Anemometry in Icing Conditions

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ABSTRACT

The accuracy of wind measurements in icing conditions is discussed, and wind tunnel calibrations as well as field comparisons are presented for three heated anemometers that use different measuring principles. It is pointed out that ice-free anemometer calibrations, including those provided by manufacturers, are affected by the blockage effect in wind tunnels that are too small. Some anemometers that measure correctly in a wind tunnel give erroneous results in the field. Overall, measuring mean wind speeds and peak values in icing conditions with the accuracy of about 5% seems possible with the present technology, both with rotational and sonic anemometers, but in the most severe environments only some internally heated rotational anemometers are reliable. Wind measurements in icing conditions without due consideration of anemometer selection, specific instrument problems, calibration inaccuracies, mean vertical velocity component, and anti-icing of the supporting structures may result in very big errors.

1. Introduction

Wind speed needs to be measured also in environments prone to icing caused by cloud droplets or freezing precipitation. In fact, in colder areas of the world many man-made structures that are especially vulnerable to high winds or require accurate wind data for other reasons, are typically located at such ice-prone sites. These include transmission towers, wind turbines, and overhead power lines, which are typically located at hilly and mountainous sites where in-cloud icing is frequent. Such conditions make accurate meteorological measurements demanding (e.g., Strangeways 1981), particularly in regard to wind speed. Similar measurement problems occur also in low lands after freezing rain events and when characterizing the atmospheric boundary layer by measuring the wind profile from tall towers (e.g. Klinov 1978), the top of which may ocassionally penetrate into icing clouds.

Conventional cup anemometers are generally considered quite reliable, as pointed out in the recent review by Kristensen (1998). This positive view, however, is not shared by the users operating in cold environments. Once iced up, a conventional cup anemometer shows incorrect values, very often zero winds, and is easely broken up by accreted ice and the related wind forces.

Thus, until recently, accurate wind measurements in a severe icing environment were not possible at all due to icing of the anemometers. Some robust on-site solutions were consequently developed, as shown in Figs. 1 and 2. While these trials were justified at the time as the only means to collect any data, severe problems were involved. For example, it is apparent in Fig. 1 that the heating system has been insufficient to prevent icing, and in Fig. 2 it is clear that the configuration used is not aerodynamically optimal.

Today, various ''ice-free'' anemometers based on different measuring principles are available. Most of these instruments utilize anti-icing of the anemometer by heating. Some of such anemometers include heating of the bearings and connections only. This heating melts the ice condensed inside the instrument and may be sufficient to quarantee operation at lowland weather stations. However, in hilly or mountainous areas, such a heating is insufficient to prevent in-cloud icing on the external surfaces of the anemometers, even when using additional external heating (see Fig. 1). Therefore, such anemometers are not considered here. We only discuss

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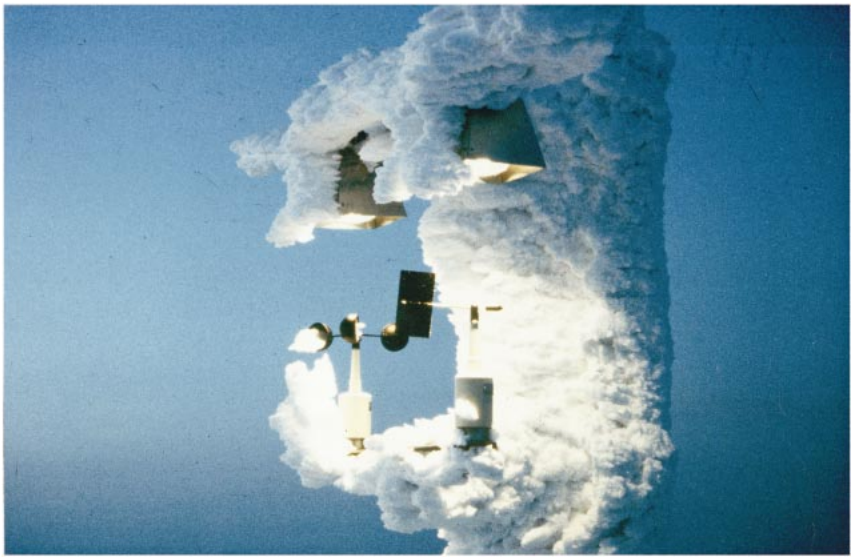

FIG. 1. Early attempt to anti-ice a cup anemometer using a 750-W infrared lamp. Photo is from 1983 at our test site on Yllas, Finland.

anemometers that include anti-icing of all the essential instrument components, such as the cups, vanes, and sensor heads.

Already now, the use of heated anemometers has thoroughly changed the view of the wind conditions in many elevated cold areas. For example, in hilly areas of northern Europe a wind potential sufficient for large-scale development of wind energy has been thus revealed. A persistent temperature inversion in wintertime causes very low wind speeds in the lowlands of these areas. It was generally thought that the wind speeds in the winter were low at high altitudes as well, considering that the few measurements on the hills showed that to be the case. Upon utilizing anti-iced anemometers on the hills, it turned out that the conventional anemometers had measured mostly zero wind speeds, only because they were iced up.

Inspite of these recent developments, the knowledge of the true wind speeds in areas prone to icing is still inadequate due to problems of poor reliability of the measurements. The heated anemometers are quite new and most have not yet been tested in the hardest environmental conditions. Also, already calibration of conventional anemometers involves significant inaccura-

FIG. 2. Cup anemometer heated by a ''frying pan'' heater. Photo is from the icing research station in Studnice, Czech Republic.

cies. Makkonen and Helle (1994) found that manufacturers' calibration constants of cup anemometers include large errors and that for many anemometers a nonlinear calibration equation should be used instead of the conventional linear form. In addition, some of the anti-iced anemometers are so different from conventional anemometers that their calibration procedures have to be adjusted, and this may introduce other types of errors. In this paper, we discuss these problems and present wind tunnel calibrations and field comparisons for three anti-iced anemometes that use measuring principles different from each other.

2. Heated anemometers

a. Rotational anemometers

The most common instrument to measure wind speed is a rotational anemometer. The rotation is initiated by wind drag on cups, vanes, or propeller blades. Today, there are several types of rotational anemometers available that include heating of the shaft and the vane cups with a power potentially sufficient to prevent atmospheric icing. These include NRG Systems Ice Free II (Kenyon and Blittersdorf 1992), Vaisala Inc. WAA25 (Aspola 1994) and WAA252, Thies Clima SK565, and Hydro-Tech WS-3, which are also accompanied by a heated wind direction vane. The heating power of these instruments varies between 70 and 1500 W and is thermostatically controlled. Out of these anti-iced rotational anemometers we have chosen the Hydro-Tech WS-3 (and the accompaning wind vane Hydro-Tech WD-3) for this calibration and intercomparison study. This is because Hydro-Tech was a pioneer in this field, for which reason we have over 14 years of experience of the use of the Hydro-Tech WS-3 in the severe icing climate of our test station.

The Hydro-Tech WS-3 anemometer is a disk rotor 0.203 m in diameter and 0.083 m in height with six cup vanes welded on the disk. The vane cups are half-cylinders with a 0.038-m radius and 0.05-m length. The material is aluminum and the weight of the rotating assembly is 1.0 kg. The anemometer and the wind vane are both equipped with a 1500-W internal electrical heater. The heater is supported on a plate fastened to the body of the anemometer. A temperature sensor is located in the air space just below the rotor and is connected to an automatic power controller. The sensor can be seen in Figs. 5 and 6.

