ELSEVIER
Agricultural and Forest Meteorology 98–99 (1999) 341–348
AGRICULTURAL AND FOREST METEOROLOGY
www.elsevier.com/locate/agrformet

Reducing systematic errors in rainfall measurements using a new type of gauge

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Abstract

The systematic errors due to aerodynamic effects and wetting losses are known to bias point measurements of precipitation. In the NOPEX project a rain gauge with a new type of wind shield and a special weighing construction is used to minimise these errors. The wind shield consists of a flange surrounding the gauge at the level of the orifice. The idea was to screen the area above the orifice from the disturbance of the wind field by the gauge. At different locations the measured precipitation amounts were compared with the amounts caught by standard gauges. The analysis showed that the catch of the new gauge was higher than that of the standard gauges. A difference of about 3% was related to reduced wind-induced losses, while a difference of about 0.25 mm per event was explained as elimination of wetting loss. At one location the differences were related to wind speed and rainfall intensity to evaluate the effect of the wind shield. The relative differences were largest (20%) for events with low intensity and high wind speed.

Keywords: Rain gauge; Rainfall and wind speed; Rainfall intensity; Rainfall measurement errors; NOPEX

1. Introduction

The systematic errors due to aerodynamic effects and wetting losses are known to bias point measurements of rainfall (Sevruk, 1986, 1987; Førland et al., 1996). Wind-induced losses are caused by the distortion of the wind field above the orifice by the gauge itself (Sevruk et al., 1991; Nešpor and Sevruk, 1998). Sevruk (1986), estimates this systematic error to 2–10%. For individual events this error can be larger, Crockford and Richardson (1990), for instance, found an undercatch of up to 20% for some events at wind-exposed locations. Another large systematic error is the loss due to the wetting of inner parts of the collector and, for some types of gauges, in the container when it is emptied. Sevruk (1986) assessed a magnitude of 2–10% to this error. Sevruk (1974) and Günther and Richter (1986), for example, found wetting losses around 0.1 mm per event for the Hellmann gauge. Both studies demonstrate that the wetting loss is not a constant but varies for different events depending on the intensity and duration of the event as well as on the inclination of the falling raindrops. Furthermore, wetting losses may vary for different gauges and

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0168-1923/99/$ – see front matter
PII: S0168-1923(99)00107-0

with their age (Sevruk, 1974; Lapin and Šamaj, 1991). The wetting losses are higher for gauges like the SMHI (Swedish Meteorological and Hydrological Institute) standard gauge where the container has to be emptied to measure the rainfall amount. Other types of errors such as evaporation losses from the container and splashing of rainfall normally can be considered to be minor (Sevruk, 1986). However, for tipping-bucket gauges water remaining in one of the buckets may evaporate before the next event and, thus, evaporation losses become significant. In addition to systematic errors, random errors are larger for tipping-bucket gauges than for other types of gauges due to clogging, mechanical disturbances, etc. (Sevruk, 1996).

Many empirical and theoretical correction methods for rainfall measurements can be found in literature (Allerup and Madsen, 1980; Lapin and Šamaj, 1991; Sevruk and Nešpor, 1997; Allerup et al., 1997; Nešpor and Sevruk, 1998). For the Nordic countries Førland et al. (1996) presented methods for the operational correction of precipitation data. These methods are of high importance for the use of historical data and data from national networks where the type of gauge is not changed frequently to avoid inhomogeneous data series. However, gauge site exposure also may change over time and this has to be considered in the correction method to avoid inhomogeneities in the data series (Sevruk and Zahlavova, 1994). While the correction methods work well for longer time intervals correction of individual events is far from trivial and not only precipitation but more variables (e.g. wind speed, temperature, intensity) which may not be available at each gauge site are needed (Sevruk, 1987). Therefore, for research projects, where accurate measurements of individual events are of importance and homogeneity with historical data is of less concern, the use of gauges, which reduce the errors, should be preferred.

To avoid systematic errors in the measurement of rainfall a new type of rain gauge manufactured by InSitu (Ockelbo, Sweden) was used within the NOPEX project (Halldin et al., 1999). It was claimed that wind-induced losses were minimised by a new type of wind shield (Lindroth, 1991) and wetting losses became virtually zero due to a special weighing construction. In this study these expectations were tested by comparing the new gauge with standard gauges.

