Precipitation amount and intensity measurements using a windscreen

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1. Introduction

Measurements of precipitation amounts with precipitation gauges are affected by various error sources. An overview of the errors is given in WMO (1994). One of the errors is the so-called wind effect that causes loss of precipitation due to wind field deformations near the gauge rim. The precipitation amount measurements are performed automatically by KNMI using an electronic precipitation gauge in a so-called English setup[*]. This setup is used to create a horizontal airflow above the orifice of the precipitation gauge in order to reduce the errors induced by wind field deformations. The setup is rather costly to build and requires additional maintenance. At some locations in the Netherlands the setup is particularly impractical as a result of high ground water level and/or poor drainage. In addition, the setup with the precipitation gauge orifice at the level of the measurement field is sensitive to debris, since leafs, grass and sand are easily blown into the precipitation gauge and cause instrument failures. Therefore, KNMI performed tests with the precipitation gauge simply placed on the measurement field. In such a setup the precipitation amount measurements are affected by errors induced by a deformation of the wind field by the precipitation gauge itself. The wind field deformation will blow part of the precipitation that would otherwise fall into the gauge over the rim and will thus cause a reduction of the measured amount of precipitation (see e.g. Sevruk and Nešpor, 1998 and Nešpor and Sevruk, 1999).

In 1998 a test was performed by KNMI with an unshielded precipitation gauge placed on the measurement field. The results showed (cf. Kuik, 2001) yearly precipitation amounts[#] of 840mm for De Bilt operational station and 842mm for De Bilt Test (both using the precipitation gauge in a English setup), whereas the precipitation gauge on the field gave 802mm. This difference of −40mm or about −5% is caused by the wind effect as can be seen from Figure 1, which shows the average differences in measured precipitation amount as a function of measured wind speed.

In this study the results of a test are described where a precipitation gauge on the measurement field is placed within a windscreen. A comparison is made of the precipitation amount measurements using about 2 years of data obtained with a KNMI precipitation gauge in an English setup and one sensor placed on the measurement field in a windscreen. The various error sources that contribute to the accuracy op the precipitation amount measurements in the field as wetting, evaporation, splashing in and out and the wind effect as well as differences caused by siting and exposure and due to spatial differences are not known individually. In this paper the wind effect is singled out by using closely collocated identical precipitation gauges in order to get the same differences for the other error sources. Specifically, a second precipitation gauge in an English setup is used to estimate the errors that can be expected between 2 nearby precipitation gauges in an English setup. These errors may result from instrumental errors as well as local differences.

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[*] The concept and terminology English setup are unknown in the United Kingdom. Therefore, it is better to speak of the KNMI setup.

[#] This is not the yearly sum since only those situations were considered where data for all 3 sensors that were used in the comparison were available.

The main question addressed in this study is:

(i) How large is the wind effect in case the KNMI precipitation gauge is placed on the measurement field in a windscreen.

In addition, the following 2 questions will be addressed:

(ii) How large is the reduction of the wind effect when using a windscreen;

(iii) Does the precipitation gauge on the measurement field give different results for precipitation detection and hence precipitation duration.

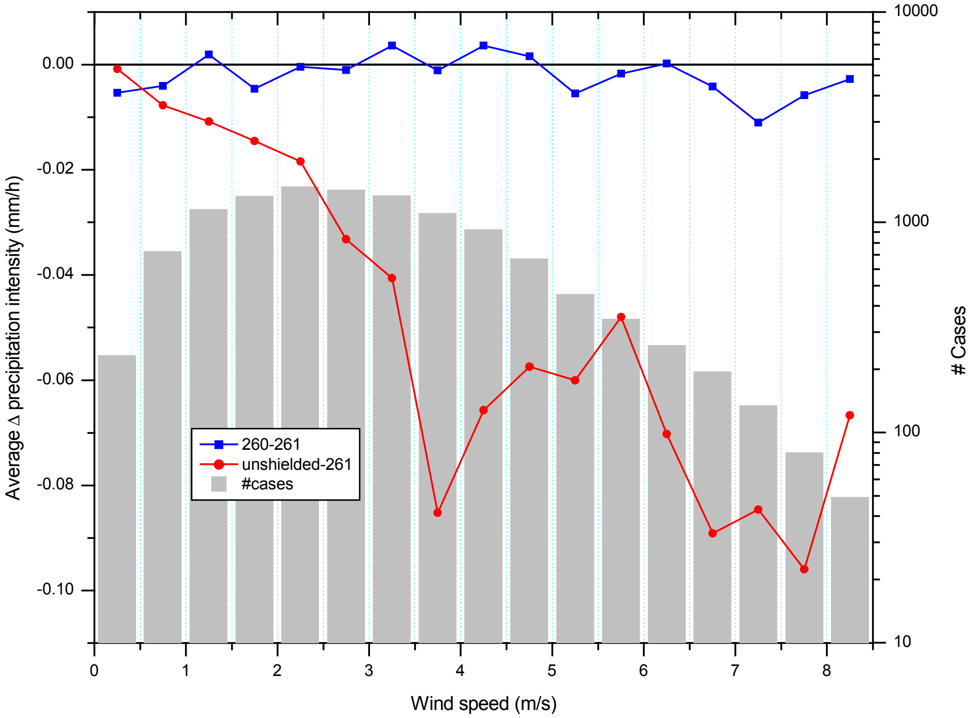

Figure 1: The averaged differences of the precipitation intensity per 10-minute interval reported in wind speed bins of 0.5m/s. The squares show the differences between the 2 precipitation gauges in the English setup, the circles show the differences between a precipitation gauge in the English setup and on the measurement field. Adapted from Kuik, 2001. The number of cases per wind speed bin is also given.

2. Precipitation gauge and measurement setup

2.1. KNMI electronic precipitation gauge

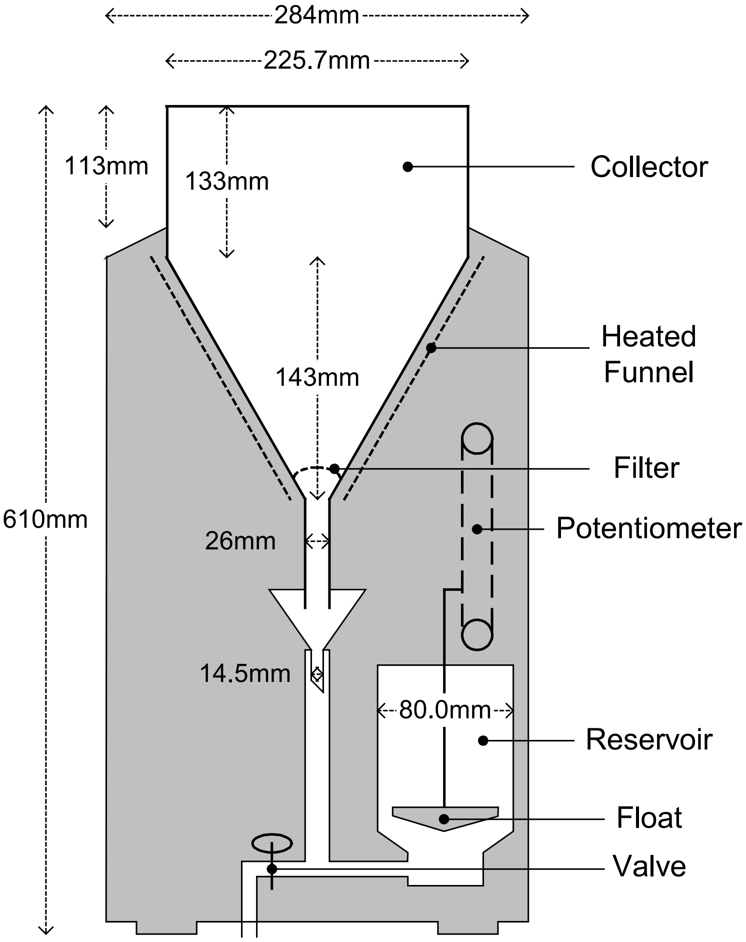

Figure 2: Schematic drawing of the KNMI electronic precipitation gauge showing the collector, heated funnel, filter, reservoir, valve, float and the potentiometer. The dimensions of the precipitation gauge and its collector and funnel are also given.

KNMI uses an electronic precipitation gauge developed indoors of the so-called float type. It measures the amount of precipitation from the height of a float in a reservoir (see Figure 2). Details of the construction of the precipitation gauge are given by KNMI (1991). The precipitation gauge has a collector with an area of 400cm^2 and is constructed according to WMO guidelines in order to minimize error sources (cf. WMO, 1994 and 1996). The collector has a sharp rim to avoid accumulation of wet snow about the rim. The rim has a thickness of 7mm and falls of outwardly with a slope of 35° with the vertical. The collector falls of vertically in- as well as outside and is sufficiently high and the lower part of the collector is sufficiently steep to prevent splashing in and out. The funnel is heated in order to melt any solid precipitation falling on it, but not too much because that causes evaporation. The precipitation is collected in a reservoir with a narrow entrance to minimize loss by evaporation. Also, the material of the collector and reservoir is selected to overcome wetting as much as possible. A float connected to a potentiometer measures the height of the water level. The change in the height is measured every 12 seconds with a resolution of 0.001mm and from this the precipitation intensity is calculated. The precipitation intensity is reported in steps of 0.006mm/h. The reservoir has a capacity of 11cm and is emptied when it is nearly full. Emptying is performed automatically and takes about 15 seconds during which the last measurement is persisted. After emptying about 1cm of water is left in the reservoir in order to avoid the hysteresis of 0.06mm of the float. The sensor checks for leakage of the reservoir, which can be caused by debris that remains in the shutter after emptying the reservoir. Furthermore, evaporation and temperature effects can cause negative changes to the water level in the reservoir. These negative readings are detected and the reduced level serves as the reference for reporting future precipitation amounts. Precipitation losses less than 0.006mm/h are not detected and therefore cannot be compensated by the precipitation gauge.

Table 1: Overview of KNMI precipitation gauges used during the windscreen test in De Bilt.

Location 260		
Sensor ID	*Date Replacement*	*Comments*
42	19 Dec 2000	-
22	25 Jun 2001	Valve not closed due to contamination.
10	18 Aug 2002	-
Location 261		
Sensor ID	*Date Replacement*	*Comments*
34	16 Sep 2000	-
27	22 Oct 2001	-
06	17 Dec 2002	-
Location Screen		
Sensor ID	*Date Replacement*	*Comments*
39	04 Dec 2000	-
02	22 Jan 2002	-
27	16 May 2002	End of test

The area of the orifice of the precipitation gauge is 400±0.5cm^2 and that of the reservoir is 50.2±0.1cm^2. Thus the accuracy of the precipitation measurements is in principle about 0.2%. The calibration of the precipitation gauge is done at the calibration facilities at KNMI. During that process the readout of the potentiometer is readjusted at the lower and upper limit of the float. The calibration is verified every 50cm^3 for a reservoir content between 0 and 400cm^3. The reference used in the calibration process is a calibrated digital scale with an accuracy of 0.1g, with which the amount of water siphoned into the gauge is determined. The absolute accuracy of the calibration is 2% over the full range of the float, but experience shows that the accuracy is within 1% (KNMI, 1997). After the calibration the precipitation gauge is ready to be used in the field for a period of maximally 14 months, or shorter in case of any problems. After replacement of a precipitation gauge, the sensor is verified before maintenance and recalibration.

Generally, the calibration of the gauge is still within 2% and if not, an error report is send to the climatological department.

Table 1 gives an overview of the precipitation gauges used during the windscreen test in De Bilt between September 1999 and May 2002. Only one sensor was replaced before the end of the14-month calibration interval due to a leaking valve as a result of contamination. All the other sensors did not report any problems and the verification after replacement showed that the sensors were within 2% of the original calibration.

2.2. KNMI-English precipitation gauge setup

Sevruk and Zahlavova (1994) and WMO (1996) give some rules on the siting and exposure of precipitation measurements. There should not be any objects closer to the gauge than twice their height above the gauge orifice. Sites for measuring solid precipitation should be sheltered from the wind as much as possible. The measurement of precipitation is very sensitive to exposure, and in particular to the wind, which can introduce typical errors of 2 to 10% for precipitation and 10 to 20% for snow. The effects of the wind, and of the site on the wind can be reduced by using a gauge at ground level in a pit or by making the airflow horizontal above the gauge orifice. The reference setup for a precipitation gauge of WMO uses a precipitation gauge in a pit (WMO, 1984). The most effective solution for reducing the wind effect for an elevated precipitation gauge is dense and homogeneous vegetation kept at the same level as the gauge orifice, or else screens or structures simulating this effect.

KNMI uses the so-called English setup to measure the precipitation amount (see Figure 3). In this setup the precipitation gauge is installed in a pit surrounded by a circular wall with a diameter of 3m and a height of 40cm. The gauge is placed on a small concrete box with a drainage tube. The pit is filled with gravel in order to avoid vegetation and splashing in of precipitation. The earth around the outer rim gently slopes upward to the brick wall in order to create a horizontal airflow above the orifice of the precipitation gauge in order to reduce the errors induced by wind field deformations due to the presence of the sensor itself. The slope and surroundings are covered with grass. No information is available on the performance of this English setup versus the WMO reference pit in relation to the wind effect. In this paper the English setup is assumed to have no wind-induced loss.