The Hydro-Tech anemometer used in this study is of the type where the original tachometer has been replaced by electronics, which give an output frequency proportional to the rotating speed. Hydro-Tech WS-3 anemometers have been used at our test site from January 1986. Prior to this, other tested anemometers were not only iced up, but often lost their cups or were otherwise broken. In spite of this severe environment no mechanical failures of the Hydro-Tech anemometers have occurred, and icing on the devices has been observed only in the few events where the heating system has failed, for example, due to damage by lightning.

On the other hand, the potential problems with the Hydro-Tech anemometer are also related to its sturdy design. The distance constant is 58 m and the threshold wind speed is 2.2 m s^{-1} (Lockhart 1987). The high distance constant could theoretically result in overspeeding in a real turbulent flow (Busch and Kristensen 1976; Kaganov and Yaglom 1976). Also the sensitivity of the output to nonhorizontal flow, that is, the off-axis response, of the Hydro-Tech WS-3 is high (Lockhart 1987). This could result in systematic errors particularly at sites where the wind vector has a significant vertical mean component due to the shape of the terrain.

b. Pressure sensing anemometers

Because the cup vanes of rotational anemometers are vulnerable to icing, some manufacturers have developed so-called solid-state anemometers. These include no external moving parts, which makes them mechanically stronger and easier to anti-ice than a rotating assembly. A Franklin Engineering Co. device (Franklin and Howe 1991) includes a cylinder that measures the wind drag. The device is pneumatically de-iced by two rubber boots. An anemometer based on the same principle has been developed for an entirely pneumatically de-iced weather station (Strangeways and Hudson 1991). A Metrex ice-free anemometer (Krishnasamy and Motycka 1991; Pon and Kastelein 1997) also measures the wind pressure on a drag sphere on top of a vertical shaft. This device is internally heated to prevent icing. Environmental Instruments Model 200 wind probe (Bates and Govoni 1984) includes two static pair heated resistive sensing elements mechanically supported at right angles and an electrically heated cage to melt ice. The Rosemount solid state anemometer measures the air impact pressure through small holes on a heated cylindrical sensor probe. Out of these pressure sensing anemometers we have selected the Rosemount solid state 1774W for our tests simply because it was most readily available to us being lended for the tests by the manufacturer.

The Rosemount solid state 1774W anemometer measures wind impact pressures along two horizontal axis. The wind vector components calculated from the differential pressure measured through small holes on the sides of the cylindrical probe are then used to determine the resultant scalar wind speed and wind direction. The sensing probe is a 0.355–m–long vertically oriented tube with the diameter of 0.03 m. The weight of the probe is 5.7 kg, and it is internally heated at the 370-W power at maximum. The instrument is precalibrated at the factory. The Rosemount anemometer can be seen in Fig. 5.

c. Sonic anemometers

Sonic anemometers are based on measuring either in two or three dimensions the time required by ultrasonic

TABLE 1. Measurement range and accuracy of the parameters for determining the calibration reference velocity in the VTT wind tunnel.

Quantity	Range	Accuracy
Kinetic pressure	0–10 kPa	0.01 Pa + 0.08%
Barometric pressure	80–106 kPa	0.04 kPa
Temperature	−20° to +80°C	0.2°C
Relative humidity	0%–100%	1% RH

pulses to travel from a transmitter to a receiver. A sonic anemometer is expected to measure correctly also in icing conditions provided that the ray paths are not obstructed by accreted ice. The cloudy conditions, as such, do not seem to affect the behavior of a sonic anemometer (Siebert and Teichmann 2000). Several manufacturers, Gill Instruments, Theodore Friedrich, Vaisala Inc., Metek, and Handar provide sonic anemometers with heating of the transmitter and receiver sensor heads. Out of these we have chosen the Metek USA-1 anemometer for our tests, because we wanted to measure in three dimensions in order to study the off-axis response of other anemometers, and because the Metek includes the highest heating power of the available heated 3D sonic anemometers.

The Metek USA-1 anemometer uses ultrasonic pulses along three noncomplanar ray paths to measure wind speed and direction, or alternatively the three orthogonal wind components *x, y, z.* The distance between the transmitters and receivers, that is, the length of the ray paths is 0.175 m. The weight of this anemometer is 2.3 kg. The Metek has no moving parts and its surface area is small. These properties make it an attractive option in an icing environment. Also, this anemometer has theoretically no thresold wind speed and no off-axis response, because the measurement is acoustic and is done in three dimensions. The device used in our study has internal electric sensor heating on each of the six sensor heads with a total heating power of 50 W.

We had no experience of the accuracy, rigidity, or anti-icing capability of the Metek anemometer prior to this study. The device we used was precalibrated at the factory. In the case of acoustic sensors of this type the calibration procedure is essentially to determine the length of the ray path. The sensor also includes an onsite calibration routine that uses measured ray path lengths as input. The Metek anemometer is shown in Figs. 6 and 7.

3. Calibrations

a. The wind tunnel and calibration procedures

The anemometer calibrations were made in the VTT closed-circuit wind tunnel, which has a test section 2.5 m wide, 1.5 m high, and 12 m long. The highest attainable reference velocity in the tunnel is about 25 m s^{-1}. The reference velocity Ur in the test section is determined by measuring the dynamic pressure p of the airflow and using the Bernoulli equation,

TABLE 2. Measurement error of the reference wind velocity Ur in the VTT wind tunnel.

Ur (m s^{-1})	Error
0.5	3.48%
1	1.03%
2.5	0.33%
5	0.23%
7.5	0.21%
10	0.21%
25	0.20%

$$Ur = (2p/r)^{0.5}, \quad (1)$$

where r is the air density. The air density, barometric pressure, temperature, and humidity in the wind tunnel are measured with errors shown in Table 1, and transferred into a PC, so that the instantaneous reference wind speed can directly be used during the calibration. The error of the reference velocity, based on the uncertainty calculation using the values of Table 1, is shown in Table 2. The data collection system has a sampling rate of 10 kHz.

The calibration procedures were according to the American Society for Testing and Materials standard (ASTM 1990). The standard sets the calibration interval in terms of determining the linear calibration constant to be from 0.1 to 0.5 times the maximum application range of the anemometer. Accordingly the linear calibration constant was determined for the speed interval of about 5–25 m s^{-1}.

The calibration constants were, following Lockhart (1987), determined separately for the linear range (speeds higher than a transition speed U1) and for the nonlinear range (speeds higher than U1), so that

$$\text{if} \quad a + bR > \text{U1}, \quad \text{then } U' = a + bR,$$
$$\text{else} \qquad U' = (a + bR) - [a' + b' \ln(a + bR)], \quad (2)$$

where R is the rotation rate in hertz and U' is the wind tunnel speed in meters per second as predicted by the calibration equation using the linear calibration constants a and b and the nonlinear calibration constants a' and b'.

b. Calibration results

A complete calibration was made in our wind tunnel for a Hydro-Tech WS-3 anemometer identical with the one used in the field measurements. The results of the calibration are

$$\text{U1} = 5.4 \text{ m s}^{-1}, \qquad a = 0.063 \text{ m s}^{-1},$$
$$b = 3.236 \text{ m}, \qquad a' = 0.699 \text{ m s}^{-1}, \quad \text{and}$$
$$b' = 0.416 \text{ m}.$$

The favorable effect of applying a nonlinear calibration at low speeds is demonstrated graphically in Fig. 3.