2. Material and methods

The new gauge (InSitu, IS200W) measures the total weight of the collector with a load-cell connected to a datalogger. Precipitation is calculated from the increase in measured weight. Since the entire collecting device is weighed (Fig. 1), rain is measured as soon as it reaches the collector surface, and there should be no wetting losses. The container has a capacity corresponding to 200 mm of rain before it is emptied automatically by siphoning. The duration of emptying the container is about 5 min. To avoid errors due siphoning during rainfall events, the containers usually were emptied manually. The few events during which emptying occurred were excluded from the analysis presented in this paper. The gauge is equipped with a flange surrounding the gauge at the level of the orifice at 1.40 m above the ground (Fig. 1). A special cloth on the upper surface of the flange prevents splash-in of raindrops. Shower-bath tests confirmed that the special cloth was capable of quickly draining large amounts of water and to hinder splash-in. The idea of the new wind shield is to screen the area above the orifice from the wind field deformation

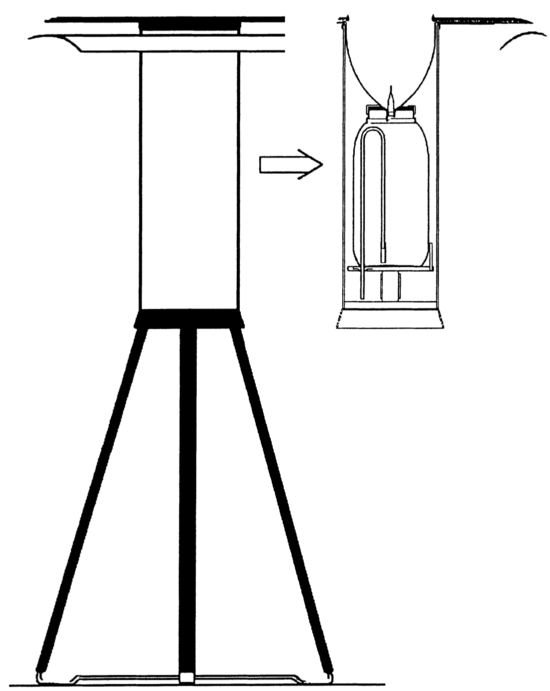

Fig. 1. The new rain gauge.

Table 1
Locations and type of standard gauge used for comparison

Station	Exposure to wind	Standard gauge	Measurement period [a]	Number of events used in the analysis
Dansarhällarna	On a clearing, sheltered by forest (height ~20 m) 50–100 m from the gauges	Tipping bucket	1995	83
Marsta	Very exposed on plain, agricultural land, forest in N, 500 m away	Hellmann	1994–1996	225
Köping	Sheltered by 7 m high forest, 20 m from the gauges towards W, 20 m high forest, 100 m away towards E, open in direction N–S	Tipping bucket	1992–1994	198
Tisby	Exposed on plain, agricultural land, but sheltered by buildings and trees about 50 m from the gauges	SMHI gauge	1995	43[b]
Ultuna	Sheltered by forest (height max. 7 m) 30 m from the gauges	SMHI gauge	1992	28[b]
Uppsala-Näs	Exposed but somewhat sheltered by a forest surrounding the station in a semicircle ~200 m from the gauges	Hellmann	1994–1996	190
		Tipping bucket	1994–1996	167

[a] Only summer periods (April/May until October/November).
[b] Days with rain.

caused by the gauge. Tests made with a prototype of the new wind shield in a wind tunnel showed that the wind field above the orifice is much less disturbed (Lindroth, 1991). The prototype used in the study of Lindroth (1991) was extremely thin at its edge. When the new wind shield went into production it turned out that such a thin edge could not be achieved (Norén, 1997, pers. commun.). Therefore, a circular vane has been added to the wind shield (Fig. 1). The intention is to deflect the wind field somewhat downwards preventing the generation of upward-moving air in eddies at the edge of the wind shield. Smoke-trail experiments in a wind tunnel indicate that the wind field is as undisturbed above the modified wind shield as above the prototype (Norén, 1997, pers. commun.).

Rainfall amounts, with a temporal resolution of 10 min, were computed using the algorithm described by Seibert and Morén (1995). This algorithm includes a correction for the temperature dependence of the load-cell and noise caused mainly by wind-induced vibrations of the measuring device. Each gauge was calibrated in situ by placing a known weight onto the collecting device at different starting values for the accumulated weight. This was repeated at different times during the study period, however, the calibration factor was found to be almost constant over time.