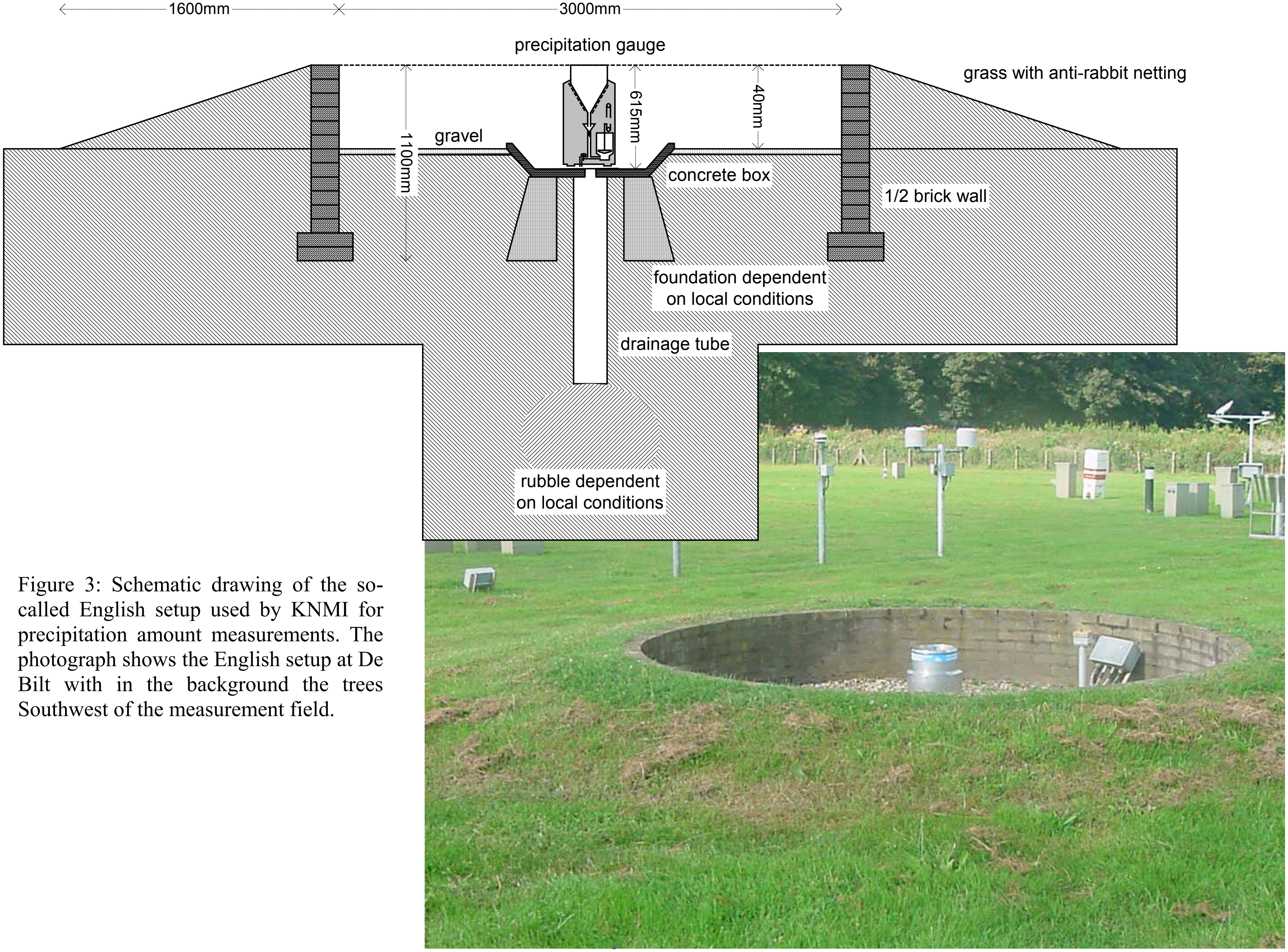

Figure 3: Schematic drawing of the so-called English setup used by KNMI for precipitation amount measurements. The photograph shows the English setup at De Bilt with in the background the trees Southwest of the measurement field.

Figure 4: Picture of the precipitation amount measurement setup on the measurement field with a KNMI precipitation gauge within an Ott windscreen. In the background the main building of KNMI located to the North-Northeast of the measurement field.

2.3. Windscreen setup

The KNMI setup is rather costly to build and sometimes construction permits are needed. At some locations in the Netherlands the setup is particularly impractical as a result of high ground water level and/or poor drainage. In addition, the setup with the precipitation gauge orifice at the level of the measurement field is sensitive to instrument failures caused by debris, like leafs, grass and sand, that is blown into the precipitation gauge. Hence the setup requires additional maintenance. Therefore, tests have been performed using a gauge placed on the measurement field and shielded by a windscreen. Figure 4 shows a photograph of the setup with the windscreen that has a height and a diameter of 1m. The Tretyakov type windscreen (cf. e.g. Dover and Winans, 2002) is manufactured by Ott Hydrometrie (2002) and consists of a circular arrangement of 16 stainless steel flaps. The KNMI precipitation gauge is placed in the center of the screen on an elevated platform such that the rim at the gauge is at the same level as the windscreen. Both the screen and the gauge orifice are aligned horizontally.

2.4. Measurement site

The test with the KNMI precipitation gauge in the English setup and on the measurement field in a windscreen has been performed at De Bilt between September 1999 and May 2002. De Bilt is located near the city of Utrecht at 52.1ºN and 5.18ºE in the middle of the Netherlands at 2msl. For that purpose precipitation data from the operational setup of De Bilt (WMO number 06260, denoted in this paper by “260”), De Bilt Test (“261”), both using the so-called English setup, and data from a precipitation gauge on the field in a windscreen (denoted “screen”) are compared. The site of the comparison was the measurement field about 150m South-Southwest of the main building of KNMI at De Bilt. The precipitation gauge of 260 and 261 are about 30 meter apart with 261 to the East-Southeast of 260. The precipitation gauge in the windscreen is located roughly halfway between 260 and 261, but 20 meter towards the North-Northeast. Apart from the precipitation amount data also temperature, humidity and wind speed and direction measurements of De Bilt Test have been collected. An impression of the meteorological situation during the field test can be obtained from the results given in section 4, where the precipitation results are analyzed as a function of various meteorological parameters. The measurement site in De Bilt is not optimal because of the trees in the South to Northwest directions. However, in this study we not only compare the results of a precipitation gauge in a windscreen with the result of an identical sensor in the English setup, but the result of 2 precipitation gauges in an English setup. The comparison of the 2 precipitation gauges in an English setup gives an estimate of the error caused by differences in siting and exposure of the closely collocated sensors as well as instrumental errors.

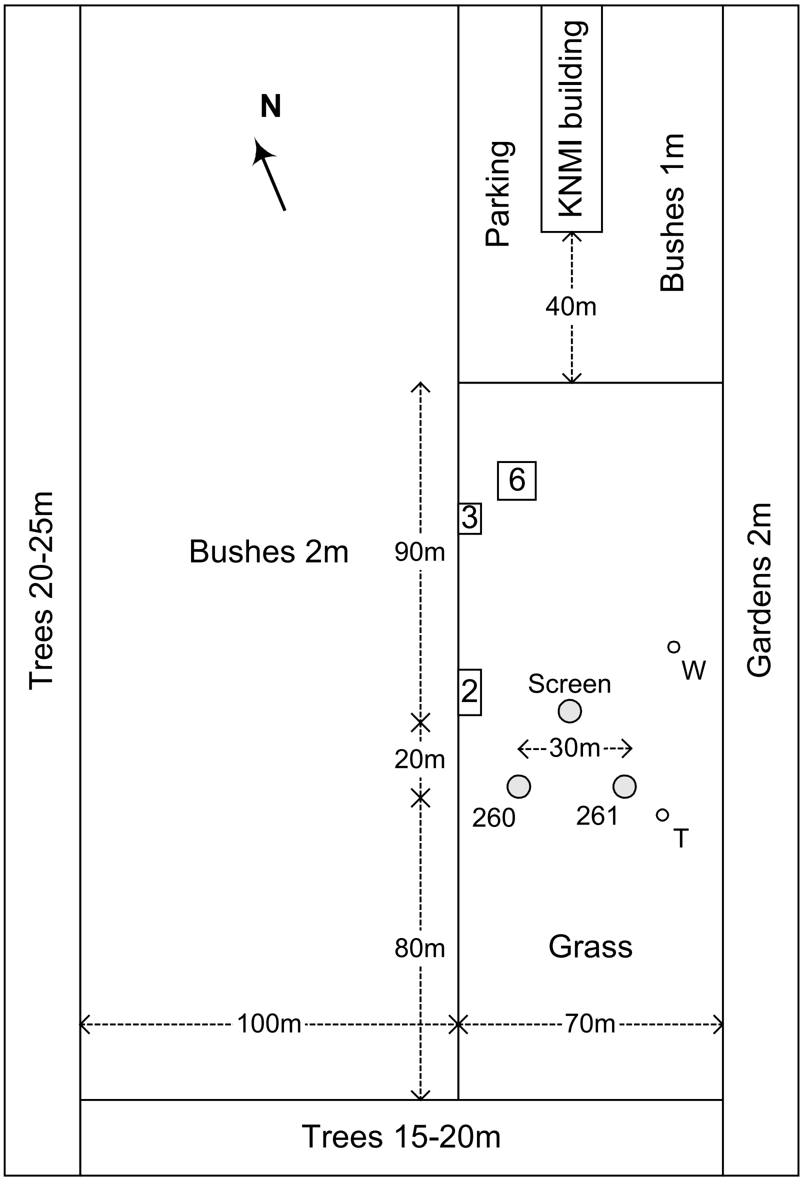

Figure 5: Sketch of the measurement site in de Bilt with the locations of the relevant sensors and obstructions in the surroundings. The dots indicate the positions of the precipitation gauges of 260, 261 and screen. The circles denote the location of the temperature and humidity sensors (T) and the wind mast of 261 (W).

3. Precipitation data

3.1. Sensor data

The data-acquisition was performed with the operational meteorological measurement network of KNMI. All three precipitation gauges are connected to a sensor interface, which calculates the precipitation intensities and performs a first level quality control (cf. Bijma, 1995). The data is forwarded to an automatic weather station that stores the 10-minute averaged data. The 10-minute averaged data have been extracted from the automatic weather station and archived for this comparison. The archived 'raw' data is used for the comparison. Note that these values may differ form the validated hourly reports archived by the climatological department (denoted "KD"). There are several reasons for these differences such as:

(1) The climatological hourly data also use the Eigenbrodt[*] precipitation detector for the determination of very light precipitation and the correction of faulty precipitation amounts.

(2) There is a 5-minute shift between the time window of the 10-minute database of the automatic weather station (H+45-H+55, etc.) and the generation of the climatological report at manned stations (at H+50).

(3) The values in the climatological reports are rounded to 0.1mm due to coding, whereas the internal resolution of the precipitation intensity is 0.006mm/h.

(4) Faulty sensor data are corrected either by the observer at the time the report is generated or afterwards during validation.

(5) Missing sensor data are complemented using precipitation information from e.g. radar or neighboring stations.

The use of raw 10-minute precipitation data for the comparison eliminates these possible causes for differences. However, one has to be alert for faulty sensor readings in the raw data set.

The resolution of the available precipitation intensity data per 10-minute interval is 0.01mm/h. In addition to the precipitation intensity of the three precipitation gauges at 260, 261 and screen, the precipitation duration determined by the Eigenbrodt at 260 and 261 is archived for the comparison as well. Furthermore, the air temperature and relative humidity measured at 1.5m and the wind speed and direction observed with the 10-meter mast of 261 are stored.

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[*] Note that the Eigenbrodt was removed form the KNMI meteorological measurement network during the windscreen test. This occurred on December 11, 2001 for the meteorological stations in De Bilt. Afterwards the duration was determined by the sensor interface of the precipitation gauge. A 12-second interval is considered having precipitation duration when in the last 5 minutes at least 2 samples with precipitation occurred.

3.2. Data rejection

The comparison considers only those 10-minute intervals were the precipitation measurements of all three precipitation gauges are available and valid. Intervals where data of one or more of the precipitation gauges are missing are ignored. For the comparison in this paper these omitted intervals do not matter. However, the rejections affect the total sums reported in this paper, which should therefore not be taken for the actual daily, monthly and annual precipitation amounts. Note that the missing data was largely caused by gaps in the data acquisition and maintenance of one of the sensors. Monthly sums of the precipitation amounts obtained by all 3 sensors are given in Figure 6 for the period of the windscreen test. The monthly results show that the sums for precipitation gauges 260 and 261 in the English setup are quite close, and the sum for the precipitation gauge in the screen is generally less. However, Figure 6 also shows some striking features. In September and October 1999 260 reports less precipitation than the other 2 sensors; in June 2001 there is a large difference between the precipitation amount of 260 and 261; in July the precipitation amount of the sensor in the windscreen is higher than that of the other 2 sensors; after November 2001 the precipitation gauge of 261 reports significantly lower precipitation amounts than the other 2 sensors.

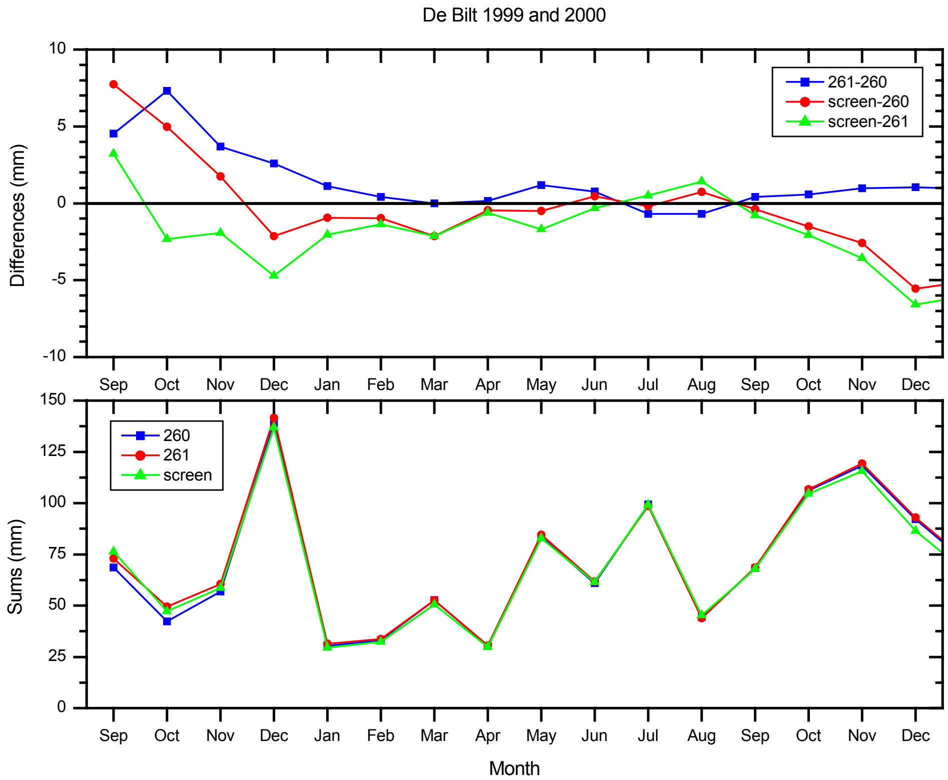

Figure 6: Monthly precipitation amounts during the windscreen test at De Bilt using the ‘raw’ 10-minute data for all intervals where data of the three precipitation gauges of 260, 261 and screen is available.