The original calibration constant $b = 2.904$ m has

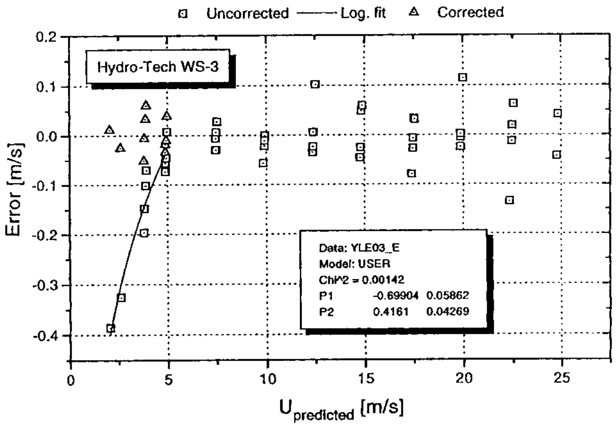

FIG. 3. Calibration error of Hydro-Tech WS-3 after applying the correct linear calibration constant at all speeds (squares). The triangles show the calibration error at low speeds after applying the nonlinear calibration.

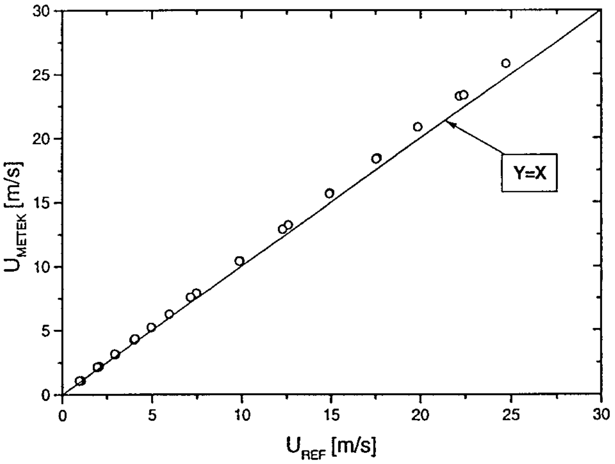

FIG. 4. Metek anemometer wind speed vs wind tunnel reference wind speed at wind direction of 0°.

been provided by the manufacturer. Lockhart (1987) determined the calibration of the Hydro-Tech WS-3 in the range of 10 m s^{-1} $< U <$ 20 m s^{-1} and obtained $a = -0.010$ m s^{-1} and $b = 3.163$ m. Lockhart (1987) also suggested U1 = 8.1 m s^{-1}, $a' = 0.638$ m s^{-1}, and $b' = 0.305$ m to be used. Our calibration results to wind speeds approximately 12% higher than those of the manufacturer and 3% higher than those of Lockhart (1987). We also tested the Hydro-Tech anemometers equipped with three different rotors. One of these was the device used in the field tests. The effect of varying the rotor was less than 2% in the whole range of the wind speed.

The Rosemount solid state sensor was calibrated similarly. The device was tested both having the heater on and off. A small difference was found between these cases, but overall the error in the wind speed was less than 3% in both cases at all speeds. Thus, the factory precalibration of the Rosemount solid state anemometer was within the manufacturer's specifications (error < 1 m s^{-1}). The direction output was also within the specifications.

The calibration results of the Metek USA-1 in Fig. 4 show that, at one anemometer orientation, the precalibrated sensor overestimated by 4.5%. An error of this magnitude in manufacturer's calibrations is a common problem with anemometers (Makkonen and Helle 1994) including those based on ultrasonic measurements (Pinard 1998). When testing the Metek with the heating on and off, the effect of the heating of the sensor with the maximum power was found to be less than 1% in the wind speed output.

An unexpected feature of the Metek device was observed when rotated around its vertical axis. The instrument's velocity output, at least in the laminar flow of the wind tunnel, seems to be sensitive to the wind direction. This caused variations of about 5% in the velocity depending on the anemometer orientation. The velocity appears to fluctuate with a period of 120° when rotated corresponding to the configuration of the device. The mean of the calibration constants determined in the wind tunnel for various directions was used in our final calibration applied to our field comparisons. This resulted in a constant −3.5% correction to the velocity output of the Metek USA-1 sensor.

4. Field comparisons

a. Test arrangements and data analysis

The field measurements were made in northern Finland at the Yllas broadcasting station. The station is located at a hilltop extending some 460 m above the surrounding terrain and 700 m above the sea level. The site is known for heavy ice and wind loads. The observed extreme rime ice loads are up to 1700 kg m^{-1} on a tranmission tower and the maximun mean wind speeds are of the order of 40 m s^{-1} at the height of the anemometers tested here. The station is manned and equipped with outside video cameras, so that the anemometer performance and data collection systems can readily be monitored.

The Hydro-Tech WS-3/WD-3 anemometers at the test site are a part of the ice and wind monitoring system of the broadcasting tower. The wind speed measured by the Hydro-Tech anemometer considered here is also used in the analysis of the cloud liquid water content and droplet size measurements performed at the site (Makkonen 1992). This anemometer is installed on a vertical steel tube on the roof of the transmitter building 4 m above the roof and 8 m above the ground level, as seen in Fig. 5. Because the site is at a hilltop, the terrain is very open in all directions (see Fig. 6).

The Rosemount solid state 1774W anemometer was installed at the same height for comparative measurements during the period of 4 January–28 April 1995. This anemometer is also shown in Fig. 5. The extra heating cables added to prevent icing of the supporting

FIG. 5. Rosemount (left) and Hydro-Tech (right) anemometers at the field site. The supporting boom of the Rosemount is pointing to the south. Note the added heating cables to prevent icing of the supporting structures.

structures can be seen in Fig. 5 as well. Ten-minute mean values and peak values measured by the anemometers were recorded simultaneously once every 3 h. Altogether 657 such measurements were recorded. The Rosemount anemometer was programmed to send 1-s mean values each second via the serial interface to the measuring computer. The computer measured the output of the Hydro-Tech anemometer 4 times per second.

The field measurements using the Metek USA-1 sonic anemometer were made during the period of 16 January 1997–3 April 1998. The Metek anemometer was installed at the same height as the Hydro-Tech anemometer (see Fig. 6). The spacing of the two anemometers was 2.0 m. Ten-minute mean values of both the anemometers were recorded simultaneously once every 3 h. Altogether, there were 3521 of these such recordings.

FIG. 6. Hydro-Tech (upper left) and Metek (separate support) anemometers at the field site. The supporting boom of the Hydro-Tech points to the south. The instrument on the other boom on the left is an Instrumar ice detector. The iced object at a lower level on the left is a 30-mm diameter cylinder used as an ice collector.

FIG. 7. Ice on a Metek sonic anemometer at the test site. This situation is atypical, but shows that sometimes icing of the instrument occurs in spite of the heating.