The amount of rain measured with the new gauge was compared to the measurements of standard gauges at six stations (Table 1). The standard gauges were tipping-bucket gauges (manufactured by Ota Keiki Seisakusho, Japan) with a resolution of 0.5 mm, Hellmann gauges (manufactured by Lambrecht, Göttingen, Germany) and the standard gauge of the SMHI (Table 2, Fig. 2). The last one consists of

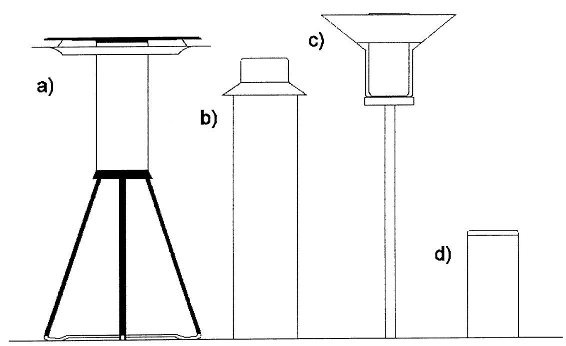

Fig. 2. Rain gauges used in this study: the new gauge (a), Hellmann gauge (b), SMHI-gauge (c), and tipping-bucket gauge (d).

Table 2
Types of gauges used in this study

Type of gauge	Height of orifice (m above surface)	Orifice area (cm^2)
New gauge	1.4	250
Hellmann gauge	1.3	200
SMHI gauge	1.5	200
Tipping-bucket gauge	0.5	314

an aluminium cylinder closed at one end, equipped with a removable funnel fitted inside the cylinder to reduce evaporation of the collected water and a modified Nipher wind shield. Both the Hellmann gauge and the tipping-bucket gauge were unshielded. The distance between the new gauge and the corresponding standard gauge was at most 10 m. The vegetation on the ground surface around the gauges was short grass except for the station Dansarhällarna which was located on a clearing with vegetation of varying height up to about one meter.

Rainfall amounts were compared for individual rainfall events. An event was defined to be ended if there was at least one hour without any rainfall recorded by the new gauge. For those stations where the new gauge was compared with the SMHI standard gauge daily sums were used in the analysis. For four events the catch of the new gauge was much higher than that of the standard gauge, these measurements were assumed to be erroneous and were excluded from the analysis. Furthermore, in the comparisons with tipping-bucket gauges all events with less than 0.25 mm were excluded to avoid a bias caused by the lower resolution of the tipping-bucket gauge. The catches of the new gauge during distinct events, P_{new}, were plotted against the values from the standard gauge, $P_{standard}$, for all the stations. The coefficients of the regression line, m and c, (Eq. (1)) and their confidence intervals (Haan, 1977) were calculated.

$$P_{standard} = c + m \cdot P_{new} \tag{1}$$

Since the new gauge is aimed to reduce two errors it was necessary to distinguish between the effects of wind shield and/or weighing construction. The deviation of the slope of the regression line from unity was interpreted as an effect of the wind shield and the offset was assumed to reflect the eliminated wetting loss. The effect of the wind shield does not only depend on wind speed but also on raindrop size (Allerup and Madsen, 1980; Nešpor and Sevruk, 1998). Rainfall intensity may be used as surrogate for the drop size distribution. Therefore, the events at each station were classified depending on whether the intensity was below or above 1 mm h^{-1} and the coefficients of the regression line were computed for both groups of events separately.

At Marsta the effect of the new wind shield was related to wind speed. Wind speed was measured at a height of 2 m above ground surface. During 1996 data from 2 m was not available. For this period velocities at 2 m were estimated from measurements at a height of 10 m using the logarithmic wind law. For each rain event mean velocities were computed. According to wind speed and rainfall intensity the events were divided into approximately equally large groups. For each group the relative difference was computed. In order to evaluate the effect of the new wind shield alone, the values from the Hellmann gauge were roughly corrected for wetting losses by adding 0.1 mm for each event. Additionally, the dependence of the relative differences between the catch of the Hellmann gauge (H, mm) and the new gauge (N, mm) on wind speed (V, m s^{-1}) and rainfall intensity (I, mm h^{-1}) was examined using multiple linear regression analysis with logarithmic values for the intensity (Eq. (2)).

$$\frac{H + 0.1 - N}{N} = b_0 + b_1 V + b_2 \log(I) \tag{2}$$

b_0, b_1 and b_2 : Regression coefficients

For small events small inaccuracies have great influence on the relative difference. Therefore, only events with more than 1 mm rainfall were used in this analysis.