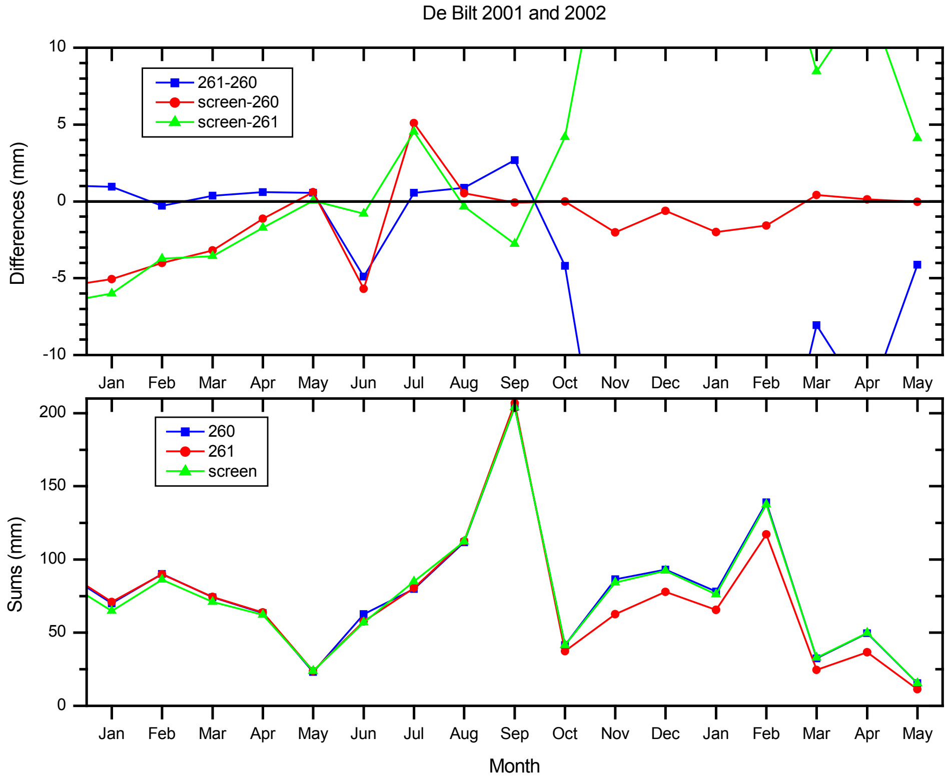

Figure 6: Continued.

The above-mentioned features are investigated in more detail in Figure 7, which shows the daily precipitation amounts for June and October 2001. Starting at October 23 the precipitation amounts of 261 are always significantly lower than those of the other 2 precipitation gauges. This lasts until the end of the comparison in May 2002. The precipitation gauge of 261 was replaced on October 22, 2001 (cf. Table 1). Probably the precipitation gauge of 261 was malfunctioning, but since the sensor interface did not report a warning or an error, it was not noticed. Note that 261 is the test station of De Bilt, which is not part of the operational validation by the climatological department. However, the pre-calibration that was performed after the precipitation gauge was replaced did not report any problems. In this study the data obtained after October 22, 2001 will be disregarded. Furthermore, the results for September and October 1999 showed that the sums of 261 and screen are always higher than those of 260. Even when the rejections discussed below are applied, the monthly differences 261–260 and screen–260 for September and October 1999 are always about 4 mm or larger, and always positive, whereas for all other months the differences do not exceed 2mm. The daily differences show that in these 2 months the precipitation amount of 260 is always less than that of the other 2 precipitation gauges. The reason for this is unclear. The period considered in the comparison is restricted from 1 November 1999 to 22 October 2001.

The daily data of June show that on the 22nd 260 reported about 7mm precipitation whereas the other 2 sensors did not report any precipitation. The raw 10-minute data revealed that the precipitation gauge of 260 reported precipitation for several hours, with intensities up to 2 to 6 mm/h. In the same period the other 2 precipitation gauges and the 2 precipitation detectors did not detect any precipitation. Verification in validated data of the climatological department revealed that on June 22, 2001 no precipitation was reported for De Bilt. A similar situation occurred on July 12, when the precipitation gauge in the windscreen reported about 5mm during several hours while the other 2 precipitation gauges did not report any precipitation at all. These faulty readings, since the precipitation detectors and the climatological data reported precipitation, also need to be removed from the data set. Furthermore, on June 15 a situation can be seen where the sum of 260 is about 2mm less than for the other 2 sensors. In the 10-minute data an entry can be found where 260 reports 18mm/h whereas the other 2 precipitation gauges report 23 and 27mm/h. In the adjoining intervals the reported precipitation amount is nearly the same. Therefore this isolated deviation also needs to be rejected. Table 1 shows that the precipitation gauge of 260 was replaced on June 25, 2001 due to a leaking valve. This can explain the underestimation of precipitation by 260 between June 15 and 17, but not the faulty reports between June 22 and 24.

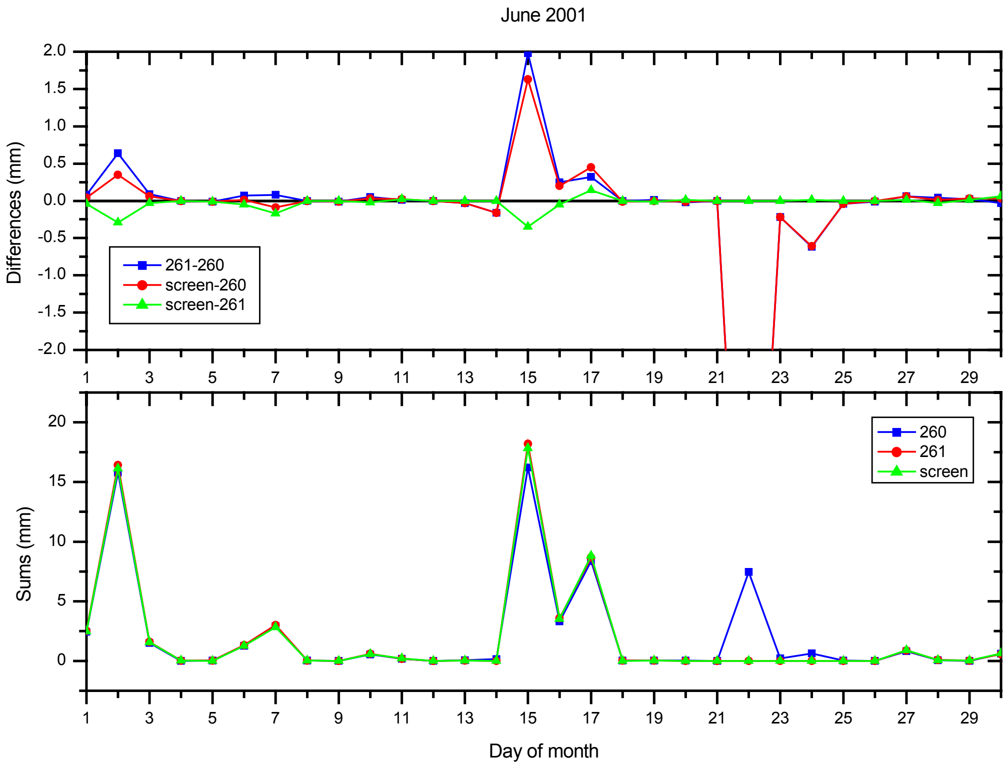

Figure 7: Daily precipitation amounts for June and October 2001 using the 'raw' 10-minute data for all intervals where data of the three precipitation gauges of 260, 261 and screen are available.

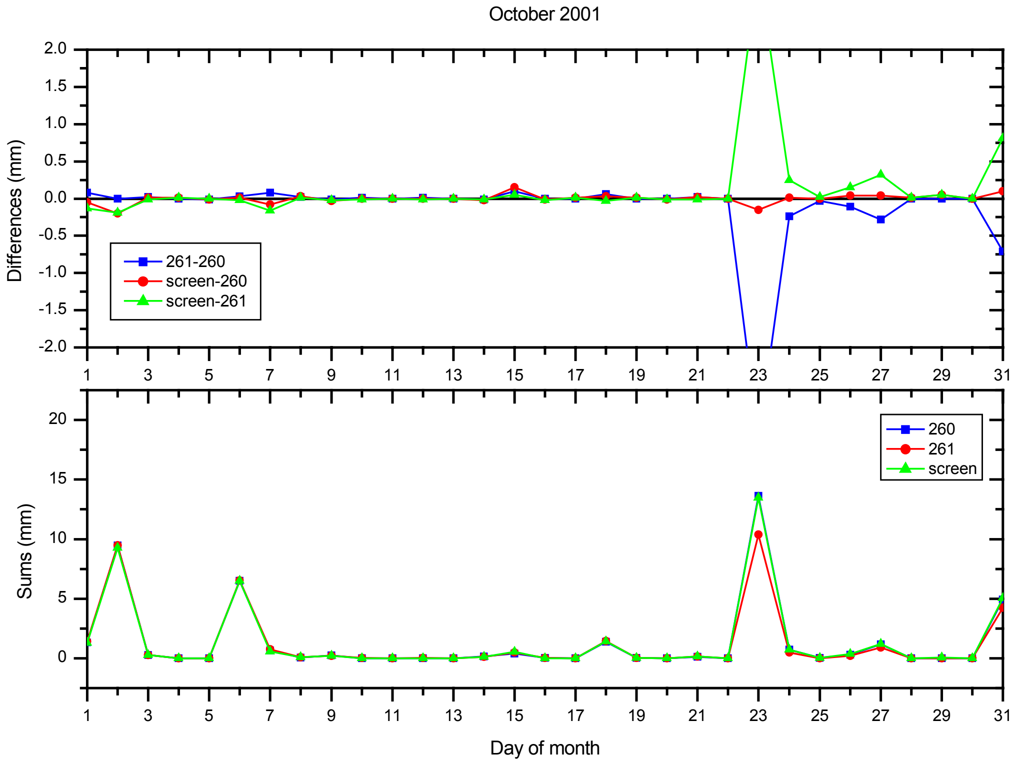

Figure 7: Continued.

Next a method was constructed to automatically remove the faulty sensor readings from the data set. For that purpose the climatological hourly precipitation sums denoted by KD are used as a reference. First only those hours are considered where all 10-minute intervals have valid readings. Since the time window is shifted 5 minutes, the hourly value at H containing the sum from H-70 to H-10 requires 7 valid 10-minute intervals from H-75 to H-5. Furthermore, if an hourly value is rejected and the first 10-minute interval reports precipitation then the previous hour is also disregarded. Similarly the next hour is disregarded in case the previous hour is rejected and the last 10-minute interval reported precipitation. Table 2 shows that by using these rejection criteria 15,843 of the 17,328 hours remain valid and that the precipitation sum of the KD exceeds the sum calculated for the same station, but using the raw 10-minute values, by 97mm. The handling of the KD cases that report traces of precipitation is the main cause of this large difference. These are cases where the measured precipitation amount is below 0.1mm, or where the precipitation detector or the observer reported some light precipitation. Since the precipitation detector is more sensitive than the precipitation gauge this occurs at about 2000 hours. Rejecting these hours and adjoining hours based on the selection mentioned above, reduces the number of cases to 11,717 and the agreement between KD and 260 improves significantly. However, if the reported cases with traces of precipitation are treated as hours with no precipitation and similarly for the precipitation gauge for hours with a sum below 0.05mm, the agreement also improves. This way of handling the traces of precipitation filters out the small precipitation amounts. It is better to treat only the traces reported by the KD as zero. This is the same treatment of the traces as used by the climatological department in calculating the monthly and annual precipitation amounts. In that case the agreement between KD and 260 is also good, without reducing the number of cases with small precipitation amounts. The sum reported by 260 is higher than the KD value since the precipitation gauge of 260 may in some hours measure a little amount of precipitation that would be encoded as traces in the climatological reports.

Table 2: Differences in mm between the precipitation sums of the three precipitation gauges and the hourly climatological data over the period 1 November 1999 to 22 October 2001 for different cases of selection.

Case	#Hours	KD sum	KD–260	261–260	Screen–260
All hours	17,328	1974	-	-	-
Trace KD=0.05	15,843	1827	97	12	–27
Trace KD=//	11,717	551	–4	–1	–8
Trace KD&Gauge=0	15,843	1725	19	13	–28
Trace KD=0	15,843	1725	–5	12	–27
Trace KD=0, Dif=1	15,832	1709	–8	14	–29
Trace KD=0, Dif=1, Cor=0.10	15,725	1685	–4	18	–22
Trace KD=0, Dif=1, Cor=0.05	15,623	1668	–4	18	–23
Trace KD=0, Dif=1, Cor=0.02	15,194	1556	–3	17	–23
Trace KD=0, Dif=1, Cor=0.01	14,444	1340	–3	15	–22
Trace KD=0, Dif=1, Cor=0.00	11,185	737	1	8	–11

The precipitation gauge data of individual 10-minute intervals will be rejected for the following reasons.

(i) First, the results of all three sensors need to be available. If the data of one is missing, the other 2 sensors will also be rejected. This way the same situations will be considered when comparing any 2 sensors with one another.

(ii) Secondly, 10-minute intervals are rejected where the difference "Dif" between the precipitation amounts of any 2 sensors is larger than 1mm, and also the difference between the sum including the sensor values of the previous and next interval is larger than 1mm (thus no compensation by adjoining intervals). In fact this correction only rejects 4 cases on June 15, June 22, and July 12 2001, mentioned above.

(iii) Thirdly, intervals will be rejected where one sensor falsely reported precipitation. If the precipitation intensity of 1 precipitation gauge is above a certain threshold "Cor", but the other 2 precipitation gauges do not report precipitation in that 10-minute interval, nor in the previous or next interval and also the precipitation detector (if available) did not detect any precipitation, than that interval is rejected.