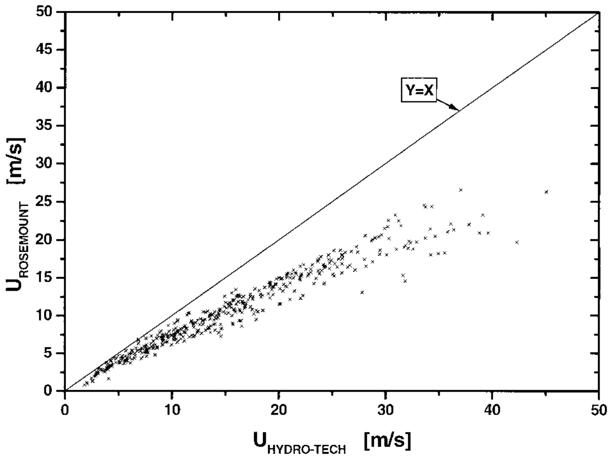

FIG. 8. Rosemount mean wind speed vs Hydro-Tech mean wind speed in the field measurements. Data are for 10-min mean values.

The internal sampling frequency of the Metek was 10 Hz. Metek sent one second mean values to the measuring computer. The Hydro-Tech data were recorded as explained above.

For the comparisons of the Rosemount anemometer measurements where the wind direction was 110°–320° only were included in the analysis of the wind speed, because for other directions the Hydro-Tech sensors and the supporting structure may cause shadowing effects. For the comparisons of the Metek the wind speed data from the sector of 160°–190° were neglected for the same reason. In order to avoid including cases where the Hydro-Tech anemometer may have been stationary due to its high thresold wind speed, data points for which the lowest instantaneous wind speed, as measured by the Hydro-Tech, was lower than 0.2 m s^{-1} were rejected. In all of the analysis of the field data the anemometer calibrations used were those determined in our wind tunnel tests (section 3).

Out of all potential data for the comparison of the Hydro-Tech and the Rosemount anemometers 71% were available for the analysis. The recording system was needed for other purposes 2% of the time, 4% of the Rosemount data were excluded because of data transfer errors, and 23% of the time the Rosemount was unoperational because of jamming, probably due to a software problem. In the comparison period between the Hydro-Tech and Metek anemometers there were no data lost by the Hydro-Tech. However, a complete 10-min measurement from the Metek was recorded only in 49% of the measurements. Part of the data from the Metek was unavailable due to a problem in the commercial serial to parallel interface converter used between Metek and the computer, but mostly data was lost due to rejection based on the Metek's internal data quality indication.

The reason for the frequent low data quality as signaled by the Metek is not clear to us, but may have been related to icing of the sensor heads, which happened ocassionally, as seen in Fig. 7. Unfortunately, the lost Metek data included all cases where the Hydro-Tech showed wind speeds over 23 m s^{-1}. Since high wind speed were not measured by the Metek even at temperatures above 0°C another possible error source warrants attention. A directional sound signal is deflected by motion of air perpendicular to it, so that it may be that strong enough signals from the Metek transmitters never meet the receivers in very strong and turbulent winds.

b. Results of the field tests

The results of the field comparison of the Hydro-Tech WS-3 and the Rosemount solid state anemometers for the 10-min mean wind speed are shown in Fig. 8. The mean wind speed measured by the Rosemount sensor was typically 30% lower than that measured by the Hydro-Tech. The relative difference slightly increases with increasing wind speed. The linear correlation coefficient between the two mean wind speeds is 0.97.

The results of the field comparison of the Hydro-Tech and the Metek sonic anemometers for the 10-min mean

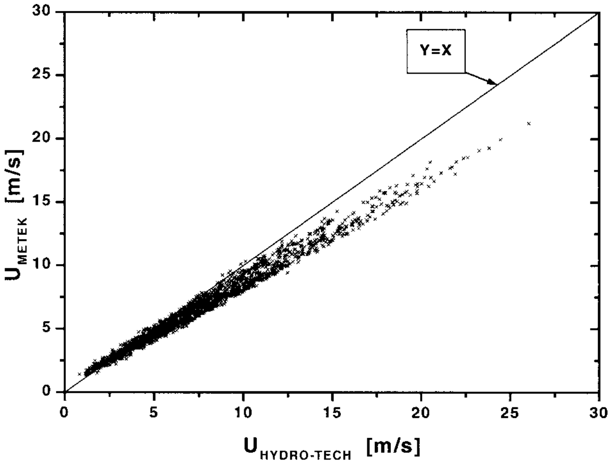

FIG. 9. Metek wind speed vs Hydro-Tech wind speed in the field measurements. Data are for 10-min mean values.

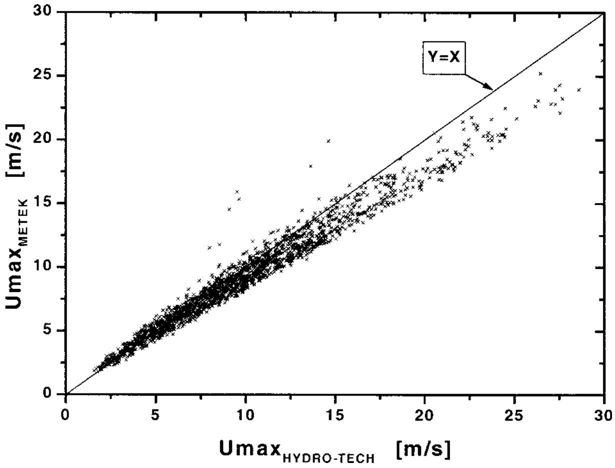

FIG. 11. Metek gust speed (1-s mean) vs Hydro-Tech gust speed (recorded at 4 Hz).

wind speed is shown in Fig. 9. The best-fit regression equation for these data is U(Metek) = 0.804U(Hydro-Tech) + 0.63 m s^{-1}, thus showing a maximum difference of 17% at the highest recorded wind speeds. When plotting the linear regression line through the origin, the systematic difference is such that the Metek shows 13.5% lower wind speeds than the Hydro-Tech. The linear correlation coefficient is 0.99 showing good statistical correspondence. The comparison of the Hydro-Tech and Rosemount sensors for the maximum (gusts) values is shown in Fig. 10. This shows results similar to the mean wind speed in Fig. 8.

Figure 11 shows the comparison of the Hydro-Tech and the Metek for the maximum values. When plotting the regression line through the origin Metek shows 8.5% lower gust speeds in the mean. However, it should be noted that Fig. 11 does not include data where the Metek quality check indicated poor data quality. The criterion of data selection of the Metek instrument was set to be such that points where less than 20% of the received data strings included a message of low quality were rejected. As mentioned above, these rejected data included all cases where the Hydro-Tech showed mean speeds over 23 m s^{-1}. Thus while the Metek seems to measure gust speeds well, its general ability to measure high wind speeds at all is uncertain based on these tests.

Figures 12 and 13 show the comparison of the two anemometers for the turbulence intensity calculated as

$$I = u'/U, \tag{3}$$

where u' is the standard deviation of the measured instantaneous wind speed values and U is the 10-min mean wind speed. The results for I show considerable scatter. This is probably largely due to the high inertia, that is, distance constant, of the Hydro-Tech anemometer.