3. Results

The new gauge caught significantly more rain than the standard gauges. The deviation of the slope of the regression line from unity interpreted as an effect of the wind shield was below unity for all stations (significant ($\alpha = 0.025$) for all except Dansarhällarna, Ultuna and Tisby) (Fig. 3 and Table 3). The slope of the regression line was smaller for events with low intensity than for events with high intensity at all locations. The offset of the regression line, assumed to reflect the eliminated wetting loss, was significantly ($\alpha = 0.025$) below zero for all the stations. It was most negative for the stations where the new gauge was compared with tipping-bucket gauges.

At Marsta, the effect of the wind shield was greatest for events with high wind speed and low intensity (20%) (Table 4). The correlation between wind speed and difference in catch was not as clear as the grouped presentation suggests. Looking on single events the tendency can be seen, but the points scatter very much (Fig. 4). The multiple coefficient of determination, R^2,

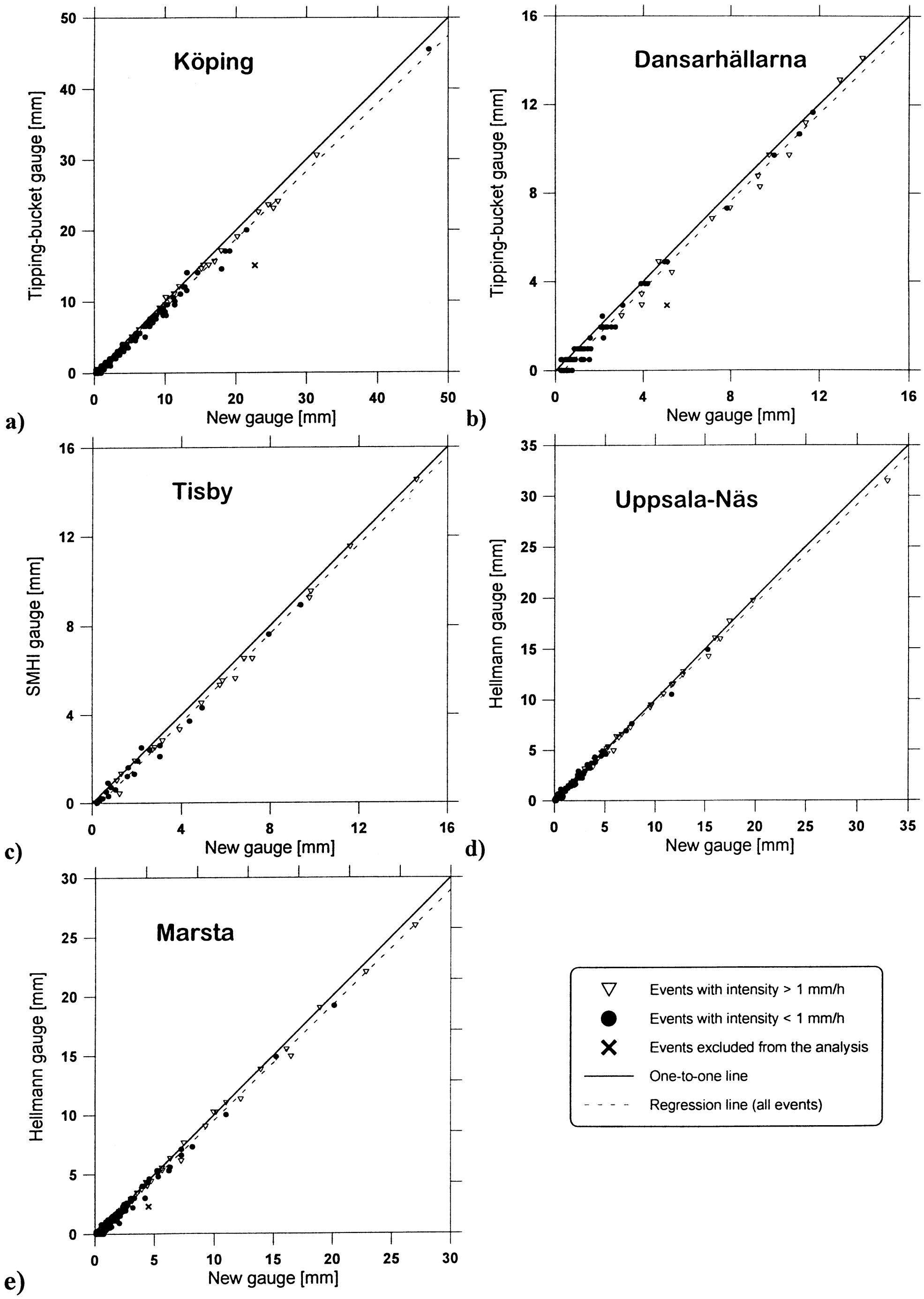

Fig. 3. (a–e) Comparison between the new gauge and different standard gauges using the sums for rainfall events (solid: one-to-one line, dashed: regression line).