(iv) Fourthly, intervals will be rejected where one sensor falsely did not report precipitation. If the precipitation intensity of 1 precipitation gauge is zero in a certain 10-minute interval, as well as in the previous and next interval, but the other 2 precipitation gauges report precipitation above a certain threshold "Cor" in the 10-minute interval under consideration and the precipitation detectors (if available) report precipitation, than that interval is rejected.

(v) Lastly, within a period of precipitation no gaps with missing data are allowed. Due to spatial and temporal differences, a precipitation event can be partly assigned to different 10-minute intervals for different sensors. Thus, in case of missing data all adjoining 10-minute intervals will be rejected where at least one of the sensors reported precipitation.

Note that the tests for faulty precipitation or no precipitation, tests (iii) and (iv), do not include the temperature. This might be useful to filter out the cases with solid precipitation, during which precipitation measurements can be postponed until the precipitation has been melted in the precipitation gauge. Using a temperature threshold to avoid melting snow at 1 of the sensors to be omitted by mistake, failed since the temperature of the test station showed faulty negative readings in June 24. Inspection of the rejections without a temperature threshold showed, however, that most cases occur at temperature well above zero. Furthermore, the cases with temperatures near or below zero correspond either to small precipitation amounts or several consecutive intervals with rejections for 1 sensor. Therefore rejection of these intervals has little effect and seems to be correct.

The comparison with climatological data is restricted to the hours where all 10-minute data of all three gauges is available (i). The intervals with precipitation adjoining missing sensor data are also rejected according to (v). Appling test (ii) in order to reject intervals with too large differences only rejects a small number of cases. As a result the agreement between KD and 260, and between 261 and screen gets worse (cf. Table 2). A high threshold Cor=0.1mm/h in test (iii) and (iv) detects the severe faulty cases of June 2001 mentioned above and eliminates them and the adjoining intervals (v). The rejection of the faulty precipitation reports of 260 in June 22, reduce the sum for 260, and hence reduce the differences KD–260 and screen–260, while increasing 261–260. Some other, smaller corrections are applied to other months and to other sensors. While the large errors and adjoining intervals are rejected, the low intensity readings during periods with a faulty sensor remain. Using a lower threshold removes these cases as well, but has hardly an effect on the sums. However, since most rejections are often applied to the same sensor for a certain time period (several consecutive 10-minute intervals) they seem to be related to the same sensor failure. Using a low threshold Cor=0.0mm/h reduces the number of cases considerably. The agreement in the total sums generally improves, but this can be caused by the rejection of many cases with light precipitation.

4. Comparison using filtered data

In this section 10-minute precipitation intensity data for the 3 precipitation gauges are subjected to the rejection criteria (i) to (v) as described in the previous section. The threshold “Cor” for rejecting faulty precipitation readings is set to 0.1mm/h. The period considered is from 1 November 1999 to 22 October 2001.

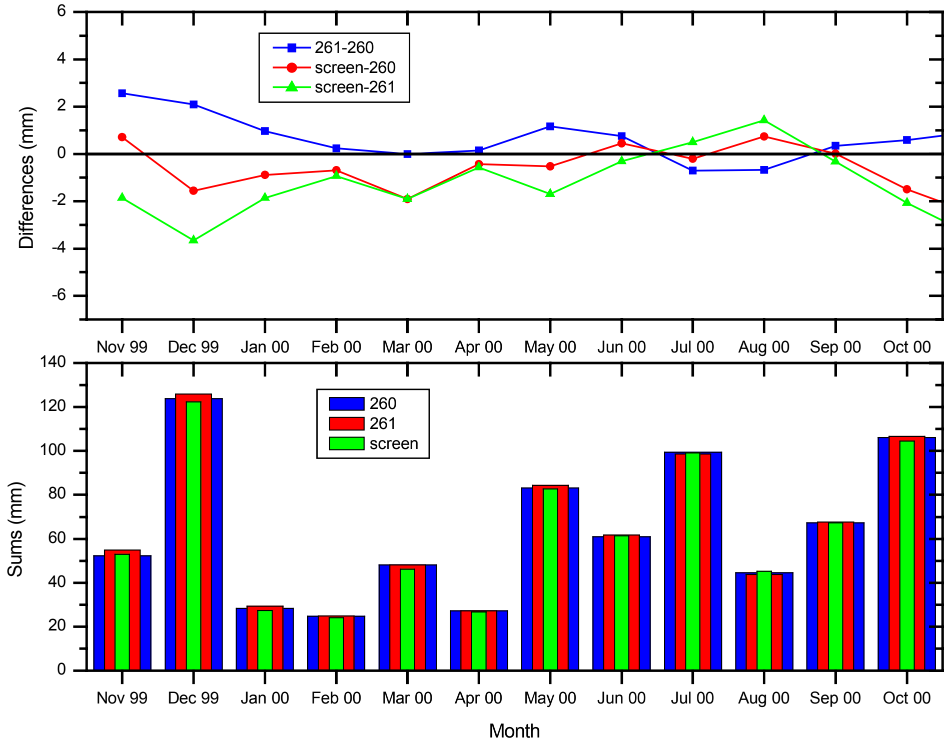

Figure 8: Monthly precipitation sums (in mm) of the filtered 10-minute data for the precipitation gauges of 260, 261 and screen and their differences for the period November 1999 to October 2000.

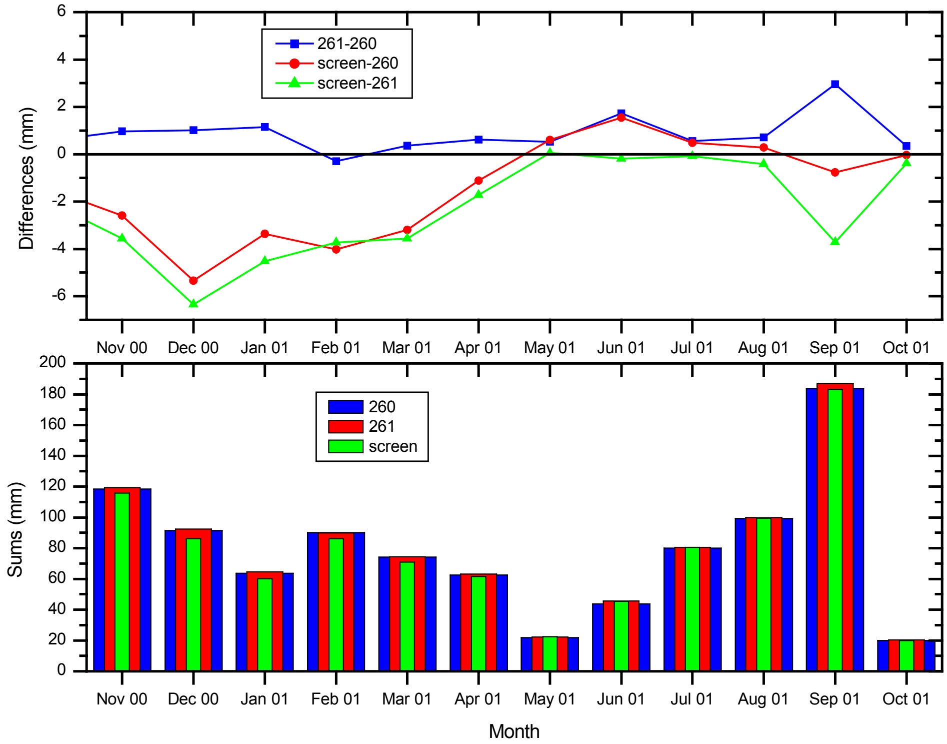

Figure 9: As Figure 8, but now for the period November 2000 to October 2001.

4.1. Analysis of monthly precipitation sums

First an analysis is performed on the monthly precipitation sums calculated for the valid 10-minute entries. The results are shown in Figure 8 and Figure 9 and in Table 3. The results are given for 260, 261 (both with the precipitation gauge in the English setup) and screen (denoting the precipitation gauge on the field in the windscreen). Note that most rejections are found for the precipitation data of 1999 and 2001. In the period May 2000 to March 2001 very little data is rejected. Overall 95,292 of the total available 103,968 10-minute intervals are valid (92%). The overall difference 261–260 for all valid 10-minute entries in the period 1 November 1999 to 22 October 2001 is +18mm or +1%. Figure 8 and Figure 9 show monthly differences of about +1mm for 261–260, with differences up to +3mm in November and December 1999 and in September 2001. The monthly precipitation amounts for 261 are generally higher, but during July and August 2000 they are slightly less (–1mm). In relative numbers the monthly differences (261–260)/260 are +4% and +5% in June 2001 and November 1999, respectively. The largest negative value is almost –2% in August 2000. The overall difference screen–260 for all valid 10-minute entries is –23mm or –1%. Figure 8 and Figure 9 show that the monthly precipitation amounts for screen are generally lower, especially during the winter months. The largest monthly differences are –5mm (–6%) in December 2000 and +2mm (+4%) in June 2001. The standard deviation for the differences 261–260 calculated from the 10-minute values where either 261 or 260 reports precipitation is

0.08mm for all intervals combined and varies monthly between 0.04 and 0.12mm. Almost identical values for the standard deviation are found for the differences screen–260.

Table 3: Overview of the monthly and total precipitation amounts (in mm) of the filtered 10-minute data for the precipitation gauges of 260, 261 and screen and their differences for November 1999 to October 2001. Also reported are the number of valid intervals and the precipitation structure parameter *N* (see section 4.4).

Month	**Sum (mm)**			**Difference (mm)**			**Difference (%)**			**#**	**N (%)**
MMYY	*260*	*261*	*Screen*	*261-260*	*Screen-260*	*Screen-261*	*261-260*	*Screen-260*	*Screen-261*	*Valid Intervals*	*260*
1199	52.26	54.82	52.97	2.57	0.71	−1.86	4.91	1.36	−3.39	4212	64.7
1299	123.87	125.97	122.31	2.10	−1.56	−3.66	1.70	−1.26	−2.90	4028	36.4
0100	28.29	29.26	27.40	0.97	−0.89	−1.86	3.45	−3.15	−6.37	3658	64.6
0200	24.68	24.92	23.99	0.24	−0.69	−0.93	0.95	−2.81	−3.72	1575	61.0
0300	48.11	48.10	46.20	−0.01	−1.91	−1.90	−0.02	−3.96	−3.95	3018	42.4
0400	27.11	27.26	26.69	0.15	−0.43	−0.57	0.54	−1.57	−2.10	3948	54.3
0500	83.19	84.36	82.66	1.17	−0.53	−1.70	1.41	−0.63	−2.01	4445	41.4
0600	60.91	61.67	61.36	0.76	0.45	−0.31	1.25	0.74	−0.50	4320	30.9
0700	99.32	98.62	99.13	−0.70	−0.20	0.50	−0.70	−0.20	0.51	4464	31.1
0800	44.47	43.79	45.21	−0.68	0.74	1.42	−1.53	1.66	3.24	4464	24.7
0900	67.25	67.59	67.26	0.34	0.01	−0.33	0.51	0.01	−0.49	4127	31.9
1000	106.04	106.62	104.54	0.58	−1.50	−2.08	0.55	−1.41	−1.95	4462	47.3
1100	118.27	119.24	115.68	0.97	−2.59	−3.56	0.82	−2.19	−2.99	4304	44.7
1200	91.35	92.36	86.01	1.01	−5.34	−6.35	1.11	−5.84	−6.88	4432	57.4
0101	63.51	64.67	60.15	1.15	−3.36	−4.52	1.82	−5.30	−6.99	4329	60.2
0201	90.13	89.84	86.11	−0.29	−4.02	−3.73	−0.32	−4.46	−4.15	4029	62.5
0301	74.07	74.44	70.88	0.36	−3.20	−3.56	0.49	−4.32	−4.78	4464	54.9
0401	62.54	63.15	61.41	0.61	−1.12	−1.73	0.97	−1.80	−2.74	3010	49.4
0501	21.75	22.28	22.35	0.53	0.60	0.06	2.44	2.74	0.28	3687	38.0
0601	43.82	45.55	45.36	1.73	1.55	-0.19	3.96	3.53	−0.41	4216	33.9
0701	79.90	80.46	80.38	0.56	0.48	-0.08	0.71	0.60	−0.10	4417	23.5
0801	99.13	99.84	99.42	0.71	0.29	−0.42	0.71	0.29	−0.42	4377	19.9
0901	183.86	186.82	183.10	2.96	−0.76	−3.72	1.61	−0.41	−1.99	4154	26.7
1001	19.98	20.31	19.94	0.34	−0.04	−0.38	1.68	−0.20	−1.85	3152	39.9
All	*1713.85*	*1732.01*	*1690.53*	*18.16*	*−23.32*	*−41.48*	*1.06*	*−1.36*	*−2.39*	*95292*	*41.1*

4.2. Analysis of 10-minute precipitation intensity

Next the valid 10-minute precipitation intensity amounts for the 3 precipitation gauges are analyzed. This analysis is performed on all 10-minute measurements in the period 1 November 1999 to 22 October 2001 where at least one of the three precipitation gauges reported precipitation. The total number of 10-minute intervals involved is 24,298. A frequency distribution of the measured 10-minute precipitation intensity is shown in Figure 10 for each of the three precipitation gauges. The distribution is given in 0.1mm/h bins for intensities between 0 and 5mm/h. Above 5 mm/h the number of events involved per bin decreases below 10, and hence statistics are poor. Between 0 and 5mm/h the frequency distribution of screen is the same as those of 260 and 261. The slightly smaller number of values of screen (e.g. between 0.2 and 1mm/h) is related to the generally lower precipitation amounts given by screen compared to 260 and 261, which was also observed in the monthly results. For the same reason the number of 261 cases is slightly higher than those of 260 (e.g. between 0.1 and 0.8 mm/h).