The comparison of the Hydro-Tech and the Rosemount for the wind direction is shown in Fig. 14. The correlation is good, and there is only about 2° mean

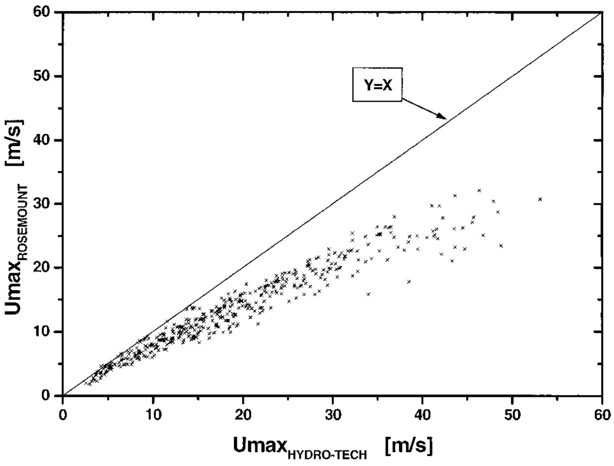

FIG. 10. Rosemount gust speed (1-s mean) vs Hydro-Tech gust speed (recorded at 4 Hz).

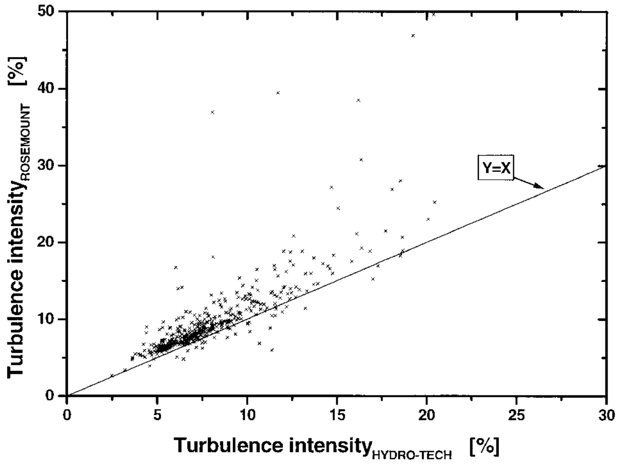

FIG. 12. Rosemount turbulence intensity vs Hydro-Tech turbulence intensity.

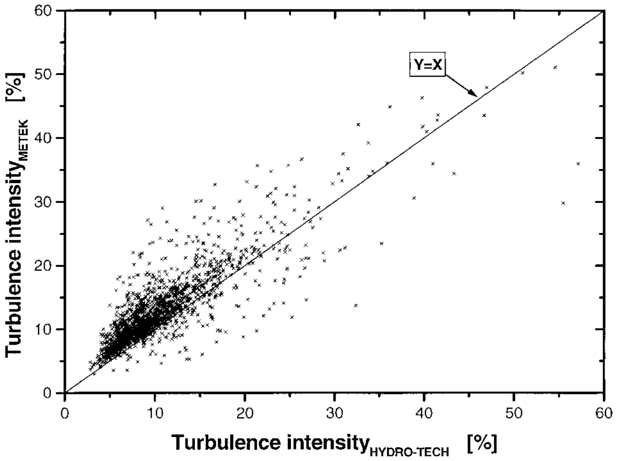

FIG. 13. Metek turbulence intensity vs Hydro-Tech turbulence intensity.

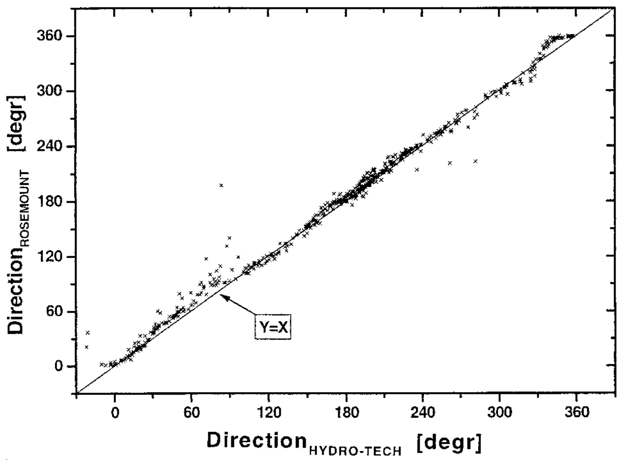

FIG. 14. Rosemount wind direction vs Hydro-Tech WD-3 wind direction.

difference. It may be pointed out that the wind vane installment alignment is accurate within about 3° in our measurement arrangement. The wind direction outputs of the Hydro-Tech and the Metek were in excellent agreement as well, as seen in Fig. 15.

5. Discussion

a. Anemometer calibration accuracy

Our wind tunnel calibrations of the Hydro-Tech WS-3 anemometer showed a significantly different linear calibration constant compared to those given by the manufacturer and by Lockhart (1987). This is most probably related to the use of too small wind tunnels in the previous calibrations. The anemometer calibration error source in the previous tests is the blockage effect when the cross section of the wind tunnel is small in relation to the objects in it. The blockage readily becomes unacceptable with a robust device such as the Hydro-Tech, which has an overall projection area of about 0.05 m^2. The ASTM anemometer calibration standard (ASTM 1990) limits the ratio of the cross-sectional areas of the anemometer and the wind tunnel test section to less than 5%. The calibrations by Lockhart (1987) were about at this limit whereas in our calibrations the blockage ratio was only 1.5%. Furthermore, the ASTM standard may give too much allowance in this matter, as the velocity increase in a wind tunnel due to blockage may be quite significant, of the order of 10%, even at blockage ratios of only 5% according to the experiments by Alexander and Holownia (1978). This velocity increase may be attempted to be corrected in the results, but the procedure is quite inaccurate and the uncertainty increases with higher blockage ratios (Farell et al. 1977).

That the manufacturers' calibration constants are in error seems to be a more general problem, however. Makkonen and Helle (1994) recalibrated nine different rotational anemometers in the VTT wind tunnel and found that the manufacturers' calibrations resulted in errors ranging from 0.1% to 22.7% at the wind speed of 5 m s^{-1} and from 0.7% to 10.5% at the wind speed of 20 m s^{-1} depending on the anemometer. While these errors may be partly related to the blockage effect in the manufacturers' calibrations, they are likely also due to the nonlinearity of the true calibration curves and deviations from the standard in manufacturers' calibration procedures.

The output of the Metek USA-1 anemometer precalibrated by the manufacturer also differed from the true wind tunnel speed. Our finding that the Metek velocity output depends on the wind direction—that is, orientation of the instrument in the wind tunnel—may not be as serious a problem in the field, however. This is because turbulence of the real wind would be likely to reduce such a direction dependence of the mean wind speed. Nevertheless, this problem warrants further studies. To this end, we postulated that the direction de-

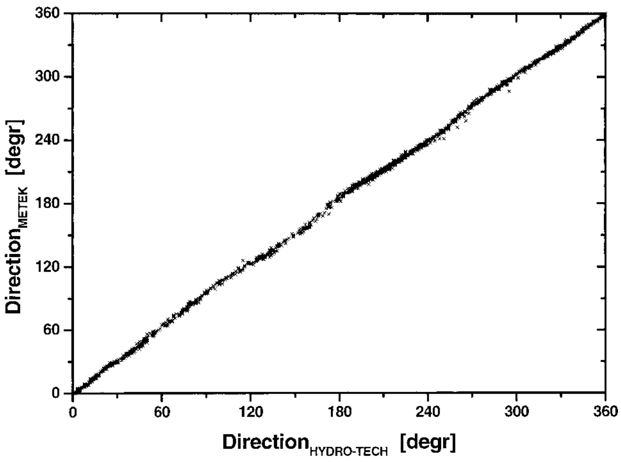

FIG. 15. Metek wind direction vs Hydro-Tech WD-3 wind direction.