Table 3
Coefficients of regression lines between the new gauge and the standard gauge at the different locations computed from events with intensities of less/more than 1 mm/h

Station	Standard gauge	Slope of regression line, m (–)			Offset of regression line, c (mm)		
		All Events	Events with intensities		All Events	Events with intensities	
			<1 mm/h	>1 mm/h		<1 mm/h^{-1}	>1 mm/h^{-1}
Dansarhällarna	Tipping-bucket	0.995	0.998	1.026	−0.33	−0.31	−0.63
Köping	Tipping-bucket	0.958	0.944	0.960	−0.45	−0.44	−0.29
Marsta	Hellmann	0.970	0.952	0.975	−0.17	−0.16	−0.16
Tisby	SMHI	0.984	0.955	0.997	−0.27	−0.21	−0.34
Ultuna	SMHI	0.998	0.965	1.010	−0.41	−0.24	−0.60
Uppsala-Näs	Hellmann	0.972	0.961	0.972	−0.04	−0.04	−0.04
Uppsala-Näs	Tipping-bucket	0.882	0.838	0.913	−0.38	−0.27	−0.67

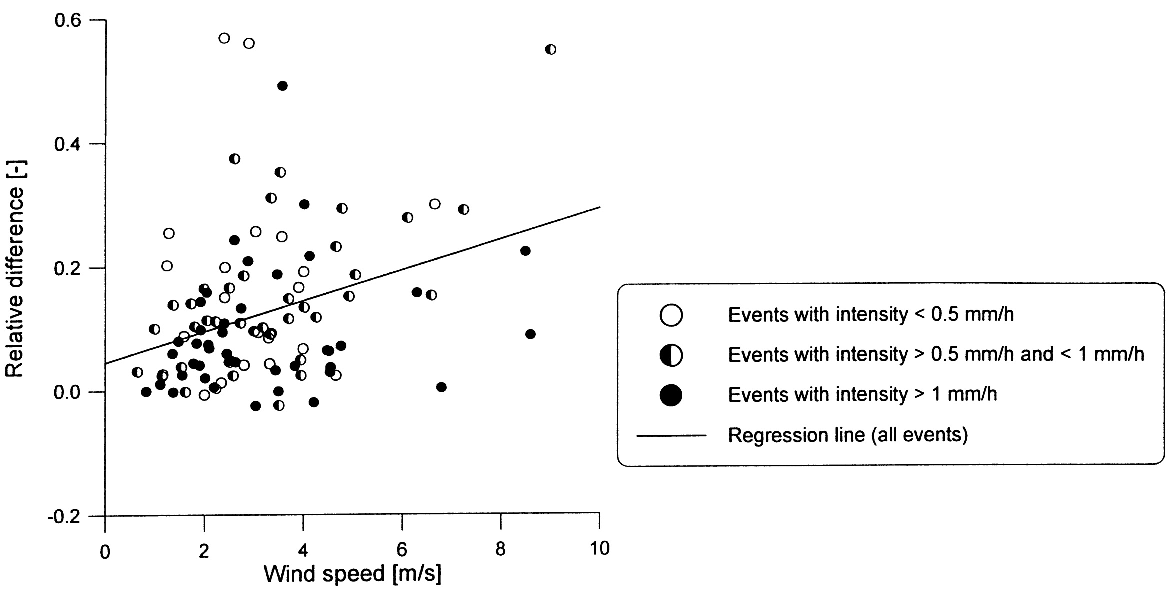

Fig. 4. Correlation between wind-speed and relative difference between the new gauge and the Hellmann gauge (corrected for wetting loss) at Marsta. Only events with more than 1 mm rainfall are shown in the figure.

Table 4
Mean differences between the new gauge and the Hellmann-gauge at Marsta, the events were grouped according to wind speed (m/s) and rainfall intensity (mm/h).