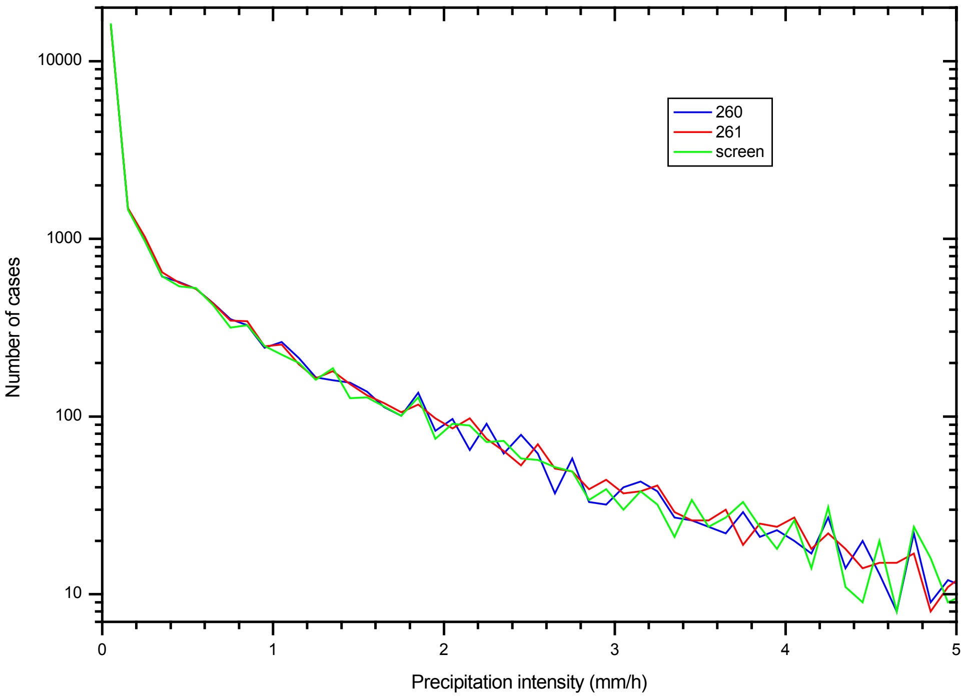

Figure 10: Frequency distributions of the filtered 10-minute precipitation intensity measurements for each of the precipitation gauges of 260, 261 and screen. The bin size is 0.1 mm/h. All valid cases for the period November 1999 to October 2001 are included where at least one of the sensors reports precipitation.

In Figure 11 the frequency distributions for intensities below 0.2mm/h are shown in more detail using 0.01mm/h bins. The distributions have lower numbers for bins at multiples of 0.03mm/h. This is caused by the 0.006mm/h reporting steps of the precipitation gauge, which results in either 2 or 1 sensor reporting steps in a 0.01mm/h frequency bin. The frequency distributions of the 3 sensors show differences of about 10%. However, this can be expected considering the closeness of the bin step size to the sensor reporting steps. The behavior at very low intensities is of particular interest, because it is related to the precipitation duration when derived from the precipitation gauge. Figure 11 shows that screen has more cases where this sensor does not report precipitation but the one of the other 2 sensors does than vice versa (roughly 6900 versus 6200 cases). Hence screen will report about 700 (3%) 10-minute intervals less with precipitation compared to the other 2 sensors, whereas 260 and 261 differ 180 cases (1%). However, note that these numbers are small compared to the 6000 cases (25%) where a precipitation gauge disagrees with another sensor whether precipitation is reported in a 10-minute interval. This number does not change much when considering only the precipitation gauges of

260 and 261. The large number of discrepancies of interval with or without precipitation can be caused by temporal/spatial differences especially when looking at 10-minute intervals and sensors about 30 m apart. The intensities (and duration) involved are generally small. Hence it may be expected that the filtering of the data did not influence this. Another reason for the discrepancy can be the known faulty precipitation reports of the precipitation gauge that occur sometimes during bright days. This is probably the result of temperature changes of the sensor or temperature gradients within the sensor due to solar illumination. This might also explain the lower number of precipitation events reported by screen, because the sensor is partly shielded from the sun by the windscreen. In addition, Figure 11 shows that screen reports fewer cases at 0.01mm/h compared to the other 2 sensors (roughly 5000 versus 5900 cases), but screen reports more cases between 0.03 and 0.06mm/h.

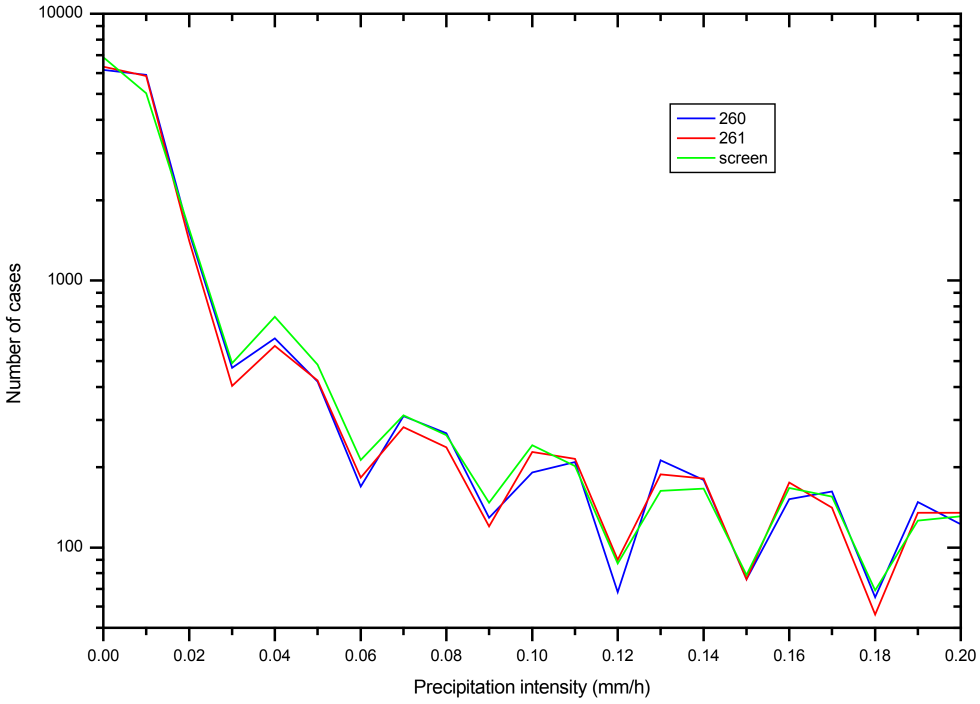

Figure 11: As Figure 10, but for low precipitation intensities and using a bin size of 0.01 mm/h.

A histogram of the differences between the 10-minute intensity measurements of any 2 gauges is presented in Figure 12. The histogram is plotted using a logarithmic scale. The histogram closely resembles a Gaussian distribution. All three histograms peak at a difference of 0.00mm/h, where the bin for 260–261 contains 26% of the cases and for both distributions involving screen 22%. The number of cases within ±0.01mm/h is 62% for 260–261 and about 58% for the screen–260 and screen–261, whereas 79% and 75% are within ±0.03mm/h and 86% and 83% are within ±0.05mm/h, respectively. The number of cases in the bins for larger differences decreases exponentially. The histogram for 260–261 shows more cases with positive than negative differences leading to the larger monthly sums for 261 compared to 260. The histograms screen–260 and screen–

261 show more cases with negative than positive differences leading to the lower monthly sums for screen compared to 260 and 261. The reason for this will be discussed in the next section.

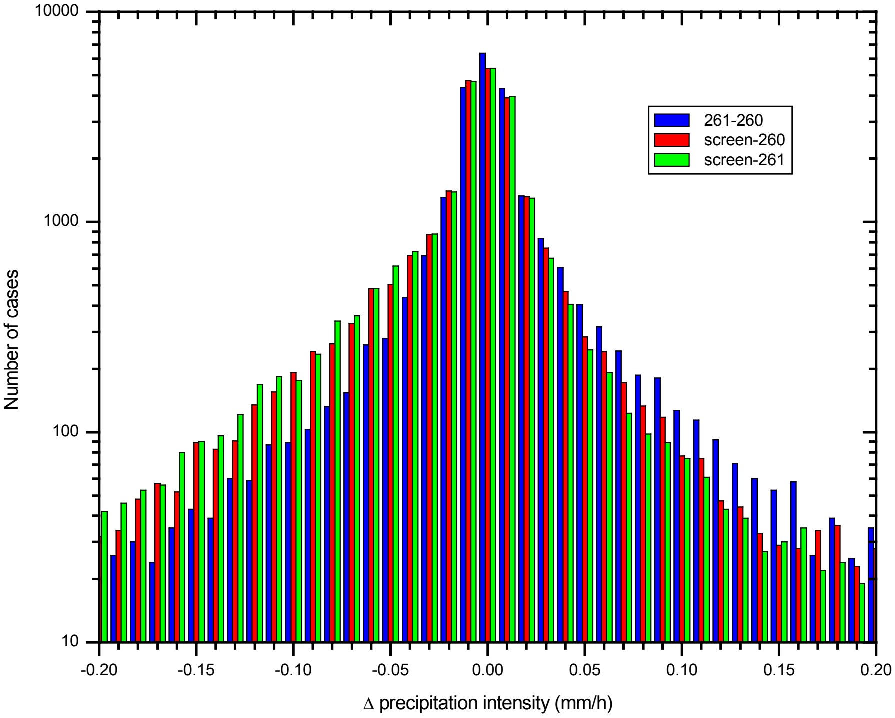

Figure 12: Histogram of the differences between the filtered 10-minute precipitation intensity measurements for any combination of 2 precipitation gauges. The bin size is 0.01 mm/h. All cases for the period November 1999 to October 2001 are included where at least one of the sensors reports precipitation.

4.3. Dependency on wind speed

In this section the differences between the measured 10-minute precipitation intensities are studied as a function of wind speed. Unless stated otherwise, the measured wind speed at 10m is used. Again, the analysis is performed on all 10-minute measurements in the period 1 November 1999 to 22 October 2001 where the result for all three sensors are valid and at least one of the three precipitation gauges reported precipitation. In addition, the wind speed needs to be available. The differences are calculated for different wind speed bins in order to determine any wind speed effect. For that purpose the wind speed range is divided in 0.5m/s bins from 0 to 10.5m/s, where the last bin also contains all the cases with wind speeds above 10.5m/s. The averaged differences between the 10-minute precipitation intensities for 2 precipitation gauges per wind speed interval are given in Figure 13. The averaged differences are close to zero for wind speeds below 2m/s. For wind speeds larger than 2m/s the curve for 261–260 has slightly positive values that seem to be increasing with increasing wind speed. The curves screen–260 and screen–261 have negative values that generally get more negative with increasing wind speed up to 8 m/s.

Above 8.5 m/s the number of cases is below 30 (see Figure 14), which may explain the strange behavior of some curves at higher wind speeds. At all wind speeds the averaged differences are less than the standard deviation. However, this does not mean that no wind effect is present.

Comparison of the above results with the results of Kuik (2001) with a KNMI gauge placed on the measurement field without a wind screen (see. Figure 1) shows the following. Kuik reported differences for 260–261 within ±0.01mm/h independent of wind speed and differences for unshielded–260 increasing gradually to –0.09mm/h at 8m/s. The current study shows differences for 260–261 slightly increasing with wind speed up to 0.02mm/h and differences for screen–260 increasing gradually to –0.06mm/h at 8m/s. Hence it seems like the wind screen reduces the wind effect only by about 30%. The reduction in the total precipitation sum due to the wind effect reported by Kuik was –5%, whereas here the difference is –1.4%, and hence indicates a reduction of 70% as a result of the windscreen. This inconsistency in the results is caused by differences in the number of cases and the total precipitation amounts per wind speed interval for the 2 test periods. Unfortunately, the data from Kuik (2001) are not available anymore and therefore the reduction of the wind effect by using a windscreen cannot easily be given.

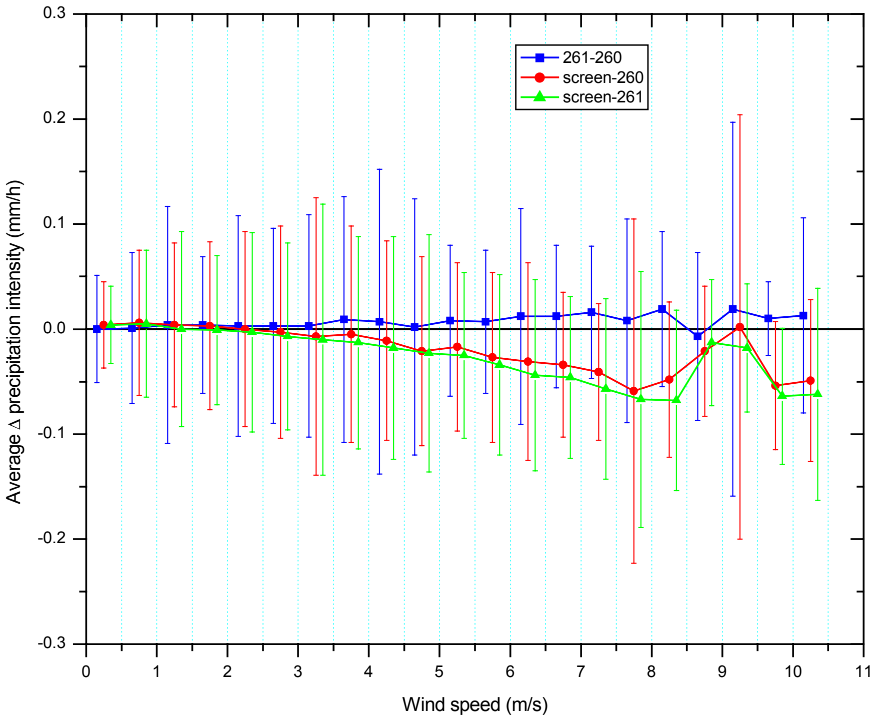

Figure 13: Averaged differences in mm/h between the 10-minute precipitation intensities measured by 2 precipitation gauges and its standard deviation as a function of wind speed measured at 10m in steps of 0.5m/s.

A better way to present the wind effect is by looking at the relative differences per wind speed interval. Such a plot is given in Figure 14. It shows that the difference 261–260 has an offset of about 1%, independent of wind speed. This corresponds with the generally higher monthly precipitation sums for 261 compared to 260 and hence also for the total sum, which are also about 1%. The relative difference involving the screen show an almost linear decrease with increasing wind speed from +2% at 0m/s to –6% at 7m/s. A linear fit to the curves screen–260 and screen–261 for wind speeds between 0 and 8m/s gives a slope of –1.2±0.1 and –1.3±0.1%/ms^{-1} with regression coefficients of –0.97 and –0.98, respectively. The corresponding intercepts are 2.5 and 2.1%, respectively. At higher wind speeds the relative differences seem to decrease only slightly, but this is probably because of the small number of cases involved. On the other hand the droplet size distribution might cause this when it varies with the wind speed.