pendence may be caused by echoes from the walls of the wind tunnel, and made special tests to reveal this effect by locating the device at different positions from the wind tunnel walls. These tests showed no significant effect of the anemometer location suggesting that the problem is a more fundamental one, and possibly involves other sonic anemometers as well (see also Sturgeon 1999).

b. Anemometer performance in the field

No specific problems showed up with the anemometers in the wind tunnel calibrations apart from the above-mentioned direction dependence of the Metek and the apparent inaccuracy of the manufacturers' calibrations. However, in the field tests several problems were revealed. Some of them, related to the data availability are mentioned in section 4a. Perhaps the most puzzling of our findings was the systematic discrepancy of the velocity outputs of the Hydro-Tech WS-3 and the Rosemount solid state anemometers (Figs. 8 and 10). Considering the good correspondence of the Hydro-Tech and the Metek (Figs. 9 and 11), as well as the previous successful field comparisons of the Hydro-Tech with other anemometers in nonicing conditions (Makkonen and Lehtonen 1994; Tammelin 1994), it is apparent that the Rosemount anemometer systematically underestimated the wind speeds by 30% in our field test.

The origin of this problem with the Rosemount anemometer, seen only in the field, but not in the wind tunnel, is unknown to us. We plotted the ratio of the wind speeds measured by the two sensors as a function of air temperature, air pressure, calculated air density, and wind direction. None of these showed any significant correlation. It is interesting to note here that a very similar discrepancy has been found by Ozawa et al. (1996) when comparing these two anemometers. Furthermore, another solid-state anemometer (Metrex) seems to have a very similar severe underprediction problem (Krishnasamy and Motycka 1991). These results suggest the possibility of some unknown fundamental problem in the solid-state anemometry. We therefore speculate on some other possible explanations for the underprediction of the Rosemount in relation to the Hydro-Tech in the following.

The response of the anemometers to turbulent wind may be different from that in the laminar flow of the wind tunnel. However, previous comparisons between the Hydro-Tech and conventional cup anemometers in nonicing field conditions (Makkonen and Lehtonen 1994; Tammelin 1994) gave no indication of such a problem with the Hydro-Tech. Therefore, if the difference is due to turbulence, it must be related to the way averaging is done by the Rosemount device. The Rosemount may also be sensitive to the low air temperatures at the test site. However, our tests with the sensor heating off and on do not indicate such a temperature dependence. Another possible problem is the sensitivity to barometric pressure. We were unable to investigate such an error source, but it is noteworthy that the mean difference in the air pressure at our test site and in the wind tunnel is about 10 kPa while the differential pressures measured by the Rosemount are of the order of 0.2 kPa even at rather high speeds of 20 m s^{-1}. Thus, the sensor resolution may become low compared to the changes in external pressures between locations at different altitudes. Yet another explanation is that the difference is related to the different off-axis response of the anemometers, that is, errors caused by a nonhorizontal mean wind vector. This problem is discussed in detail in section 5d below, where it is shown that the off-axis response of the Hydro-Tech cannot explain the observed 30% discrepancy. Finally, either of the anemometers may ice up in spite of the heating. However, such icing was not observed and our theoretical estimates based on the icing heat balance (Makkonen 1984) suggest that the heating power of the two anemometers was sufficient for anti-icing under all test conditions. Moreover, if icing was the cause of the problem, one would expect more points close to the one to one line in Fig. 8, since the data include nonicing conditions as well. Also, if either of the sensor heating systems ocassionally failed, there should be more zero readings than appear to be the case.

As to the Hydro-Tech and the Metek USA-1 sonic anemometers, a somewhat better agreement was found in the field comparison (Figs. 9 and 11). The good correlation of the outputs is encouraging regarding the reliability of both of the anemometers. The existing 13.5% mean difference in the 10-min mean values in our comparison remains to be explained, however. Possibilities for this include calibration problems of the Metek due to the direction dependence mentioned above, icing of the Metek even when it signals good data quality and dynamic effects, such as the dynamic overspeeding and the off-axis response of the Hydro-Tech.

Finally, Pedersen et al. (1991) have shown that some anemometers are surprisingly sensitive to the fine details of the base of the instrument and to the dimensions and orientation of the supporting boom. On this basis, the dependence of the Metek output on the orientation in the wind tunnel may be directly related to the aerodynamics around the instrument, and the field comparison may be hampered by the details of the anemometer installment. Furthermore, the findings of Pedersen et al. (1991) point out how important it is to also anti-ice the supporting structures, such as the anemometer boom, in order to prevent the changes in their dimensions due to accreted ice. To study the possibility that the heating cables on the booms affected our field results, we made additional wind tunnel calibrations both with and without the heating cables using the Metek anemometer. The result was that the effect of the cables on the output was below the resolution of the calibrations.

That the wind directions shown by the Rosemount Solid State and the Metek USA-1 are in excellent agreement with those shown by the Hydro-Tech WD-3 (Figs. 14 and 15) is encouraging regarding the measurements in general. This is because the calculation of the Rosemount and the Metek wind direction angles is based on the measurements of the wind velocity components, so that one would expect an error in one of these components or in the calculation software to be seen as an error also in the direction output. Since we did not find such direction errors, it appears that the observed severe underprediction of the wind speed by the Rosemount anemometer is related to similar systematic errors in all directions.

Some software problems were present during the field tests as discussed in section 4a. For Metek, the most significant problem was that especially high wind speed data were lost due to an internal quality check explained above. The reason for this is unknown to us, but it could be related to low sensitivity of the device at very high speeds, more severe icing at high speeds, or to vibrations of the instrument support and anemometer components in high and turbulent winds.

No icing of the Hydro-Tech or the Rosemount anemometers was observed in our tests in spite of frequent severe icing conditions. This indicates that the heating and its control functioned properly and that the heating power of these anemometers is sufficient for these kinds of conditions. The Metek anemometer's sensor heads iced up occasionally, as seen in Fig. 7. The heating was on in these cases, so that the power supply to Metek anemometer components should have been higher for proper operation in these extreme conditions. The sensitivity of the Metek output to ice on it remained somewhat unclear, because the device signaled poor data quality in these cases, but also in many other cases in which icing did not occur.

c. *Turbulence effects*

It is tempting to speculate that in the field the differences in the outputs of well-calibrated anemometers would be due to the turbulent nature of the natural wind. This aspect has been recently reviewed by Kristensen (1998). We investigated turbulence effects by plotting the relative differences of various outputs of the three anemometers as a function of the turbulent intensity [Eq. (3)] as determined from the measurements by the Metek anemometer. This analysis did not reveal any clear dependences on the output parameter differences on turbulence intensity, which suggests that the sources of the different outputs in the field are other than those related to the difference in the flow characteristics in the wind tunnel and in nature.

The reasonable greement of the outputs of the Hydro-Tech and Metek (Figs. 9 and 11) anemometers indicates that the dynamic overspeeding related to flow turbulence (Kristensen 1998) is not a very severe problem in measuring mean wind speeds and gust speeds by the Hydro-Tech WS-3 in spite of its very high distance constant.