Wind velocity (m/s)	Mean difference (mm)			Mean rainfall during one event (mm)			Relative mean difference (–)			Relative mean difference [–] (corrected for wetting losses)		
	>0.5 mm/h	<0.5 mm/h	All	>0.5 mm/h	<0.5 mm/h	All	>0.5 mm/h	<0.5 mm/h	All	>0.5 mm/h	<0.5 mm/h	All
>2.9 m/s	0.42	0.24	0.32	4.38	0.67	2.48	0.10	0.35	0.13	0.07	0.20	0.09
1.8–2.9 m/s	0.34	0.18	0.26	3.95	0.65	2.30	0.09	0.28	0.11	0.06	0.13	0.07
<1.8 m/s	0.21	0.14	0.16	4.84	0.70	1.96	0.04	0.20	0.08	0.02	0.06	0.03

Table 5
Regression summary for Eq. (2). $R^2 = 0.13$, significance, p, probability of the hypothesis that a parameter equals zero (t-test), wind speed at 2 m in m/s and intensity in mm/h

	Parameter estimate	Standard error	Significance, p
Intercept, b_0	0.002	0.024	0.9222
Wind speed, b_1	0.024	0.007	0.0004
Log(intensity), b_2	−0.036	0.016	0.0293

also was low (0.13). However, both wind speed and intensity explained a significant ($\alpha = 0.03$) amount of the variation of the relative differences (Table 5).

4. Discussion and conclusions

The results showed that using the new type of gauge reduced both wind-induced and wetting losses. Compared to standard gauges the differences were of the same order as those reported in literature, where standard gauges were compared to reference gauges such as the DFIR (double fence intercomparison reference, e.g. Yang et al., 1995) or gauges with the orifice at ground level (e.g. Allerup and Madsen, 1980). Therefore, it can be concluded that the new gauge may be comparable with these reference gauges.

Sevruk (1986), quantified the systematic error due to wind-induced losses with 2–10 %. For the more exposed stations the relative increase of measured precipitation assigned to the reduction of wind-induced losses, i.e., the deviation of the slope of the regression line from unity, was of this order. Furthermore, in agreement with other studies (e.g. Allerup and Madsen, 1980; Nešpor and Sevruk, 1998) the deviation was larger for events with low intensities. Wetting losses around 0.1 mm per event were found by Sevruk (1974) and Günther and Richter (1986) for the Hellmann gauge. This agreed roughly with the offset of the regression line for the gauges at Marsta and Uppsala-Näs. Different versions of the Hellmann gauge used at Marsta and Uppsala-Näs may explain the difference between the offset values. Lapin and Šamaj (1991), reported variations of similar magnitude (0.06–0.3 mm per event) between gauges of the same type but in different versions and with varying age. For the tipping-bucket gauges the offset was more negative as a result of the bucket-construction, i.e., additional losses due to evaporation of water remaining in one of the buckets.

The tipping-bucket gauges were installed with a considerable lower orifice height. Sandsborg (1972) found that a gauge at 0.5 m height measures about 2% more rainfall than one at 1.5 m. Therefore, the effect of the new wind shield would have become more visible if the tipping-bucket gauges had been installed on the same height as the new gauge.

Explanations for the weak correlation between wind speed and difference at Marsta may be that the rainfall intensity varied for different events and that the mean wind speed was not always representative for the event. Furthermore, depending on type of rainfall, for events of similar intensity, the raindrop size distribution may be different and it is the later that is of importance (Sevruk and Nešpor, 1997).

For some large rain events there was almost no differences between the new and the standard gauges. This can be explained by the smaller effect of the new wind shield for events with high intensities. An additional explanation is the shape of the sharply tooled knife edge of the rim around the orifice, which is symmetric for the new gauge. For the standard gauges, on the other hand, it is asymmetric being vertical on its inside (Sevruk and Nešpor, 1994). For a raindrop falling on the edge this asymmetry may cause some momentum towards the orifice and a larger part of the drop may enter the gauge. Compared to the symmetric edge, events with large raindrops may be overestimated by about two percent (Norén, 1997, pers. commun.).

The wind shield reduced wind-induced losses of rainfall. However, the wind-induced error is much larger (10–50%) for snowfall (Sevruk, 1986; Günther and Graf, 1991; Yang et al., 1995; Førland et al., 1996) and the new gauge is not capable of measuring snowfall because (i) snow accumulates on the wind shield and thereby disturbs the measurements, and (ii) because the collector is built from plastic and, thus, cannot be heated to melt the snow.

Acknowledgements

We thank Hans Bergström and Leif Hirsemann, Department of Meteorology, Uppsala University, for providing data of wind velocity and rainfall measured at Marsta, Jan Erik Sivander for collecting data from the SMHI gauge at Tisby and Bengt Norén for discussions about the new gauge and technical support. The constructive criticism of the anonymous reviewers helped to improve the paper.

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