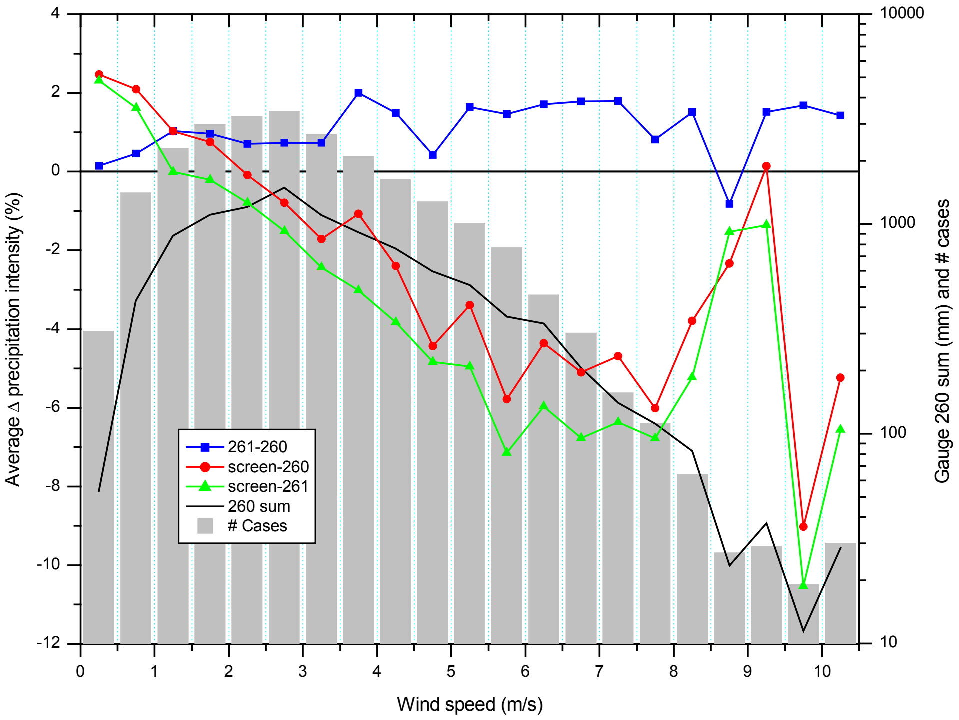

Figure 14: As Figure 13, but now the difference are presented as the percentage of the total measured precipitation amount per wind speed bin. Again, the measured wind speed at 10m is used. The number of cases and the precipitation sum of the 260 gauge are also shown per wind speed bin.

4.4. *Comparison of wind effect*

The relative differences can be compared to correction factors reported in the literature for the wind speed. In that case one has to take into account that the wind speed was measured on a 10m mast and not at the level of the rim of the precipitation gauge, which in this case is 1m. A logarithmic exposure correction can be used to translate the measured wind speed S_{10} at 10m to the wind speed S_h at height h according to (WMO, 1996):

$$S_h = S_{10} \times \frac{\ln(h/z_0)}{\ln(10/z_0)},$$

where z_0 is the roughness length which is typically 0.03m for open terrain. This results in a reduction of the wind speed at 1m compared to the measurements at 10m of 60%. Note, however, that due the influence of nearby obstructions, the above-mentioned logarithmic exposure correction is rather uncertain at De Bilt. Furthermore, the correction depends on the velocity of the falling precipitation particles and hence their size. This can be characterized, in a first approximation, by the parameter N, i.e. the amount of precipitation at low intensities. Here, N is defined as the percentage of precipitation with intensity less or equal than 0.03mm/min (≤1.8mm/h) to the total precipitation amount. For the 2 years of test data considered in this paper the average N calculated from the valid 10-minute data is 40%, but the monthly values vary between 20% and 65% (see Table 3). According to WMO (1994) the correction factors for a wind speed 6m/s at the gauge rim is about 1.08, 1.11 and 1.13 for liquid precipitation and a Hellmann gauge without a windscreen and N equal to 20, 40 and 65%, respectively. So without a windscreen errors of about –10% are expected at 6m/s for a Hellmann gauge. Considering the 60% reduction of the wind speed observed at 10m this –10% compares well with the results obtained with KNMI precipitation gauge in a windscreen. However, the wind-induced loss depends on the dimensions and shape of the precipitation gauge. Since the KNMI precipitation gauge has larger dimensions than the Hellmann gauge a larger wind effect can be expected for an unshielded KNMI precipitation gauge (cf. Nešpor and Sevruk, 1999). However, a quantitative number for the wind effect of an unshielded KNMI precipitation gauge requires detailed numerical simulations.

The information reported by Kuik (2001) is not sufficient to present the results of the wind effect in relative numbers. Kuik reported the averaged difference D_k(i) and the number of cases n_k(i) per wind speed bin (i) (see Figure 1). The total precipitation amount per wind speed bin is, however, not given. The raw sensor data of the precipitation gauge on the measurement field on which the study of Kuik was based is not available anymore. Precipitation intensity and wind speed data of 261 are available for 1998 since the data was archived for another purpose. From this data set the precipitation amount m(i) per wind speed bin is calculated for the period January to October 1998, i.e. the period where most valid data used by Kuik occurred. The precipitation amount per wind speed bin can be used to calculate the relative differences according to:

$$D_k(i) \times n_k(i) / m(i).$$

The corresponding results are given by the solid curves in Figure 15. The total precipitation amount Σ_i m(i) for 261 in 1998 is 842mm and agrees exactly with the sum reported by Kuik. The number of cases n(i) per wind speed bin can also be compared with the values reported by Kuik. Their ratio n(i)/n_k(i) is given in Figure 15 and shows differences up to 40%. This is the result of data being not taken into account in one of the two studies. Also the total difference unshielded–261 reported by Kuik is –40mm on the yearly sum, but –77mm when derived from the results given for the wind speed bins using:

$$\sum_i D_k(i) \times n_k(i) \, .$$

Probably Kuik used different selection criteria for calculation the yearly sum and the differences per wind speed bin. The precipitation amounts per wind speed bin are as a first order approximation corrected for this difference in the number of cases by multiplying the precipitation amounts by the factor n_k(i)/n(i). This gives a corrected yearly sum of 1187mm. Next the relative differences per wind speed bin can be calculated from the number of cases times the averaged difference in precipitation intensity divided by 6 as reported by Kuik (2001) divided by the number-corrected precipitation amount of 261 per wind speed bin:

$$D_k(i) \times n_k(i) / \big(m(i) \times n_k(i)/n(i)\big) = D_k(i) \times n(i)/m(i) \, .$$

The dashed lines in Figure 15 give the corresponding results. These derived relative differences as a function of wind speed between a KNMI precipitation gauge in the English setup and one unshielded on the measurement field are rather uncertain since a correction up to 40% was applied for some wind speed bins. It is assumed that the missing cases had the same averaged precipitation intensities as the other cases. As an additional check the relative differences 260–261 can be used. The range and standard deviation of the number-corrected relative differences 260–261 as a function of wind speed given in Figure 15 for 1998 data are respectively 2.5% and 0.66%, and compare relatively well with the corresponding values 2.8% and 0.69% for 261–260 from Figure 14. Furthermore, the overall relative differences of 261–260 and unshielded–261 derived from the reconstructed data by:

$$\left(\sum_i D_k(i) \times n(i)\right) \Big/ \left(\sum_i m(i)\right)$$

are –0.1% and –6.5%, respectively, and compare reasonably well with the values –0.2% and –4.7% reported by Kuik (2001).

The above checks indicate that the reconstructed relative difference between a KNMI precipitation gauge in an English setup and one unshielded on the measurement field as given in Figure 15 have to be considered with care. The comparison of the relative difference between screen–261 and unshielded–261 as given by Figure 14 and Figure 15, respectively, is also difficult due to the variations in the curves for unshielded–261. At a wind speed of 7/ms screen–261 is about –6% whereas unshielded–261 is about –12%. Hence the reduction of the wind speed effect by using a windscreen is about 50%. However, performing a linear fit to unshielded–261 gives a slope of –1.1 and –1.2%/ms^{-1} with regression coefficients of –0.60 and –0.77 for the results without and with correction for the number of cases involved, respectively. The corresponding intercepts are –4.1 and –1.8%. Based on the slopes the reduction of the wind speed effect by using a windscreen is only about 10%. Note that the reduction of the wind speed effect by using a windscreen is about 50% when the slope is derived between 0 and 4m/s.

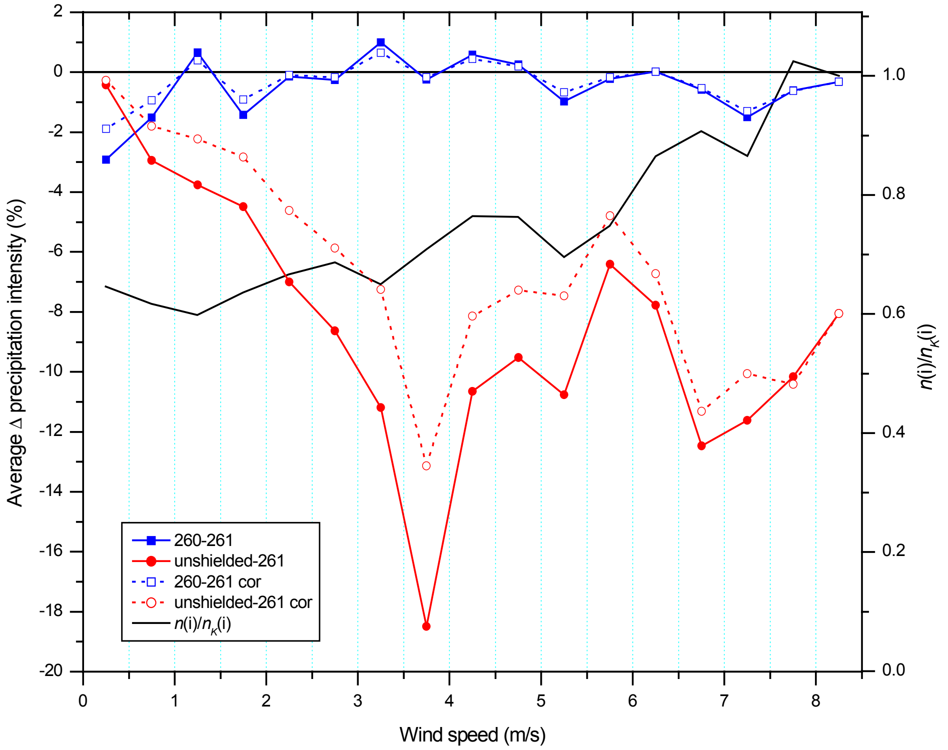

Figure 15: Reconstructed relative differences between the 10-minute precipitation intensity measurements of precipitation gauges as a function of the measured wind speed at 10m. Derived from the data of Kuik (2001) for an unshielded KNMI precipitation gauge on the measurement field and 2 precipitation gauges in the English setup. The reconstructed relative differences are given with and without a correction for the number of cases per wind speed interval.

Another way of comparing the data of Kuik (2001) for an unshielded precipitation gauge with the current results for a precipitation gauge in a wind screen is by applying the wind effect of a KNMI precipitation gauge in a windscreen, given by Figure 14, to the precipitation and wind speed data of 261 for the period January to October 1998. This gave a reduction of –1.8% in the total precipitation amount, which is comparable to the overall wind effect of a precipitation gauge on the measurement field in a windscreen of –1.4% reported in this study. This indicates that for the conditions in 1998 the use of a windscreen would have improved the results of the unshielded precipitation gauge on the measurement field from –5% to –1.8%, i.e. about 65%. However, one has to consider that in addition to the wind conditions, also the character of the precipitation may differ between 1998 and 2000-2001. The precipitation structure parameter *N* for 1998 is 35% with monthly values between 25 and 70%, whereas for 2000-2001 the corresponding values are (cf. Table 3) 40% with a monthly range between 20 and 65%. The precipitation structure parameter is generally smaller for 1998 compared to 2000-2001, hence a smaller wind effect could be expected for 1998. The dependency of the wind effect with precipitation intensity as a measure for the droplet size is not given by Kuik (2001), but will be considered here in section 4.5.

One should also note that another difference between the precipitation gauge on the measurement field discussed by Kuik (2001) and the present study using a windscreen is that the height of the orifice was 60cm instead of 100cm. The difference in wind speed between 60 and 100cm, assuming a logarithmic exposure correction with a roughness length of 0.03m typical for grassland, is about 15%. Hence the wind effect of Kuik (2001) obtained for 60cm at 8m/s should be compared to the results reported here for 100cm at about 7m/s. This reduces the wind effect obtained for the measurements using the windscreen (Figure 14), compared to the wind effect for an unshielded precipitation gauge reported by Kuik (Figure 15). Also, Kuik mentions that the wind speed measurements of 260, which has a 20m mast, are used, but that is not correct. As in the current study, the wind measurements of the 10m mast of 261 were used. Hence the comparison with results of Kuik (2001) indicates that the use of a windscreen reduces the wind effect of a KNMI precipitation gauge placed on the measurement field between about 25 to 70%, but most likely by about 60%.

4.5. Dependency on other variables

In this section the differences between the measured 10-minute precipitation intensities are studied as a function of other variables. The results are affected by the general meteorological situation during the period of the test. This does not mean the general wind conditions, but specifically the wind speed during precipitation as studied in the previous section. Furthermore the type of precipitation as a function of wind speed plays an important role, since the wind effect depends on the fall velocity of precipitation and hence on the type (snow or rain) and on the size or the precipitation particles. The wind effect will be larger for snow compared to rain, but it will also be larger for smaller particles. The influence of droplet size will be investigated by analyzing the results as a function of the precipitation intensity, although this is not a good measure of the droplet size. Furthermore, the results will be checked for a dependency on wind direction, the ambient temperature and the relative humidity.