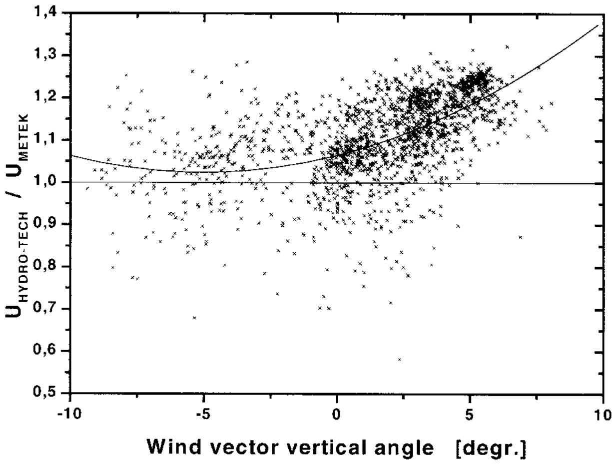

FIG. 16. Ratio of the Hydro-Tech and Metek mean wind speeds vs the wind vector vertical angle as measured by the Metek. The curve is a second-degree polynomial fit to the data.

d. *Off-axis response*

It is known from the wind tunnel experiments by Lockhart (1987) that when the Hydro-Tech WS-3 is tilted, that is, when the wind vector is nonhorizontal, large errors appear. These off-axis errors are according to Lockhart (1987) as high as 5% overspeeding at the wind vertical angle of 1° and 25% at 5°. This would mean that on hilltops, such as our test station, the off-axis response may cause significant overspeeding of the Hydro-Tech WS-3. Furthermore, the off-axis response of the Hydro-Tech is nonsymmetric in such a way that for negative angles (downwards flow) the error is much smaller. Therefore, theoretically, in very turbulent flow conditions off-axis errors may occur even if the mean vertical wind angle is 0°.

We studied the off-axis response of the Hydro-Tech WS-3 in the field by comparing its results with those of the Metek sonic anemometer. Because the Metek measures in three dimensions, it also measures the vertical wind component and the vertical wind angle. Thus we were able to plot the 10-min mean wind speed values from the two instruments versus the mean vertical wind angle. This is shown in Fig. 16. The results show that the deviation of the Hydro-Tech output from that of the Metek is indeed statistically related to the vertical wind angle, but the scatter is high.

However, the apparent off-axis effect in Fig. 16 is weaker than that expected for the Hydro-Tech based on the wind tunnel experiments by Lockhart (1987). One possible explanation for this is that the off-axis response is weaker in natural flow than in the laminar flow in the wind tunnel. As discussed above, the ratio of the mean wind speed shown by these anemometers does not seem to depend on the turbulence intensity, however. Thus, it is more likely that Lockhart's (1987) off-axis results were affected by wind tunnel blockage, which increases with increasing anemometer tilt angle.

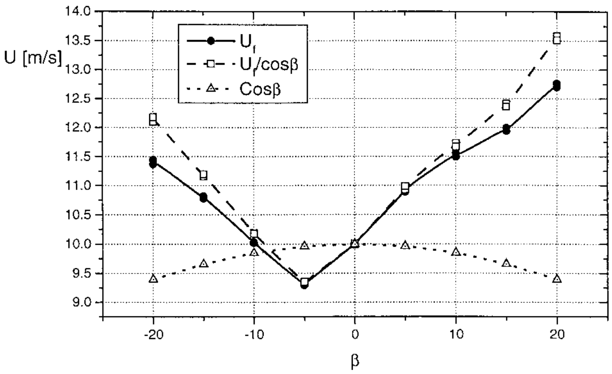

FIG. 17. Effect of the tilt angle β of the Hydro-Tech anemometer in the wind tunnel at the wind speed of 10 m s^{-1}. A positive tilt angle refers to an anemometer leaning back from the wind.

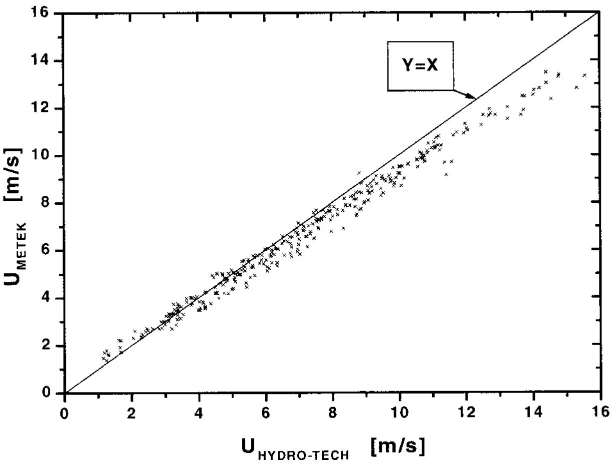

FIG. 18. Metek mean wind speed vs Hydro-Tech mean wind speed for data where the deviation of the wind vector vertical angle from the horizontal plane is less than 1°.

We confirmed this conclusion by performing a further test series on the off-axis response of the Hydro-Tech in our wind tunnel. The results of these are presented in Fig. 17 and show that the response is indeed much smaller than that determined by Lockhart (1987), and is in accordance with our results from the field in Fig. 16.

Nevertheless, at our site the mean vertical wind component together with the off-axis response of the Hydro-Tech WS-3 has been sufficient to affect the overall field comparisons. This is demonstrated in Fig. 18 where the comparison of Fig. 9 is shown for a selected dataset, which includes only data for which the vertical wind angle was less than 1°. For these data, presumably almost free from the off-axis response, the Metek gives 7.5% lower mean wind speeds than the Hydro-Tech, in contrast to the whole dataset for which the Metek showed 13.5% lower values. Thus an approximately 6% mean error in the Hydro-Tech output appears to be caused by the off-axis response in these data. This demonstrates that in all comparisons of this kind, and in measurements on hilltops using the anemometers of the type of the Hydro-Tech, attention must be paid to the vertical wind component and the possible off-axis error. This finding also means that a 3D anemometer, such as the Metek, is a particularly appealing option for locations, where a significant vertical wind vector is expected, say, due to the nature of the terrain.

6. Conclusions

Our wind tunnel calibrations demonstrate that the ice-free, as well as other, anemometers need to be calibrated in a wind tunnel big enough to avoid blockage errors and using standard calibration methods. Today's sophisticated software puts no limits on applying complex calibration equations, so that the nonlinearity of the calibration curve should be taken into account rather than using a linear calibration constant. As these procedures are not a present practice, many manufacturers' calibrations include significant errors particularly at low speeds.

The rotational Hydro-Tech WS-3 anemometer and the Metek USA-1 sonic anemometer, when carefully calibrated, show values that are in a reasonable, but far from a perfect, agreement in severe icing conditions. In our data the mean difference was 13.5%. About half of this difference was caused by the off-axis response of the Hydro-Tech and the other half probably by dynamic overspeeding of the rather robust Hydro-Tech and possible problems of the Metek anemometer. The off-axis response of the Hydro-Tech WS-3 in natural conditions is smaller than claimed earlier based on wind tunnel tests, but can still cause significant systematic overspeeding at hilltops. This and the high distance constant, resulting in turbulence intensity underprediction, may cause problems in purely meteorological research. Apart from that, the Hydro-Tech WS-3 is well applicable to the severe icing environment and, when correctly calibrated, is sufficiently accurate for, for example, structural wind load evaluations and wind energy potential estimates.

