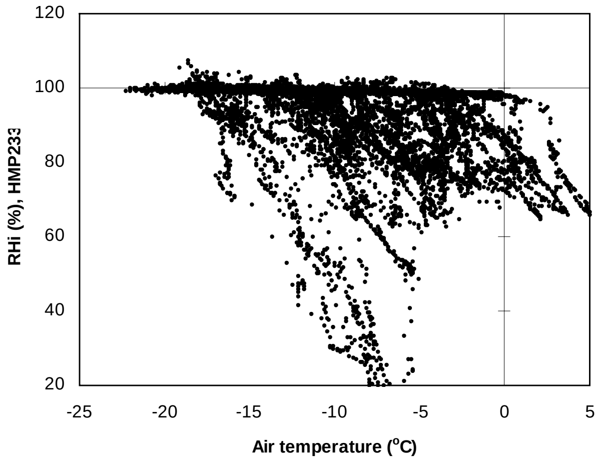

Fig. 5. Relative humidity with respect to ice RH_i as measured by HMP233 versus air temperature (Olostunturi).

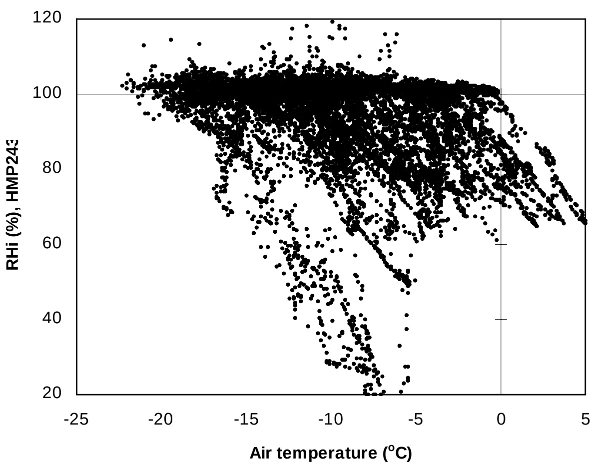

Fig. 6. Relative humidity with respect to ice RH_i as measured by HMP 243 versus air temperature (Olostunturi).

The issue of ice detection using humidity data is addressed in Figs. 7 and 8, in which the icing cases, as selected from the data of Figs. 5 and 6, respectively, are shown. The selection was done objectively based on the Labko LID ice detector outputs. Fig. 7 clearly demonstrates the icing problem of a conventional humidity probe: RH_i is in most cases fixed to 100%. Fig. 8, on the other hand, reveals a range of supersaturation in which detected icing occurs. In both figures, some scattered icing points are below the saturation humidity. According to our detailed analysis using e.g. the visual observations, these points are related to false alarms by the ice detectors. Note that no freezing precipitation icing events, during which RH is typically well below 100% [15] are included in our data. Thus, a no-icing situation can reliably be predicted when RH_i, given by HMP243, is below 100%.

However, prediction of an icing situation based on the humidity data alone appears not to be very reliable. Out of the points, for which HMP243 showed RH_i > 100%, only 47% are

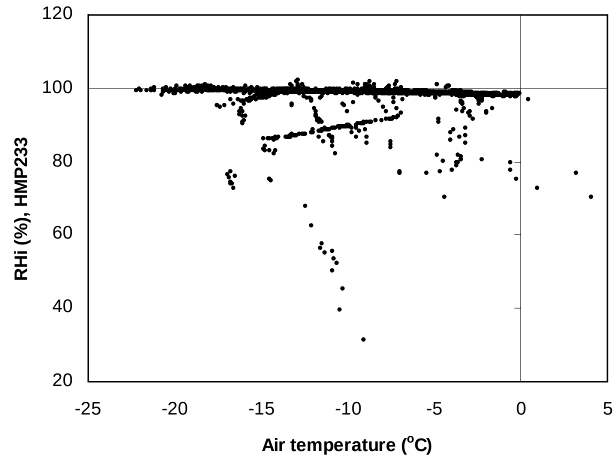

Fig. 7. As in Fig. 5, but for detected icing cases only.

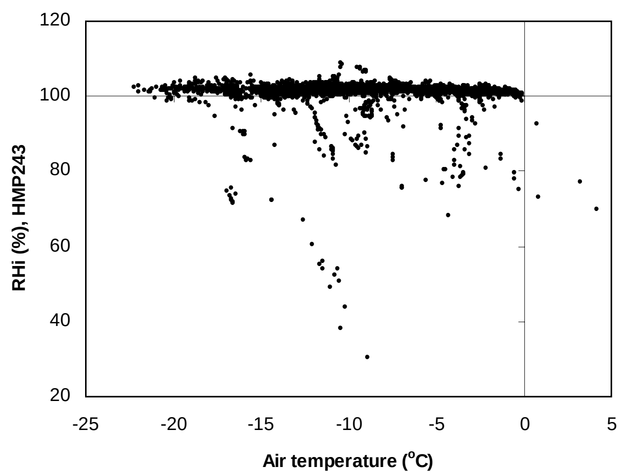

Fig. 8. As in Fig. 6, but for detected icing cases only.

icing events as indicated by the ice detector. This should not be interpreted as a problem in measuring or using the humidity data, however. The situation arises from the fact that the detection threshold of the ice detectors is quite high, so that light rime icing and hoarfrost formation are not recorded. Even light icing may, however, cause problems with, say, operation of wind turbines [16]. Therefore, humidity as measured by the HMP243 may, in fact, in some applications be more useful than an ice detector.

To conclude, the analysis of our field data shows that there are fundamental problems in measuring humidity in cold and humid air, which have seriously hampered all related previous measurement campaigns, as well as routine meteorological observations, in cold climates. It appears, however, that these problems can now be avoided by using a capacitance humidity probe that has a heated sensor head. This progress in sensor technology provides at least a limited opportunity for using humidity data in the detection of atmospheric icing.

V. ACKNOWLEDGMENTS

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