Figure 16 shows the relative difference between the precipitation intensity measured by 2 precipitation gauges as a function of the precipitation intensity. The precipitation intensity is divided into bins of 0.5mm/h from 0 to 10.5 mm/h according to the intensity measured by 260. Situations with intensities higher than 10.5mm/h are included in the 10.5mm/h bin. The first bin at zero contains the cases where the precipitation gauge of 260 reported precipitation intensities less than 0.05mm/h. Since the other 2 precipitation gauges report generally a higher intensity, if any, the relative difference at the first bin is large and positive. The precipitation intensity bins between 0 and about 3mm/h show negative differences for 260−screen and 261−screen. The behavior of the curves resembles the curves given by Nešpor and Sevruk (1999) obtained by numerical simulations. The differences vary roughly exponentially from −9% at 0.5mm/h to 0% at 3.5mm/h and remain close to zero for higher intensities. Fitting an exponential function of the form:

$$\Delta PI = \Delta_0 + \mathrm{A} \times \exp\left(-\,\mathrm{PI}/\mathrm{B}\right)$$

with PI the precipitation intensity to the curves resulted in 0.42–10.4*exp(–PI/1.11) and 0.05–13.4*exp(–PI/1.05) for screen–260 and screen–261, respectively. For intensities larger than 7mm/h the relative differences show larger variations, probably because the number of cases involved is small. The larger errors at low precipitation events is what could be expected since lower intensities generally have smaller particles and hence are more sensitive to wind field deformations. The relative differences 261–260 are again around +1% and show little dependence with precipitation intensity. At low intensities the difference 261–260 decreases continuously as a result of the binning in intensity intervals, since after selecting a low intensity value of 260 the available intensities of 261 will generally be larger.

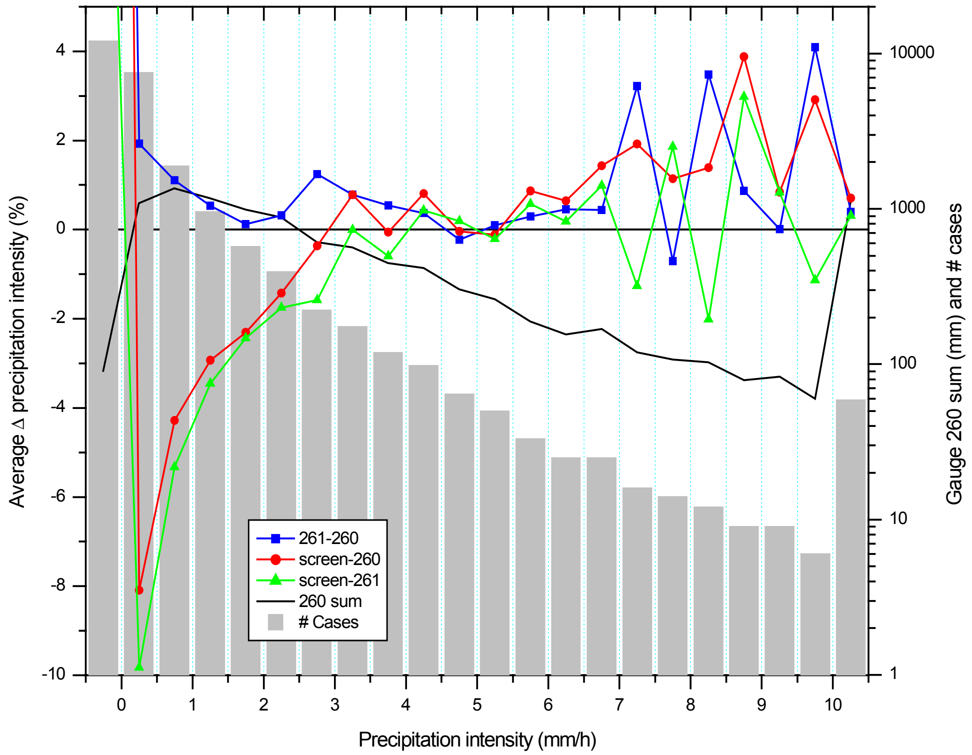

Figure 16: Relative differences between the 10-minute precipitation intensities measured by 2 precipitation gauges as a function of precipitation intensity. The binning in steps of 0.5mm/h is performed on the intensity measured by 260. The first bin contains the cases with intensity less than 0.02mm/h and the highest bin also contains the cases with intensities higher than 10.5mm/h. The number of cases and the precipitation sum of the 260 gauge are also shown per intensity bin.

Next the relative differences are given as a function of the wind direction in Figure 17. The wind direction 0° corresponds to North and 90° to East. The wind direction is the direction the wind is blowing from. The differences 261–260 show hardly any dependence on wind direction. The peaks near 0 and 90 degrees are probably caused by the small amount of numbers involved. In case one English setup would cause a disturbance on the other setup, a similar reversed effect could be expected at the opposite direction. It should be noted that the trees South and West from the measurement field influence the wind measurements performed at 261. However, the effect on the 3 precipitation gauges under consideration will probably be the same. The differences screen–260 and screen–261 are largest for wind from the East and the South. The East corresponds only to a small number of cases. The large differences for the South direction are not exactly in the direction of the highest wind speeds. The largest wind speeds come generally from the Southwest. The optimum of wind speed and precipitation with small intensity probably causes the largest differences to occur for wind direction from the South to Southeast.

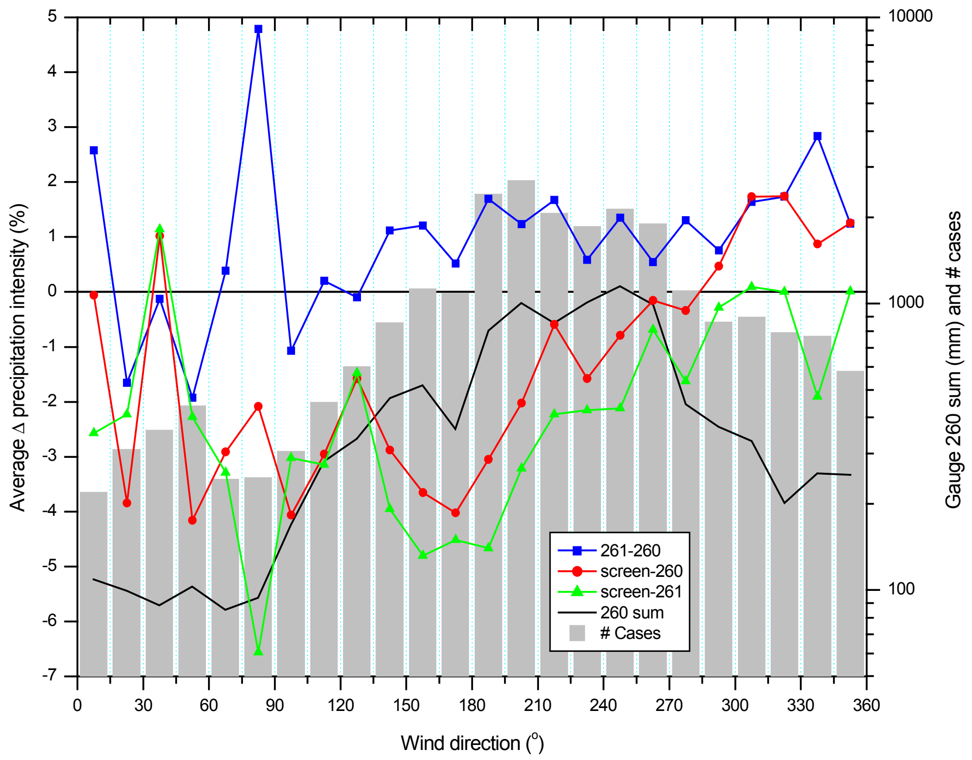

Figure 17: Relative differences between the 10-minute precipitation intensities measured by 2 precipitation gauges as a function of wind direction in steps of 15°. The number of cases and the precipitation sum of the 260 gauge are also shown per wind direction bin.

The relative differences as a function of the ambient temperature are given in Figure 18. The step size of the temperature bins is 2.5ºC. The curve 261–260 shows hardly any dependence on the temperature. The larger differences for temperatures above 20ºC are the result of the limited number of cases and the small amount of precipitation involved. The differences involving screen show the same behavior, except that at temperatures below zero the precipitation amounts for screen are less than those of the other 2 setups. This is probably caused by situations with snow, where the loss due to the wind-induced deformations is particularly large.

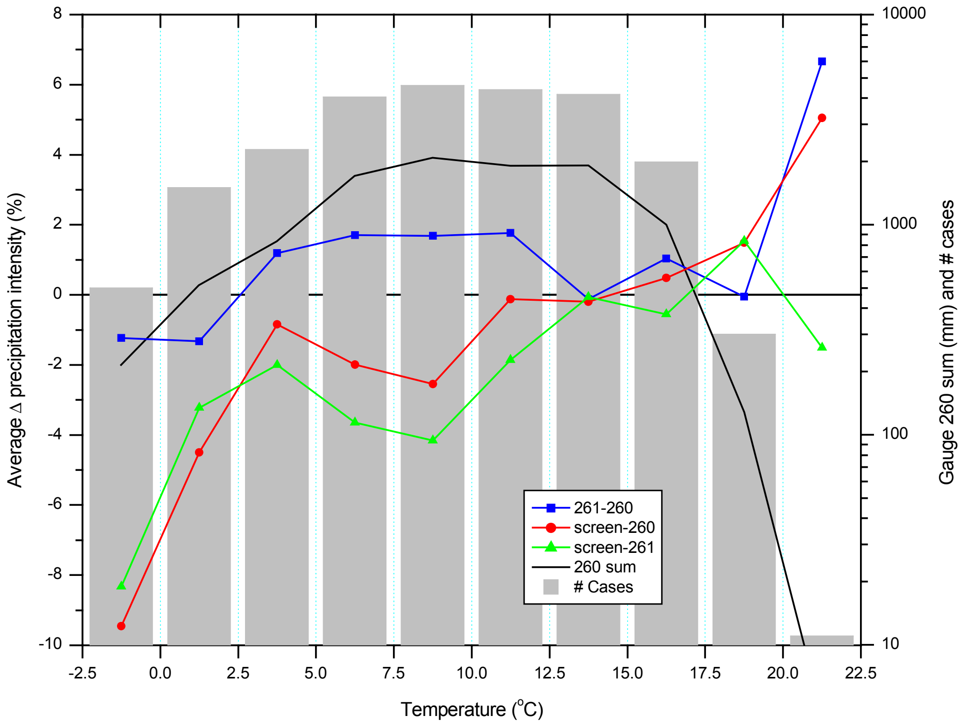

Figure 18: Relative differences between the 10-minute precipitation intensities measured by 2 precipitation gauges as a function of the ambient temperature in steps of 2.5°. The number of cases and the precipitation sum of the 260 gauge are also shown per temperature bin.

Finally, Figure 19 shows the relative differences as a function of the relative humidity in bins of 5%. The curves show hardly any dependence with relative humidity except for relative humidity below 55%. At these relative humidity values the precipitation events are dominated by cases with small intensity. In fact, the precipitation amount in each of the bins below 55% humidity is only about 1mm. The precipitation events involved are mainly cases with very light precipitation and can partly be related to the faulty precipitation reports be the precipitation gauge on bright days. The total number of faulty cases for each of the KNMI gauges is about 5% of the overall number of 10-minute intervals with precipitation reports. Here a faulty case is defined as a situation where one of the three gauges reports precipitation but the other 2 do not report any precipitation in that 10-minute interval, nor, if available, in the previous or next interval. As a result of the faulty cases at low humidity values, the relative differences are large and the trend of 260 with systematically lower values at lower humidity is not realistic.

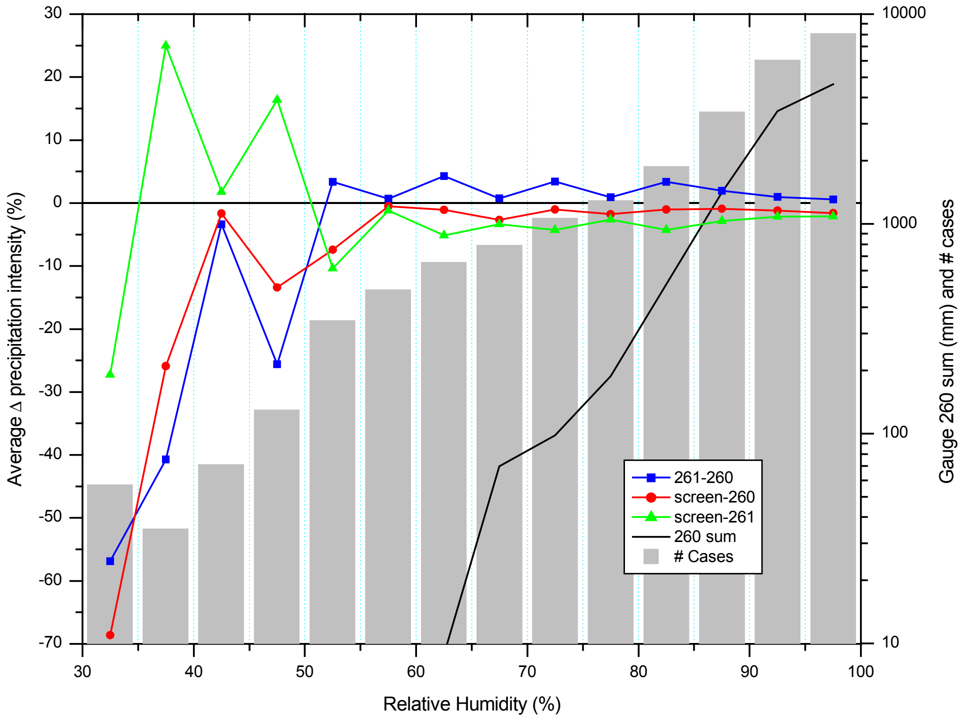

Figure 19: Relative differences between the 10-minute precipitation intensities measured by 2 precipitation gauges as a function of the relative humidity in steps of 5%. The number of cases and the precipitation sum of the 260 gauge are also shown per relative humidity bin.

The number of cases involved makes it difficult to show the differences in a multiple parameter space. The effect of wind speed and precipitation intensity combined is given in Figure 20. For that purpose the range 0 to 7m/s and 0 to 5m/h is considered and a bin width of 1m/s and 1mm/h is used in order to get sufficient cases in each interval. The number of cases is below 100 for intensities above 2mm/h. Figure 20 clearly shows the wind speed effect, which is most pronounced at low precipitation intensities and decreases rapidly with increasing intensity. For intensities above 3mm/h the wind effect is smaller than –2%. The largest wind effect is –14% for intensities below 1mm/h and wind speeds at 10m of 7m/s.