The pressure sensing solid state anemometers, such as the Rosemount 1774W tested in this work, seem to suffer from a significant underprediction of the wind speed in the field conditions. The reason for this may be related to high sensitivity of the device to changes in the atmospheric pressure.

The heated 3D sonic anemometers, such as the Metek USA-1 tested here, are promising ice-free anemometers especially in hilly areas, where the off-axis response of the other anemometers may cause inaccuracies. However, its sensor heating is insufficient in the most severe icing conditions. The Metek sensor also appeared to be unable to measure at all at wind speeds over 23 m s^{-1}. This may be related to icing, but also to the deviation of the acoustic signal with wind. If the latter, then this problem could involve other acoustic anemometers as well.

Installation of anemometers requires special attention in an icing environment. Dimensions of the anemometer booms and other supporting structures may increase significantly due to ice accreted on them, resulting in shadowing or tunneling effects. This may be avoided by additional anti-icing devices, such as heating cables attached to the supporting structures. Such a requirement, together with the necessary high heating power consumed by the feasible anemometers, unfortunately means that reliable wind measurements are presently impossible at sites with significant icing but without an ample energy supply.

Overall, there is still room for improvement in the technology of measuring wind speeds accurately in an icing environment. However, with some presently available heated rotational anemometers it is possible to collect reliable wind data even in the most severe icing environments, provided that due consideration is given to anemometer calibrations and to the error sources discussed in this paper.

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REFERENCES

Alexander, A. J., and B. P. Holownia, 1978: Wind tunnel tests of a savonius rotator. *J. Wind Eng. Indust. Aerodyn.,* **3,** 343–351.

Aspola, J., 1994: Heated anemometer WAA25. *Proc. Second Int. Experts Meeting on Wind Power in Icing Conditions,* Hetta, Finland, Finnish Meteorological Institute, 145–153.

ASTM, 1990: Standard and method for determining the performance of a cup anemometer or a propeller anemometer. American Society for Testing and Materials, Designation D 5096-90, 5 pp.

Bates, R. E., and J. W. Govoni, 1984: Meteorological Instrumentation for characterizing atmospheric icing. *Proc. Second Int. Workshop on Atmospheric Icing of Structures,* Trondheim, Norway, Norwegian Research Institute of Electricity Supply A/S, 23–28.

Busch, N. E., and L. Kristensen, 1976: Cup anemometer overspeeding. *J. Appl. Meteor.,* **15,** 1328–1332.

Farell, C., S. Carrasquel, O. Guven, and V. C. Patel, 1977: Effect of wind-tunnel walls on the flow past circular cylinders and cooling tower models. *J. Fluids Eng.,* **99,** 470–479.

Franklin, C. H., and J. B. Howe, 1991: Micro-processor controlled solid-state anemometer and ice-detector. *Proc. Third Int. Workshop on Atmospheric Icing of Structures,* Vancouver, BC, Canada, Canadian Climate Program, 259–260.

Kaganov, E. I., and A. M. Yaglom, 1976: Errors in wind speed measurements by rotation anemometers. *Bound.-Layer Meteor.,* **10,** 15–34.

Kenyon, P. R., and D. C. Blittersdorf, 1992: A heated anemometer for atmospheric icing environments. *Proc. Int. Experts Meeting on Wind Power in Icing Conditions,* Hetta, Finland, Finnish Meteorological Institute, 262–270.

Klinov, F. Ja., 1978: *Atmospheric Boundary-layer during Hazardous Weather Phenomena* (in Russian). Gidrometeoidzat, Leningrad, 255 pp.

Krishnasamy, S. G., and J. Motycka, 1991: Ice-free anemometers: Laboratory and field testing. *Proc. Third Int. Workshop on Atmospheric Icing of Structures,* Vancouver, BC, Canada, Canadian Climate Program, 311–317.

Kristensen, L., 1998: Cup anemometer behavior in turbulent environments. *J. Atmos. Oceanic Technol.,* **15,** 5–17.

Lockhart, T. J., 1987: Anemometer performance determined by ASTM methods. *J. Atmos. Oceanic Technol.,* **4,** 160–169.

Makkonen, L., 1984: Modeling of ice accretion on wires. *J. Climate Appl. Meteor.,* **23,** 929–939.

——, 1992: Analysis of rotating multicylinder data in measuring cloud-droplet size and liquid water content. *J. Atmos. Oceanic Technol.,* **9,** 258–263.

——, and L. Helle, 1994: Calibration of anemometers—An uncertainty in wind energy resource assessment. *Proc. Fifth European Wind Energy Association Conf.,* Thessaloniki, Greece, European Wind Energy Association, 273–278.

——, and P. Lehtonen, 1994: Comparison of wind speeds measured by Hydro-Tech WS-3 and Vaisala WAA12/Lambrecht anemometers. *Proc. Second Int. Experts Meeting on Wind Power in Icing Conditions,* Pyhatunturi, Finland, Finnish Meteorological Institute, 172–179.

Ozawa, A., J. Kagami, N. Sugawara, K. Hokari, M. Hirota, and S. Shimizu, 1996: Anemometer acquisition system with solar cells for transmission line maintainance in heavy icing area. *Proc. Seventh Int. Workshop on Atmospheric Icing of Structures,* Chicoutimi, QC, Canada, University of Quebec and Hydro Quebec, 396–400.

Pedersen, B. M., K. S. Hansen, S. Oye, M. Brinch, and O. Fabian, 1991: Some experimental investigations on the influence of the mounting arrangements on the accuracy of cup anemometer measurements. *Wind Energy: Technology and Implementation,* F. Van Hulle, P. Smuldens, and J. Dragt, Eds., Elsevier Science, 782–786.

Pinard, J. P., 1998: Ultrasonic instrument for remote monitoring under icing conditions. *Proc. Fourth Int. Meeting on Wind Energy Production in Cold Climates,* Hetta, Finland, Finnish Meteorological Institute, 253–262.

Pon, C., and M. Kastelein, 1997: Testing of Metrex ice free anemometer. Ontario Hydro Technologies Rep. for Canadian Electricity Association, CEA No. 017T799, 53 pp.

Siebert, H., and U. Teichmann, 2000: Behaviour of an ultrasonic anemometer under cloudy conditions. *Bound.-Layer Meteor.,* **94,** 165–169.

Strangeways, I., 1981: Instruments for mountainous areas. *Nord. Hydrol.,* **12,** 289–296.

——, and R. Hudson, 1991: The development of a de-icing weather station which uses no heat. *Proc. Third Int. Workshop on Atmospheric Icing of Structures,* Vancouver, BC, Canada, Canadian Climate Program, 293–299.

Sturgeon, M. C., 1999: A wind tunel test method for sonic anemometers. Preprints, *15th Int. Conf. on Interactive Information and Processing Systems,* Dallas, TX, Amer. Meteor. Soc., 205–208.

Tammelin, B., 1994: Icing of anemometer and its effect on estimation of wind energy potential. *Second Int. Experts Meeting on Wind Power in Icing Conditions,* Pyhatunturi, Finland, Finnish Meteorological Institute, 85–96.