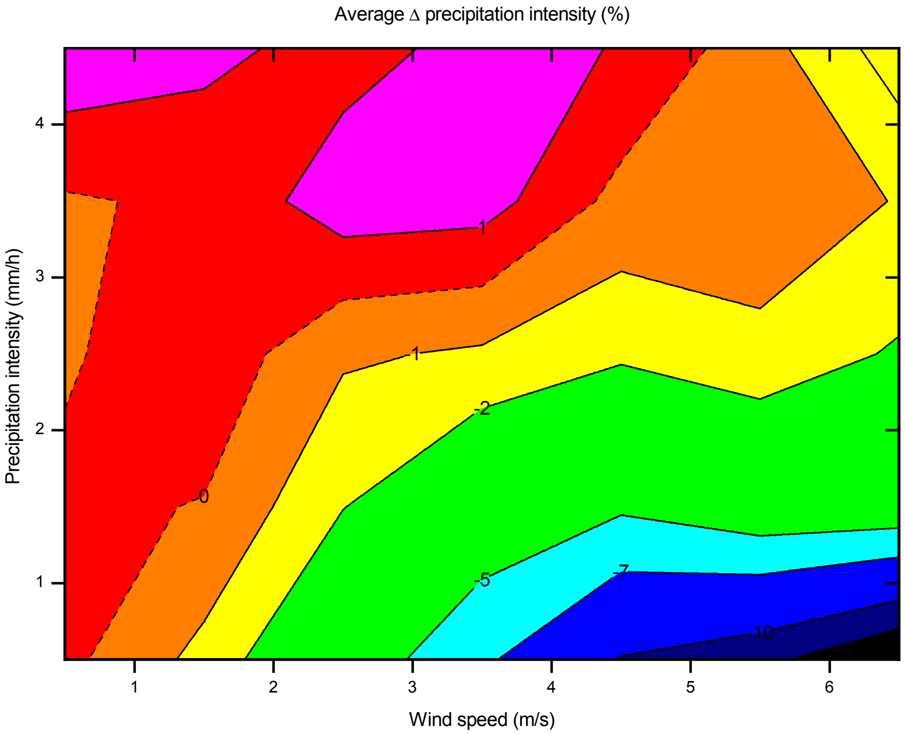

Figure 20: Relative differences between the 10-minute precipitation intensities screen–260 as a function of the measured wind speed at 10m and the precipitation intensity. The bin width is 1m/s and 1mm/h.

5. Comparison using raw data

The results given in section 4 use the filtered 10-minute data according to the rejection criteria (i) to (v) described in section 3.2. The effect of this filtering on the results, in particular the relative differences as a function of wind speed as given by Figure 14, will be considered in this section. For that purpose the data of 2001 will be used. The filtered results for 2000 and 2001 hardly differ, but since most rejections occurred for 2001 the effect of filtering will be largest there. Figure 21 shows the relative differences per wind speed bin for the data of 2001. Wind speed bins above 8m/s are ignored because the number of cases involved is below 10. Table 4 gives the values of some characteristic parameters like the number of intervals considered, the total precipitation amount, the overall differences and the results of linear fits to the wind speed dependence. Case A in the upper left panel of Figure 21 shows the wind speed effect using the data for January to October 2001 and the same filtering as used in section 4. The results in this panel agree well with the ones given in Figure 14, although the results for the higher wind speed bins show some differences. The upper right panel (case B) shows the same results, but now rejecting all inconsistent cases (iii) and (iv), i.e. using a threshold of Cor=0mm/h. The number of cases involved and the corresponding annual precipitation amount reduce (cf. Table 3), but the relative differences and the wind speed effect hardly changes compared to case A where only inconsistencies above 0.1mm/h are removed. The lower left panel (case C) shows the results when no rejections are applied to the data of January to October 2001, except that data for all 3 precipitation gauges needs to be available. This leads to some significant differences between wind speeds of 5 and 6 m/s. In that interval the precipitation intensity of 261 increases compared to the other 2 gauges. The wind speed dependence of the screen results remains, however, nearly the same. Lastly, the lower right panel of Figure 21 (case D) shows the unfiltered results for the period January to December 2001. In the last 2 months the precipitation amounts of 261 are lower. This effect can be observed at almost all wind speed bins, since the curve 261–260 has a negative offset and screen–261 has a positive offset, whereas screen–260 remains roughly the same compared to the lower left panel. Again, the wind speed effect indicated by the slopes of screen–260 and screen–261 are almost not affected.

Table 4: Overview of some characteristic parameters for the precipitation gauges of 260, 261 and screen, their differences, and the wind speed effect for 2001. Considered are 4 different cases of filtering the data.

Parameter	**Case A**	**Case B**	**Case C**	**Case D**
# intervals	39,835	37,070	40,158	50,226
Sum 260 (mm)	739	667	800	1000
Sum 261 (mm)	747	674	801	958
Sum screen (mm)	729	657	787	984
261–260 (mm)	8.7	7.4	1.8	–41.7
screen–260 (mm)	–9.6	–9.5	–13.1	–15.6
screen–261 (mm)	–18.3	–16.9	–14.9	26.1
261–260 (%)	1.1	1.1	0.2	–4.2
screen–260 (%)	–1.3	–1.4	–1.6	–1.6
screen–261 (%)	–2.4	–2.5	–1.9	2.7
261–260 intercept (%)	0.95	0.71	–0.99	–5.52
screen–260 intercept (%)	2.42	2.17	1.14	2.04
screen–261 intercept (%)	1.58	1.59	2.29	8.21
261–260 slope (%/ms^{-1})	0.13	0.18	0.47	0.39
screen–260 slope (%/ms^{-1})	–1.27	–1.31	–1.09	–1.22
screen–261 slope (%/ms^{-1})	–1.38	–1.46	–1.53	–1.70
261–260 regression coefficient	0.43	0.43	0.56	0.47
screen–260 regression coefficient	–0.93	–0.92	–0.87	–0.94
screen–261 regression coefficient	–0.95	–0.92	–0.91	–0.94

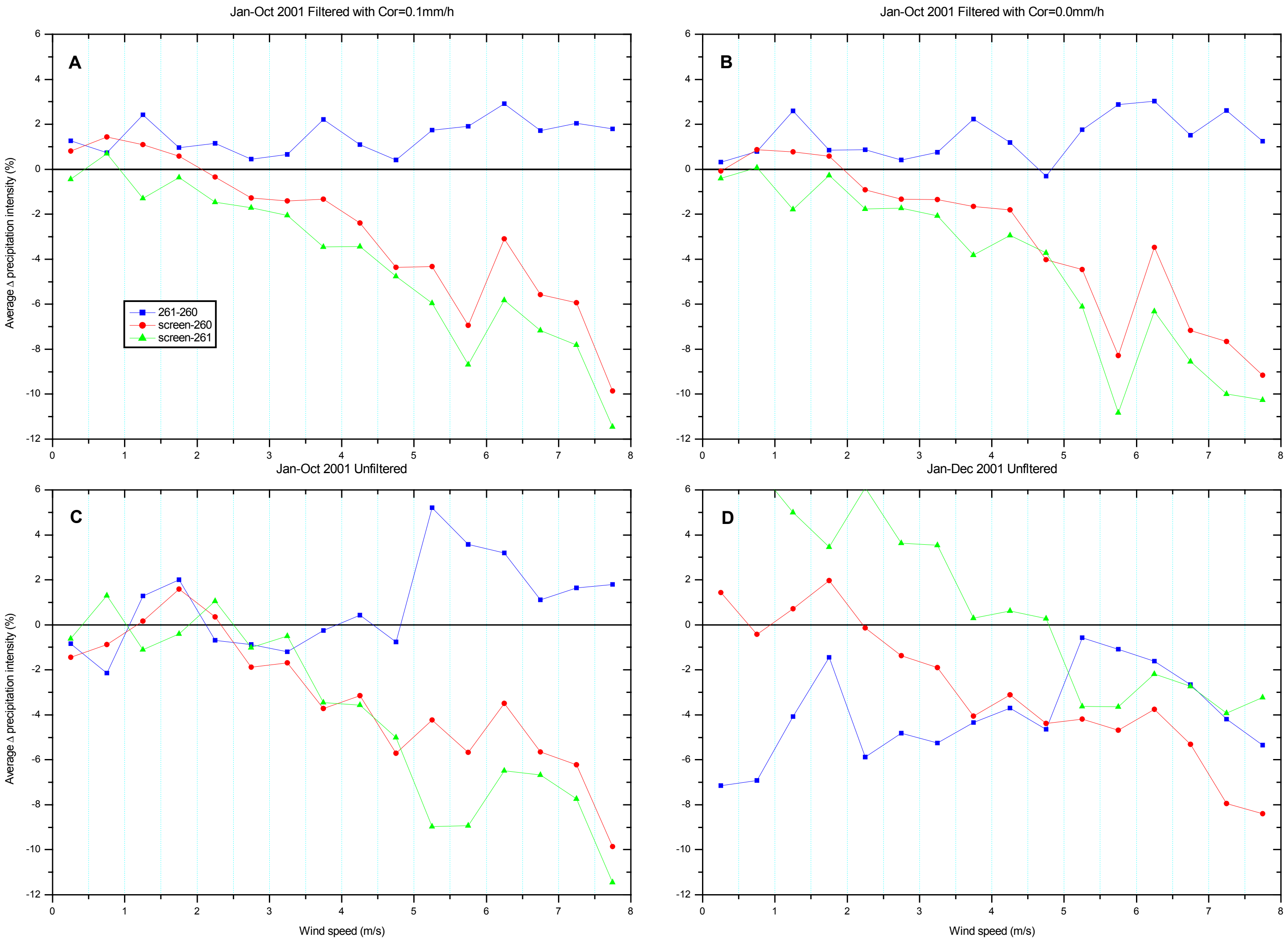

Figure 21: Relative differences between the 10-minute precipitation intensities measured by 2 precipitation gauges as a function of the measured wind speed at 10m in steps of 0.5m/s for cases A to D using different filtering of the data.

6. Conclusions and recommendations

The precipitation measurement obtained form a precipitation gauge placed on the measurement field within a windscreen have been compared with the results obtained with an identical sensor in the so-called English setup. Various random and systematic error sources contribute to the accuracy of the precipitation measurements. In this study the same precipitation gauge is used in 2 different collocated setups in order to investigate the wind effect. Furthermore, 2 identical precipitation gauges in collocated English setups give information on the typical differences caused by other error sources. These differences amount to about 1% of the annual sum with monthly differences with a standard deviation of 1.4% and a maximum deviation up to 4%. As a result of the wind effect the precipitation amount is systematically underestimated. On a yearly basis, for typical meteorological conditions in De Bilt, the reduction is about –1.5% when using a KNMI precipitation gauge on the measurement field within a wind screen. The monthly differences reach values up to –6% in the windy season. The wind effect increases almost linearly with wind speed from zero to about –10% at 8m/s measured at 10m (which corresponds to a wind speed of 5m/s at the gauge rim). The wind effect also depends strongly on the 10-minute averaged precipitation intensity between 0 and 3.5 mm/h. Low intensities generally correspond to smaller droplets which are more influenced by the deformations in the wind field.

The reduction of the wind effect by using a windscreen was difficult to estimate since the previous study for an unshielded precipitation gauge on the measurement field did not report relative numbers for the differences as a function of wind speed. The wind effect for an unshielded KNMI precipitation gauge was –5% during 1998, but this difference depends on the meteorological conditions. Using the wind speed dependence of the wind-induced loss of precipitation for the KNMI precipitation gauge within a windscreen gives a wind effect of –2% for the conditions of 1998. Hence the reduction of the wind effect for a KNMI precipitation gauge on the measurement field by the windscreen is about 60%.

The number of 10-minute intervals reporting precipitation is nearly the same for a precipitation gauge in the English setup and on the measurement field. The setup on the measurement field gives 3% less cases with light precipitation. This does not affect the precipitation amounts significantly. At KNMI the precipitation gauge is also used as a precipitation detector. Hence very small precipitation amount need to be reported by the gauge. This makes the sensor susceptible to faulty reports. In fact, faulty reports of very light precipitation occur sometimes during bright days. In addition, contamination of the precipitation gauge, which is expected to occur more easily for a setup at ground level, may cause faulty reports after the precipitation event has ceased. Furthermore, faulty precipitation detections can occur as a result of melting snow in the collector. During the comparison the precipitation gauges were operated in combination with the Eigenbrodt precipitation detector. Since the precipitation duration, as currently derived from the precipitation gauge by the sensor interface, cannot unambiguously be derived from the 10-minute precipitation intensity, the effect of the windscreen setup on the reported precipitation duration is unknown. However, it is expected that the effect on the precipitation duration will be small.

The precipitation gauge setup on the measurement field within a windscreen has some advantages related to installation and maintenance. Contamination, which is an important source of precipitation gauge failures, will be less when the sensor is placed on the measurement field. The use of a windscreen reduces the so-called wind effect by about 60%, but an annual wind effect of about −1.5% is still present. The accuracy of precipitation measurements using the KNMI precipitation gauge is about 1%. Considering that WMO requires an accuracy of 5% it is acceptable to use the setup with the precipitation gauge placed on the measurement field in a windscreen. The wind effect will cause a systematic underestimation of the precipitation amount, which is about –10% at wind speeds of 8m/s at the precipitation gauge rim. It should however be noted that other factors like wetting and evaporation can also lead to significant systematic errors under certain conditions. The systematic errors caused by the wind effect are much smaller than the random errors that can be observed in the 10-minute measurements. Furthermore other factors, e.g. contamination of a precipitation gauge or sensor failures, can easily give large systematic errors that cannot easily be detected.

Therefore it is recommended to consider the precipitation gauge setup on the measurement field in a windscreen as an acceptable alternative for the operational precipitation gauge setup of KNMI. For climatological purposes correction procedures can be considered that are currently in use worldwide and published by WMO. The characterization of the wind effect as given by Figure 20 can be used for this purpose.

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