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Comparison of automatic and manual precipitation networks in the Netherlands

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Foreword

KNMI operates two networks for in-situ precipitation measurements in the Netherlands. The first is an automatic network (AN) of 32 stations, where precipitation is measured continuously with automatic rain gauges. This network almost coincides with the network of automatic weather stations (AWS). The second is a dense manual network (MN) of about 325 stations, where voluntary observers measure 24-hour precipitation sums once per day at 0800 UTC. The AN has a high temporal resolution (currently 1-min). This is important for the study of short-duration extremes, nowcasting and, increasingly, for real-time radar calibration. The MN has a long continuity of instruments and methods and is important for climate monitoring and hydrological research and applications.

Today there is a growing need to expand AN, mainly to improve real time radar calibration for hydrological purposes. On the other hand, there is a need to continue MN for climate monitoring purposes. To obtain an optimal combination of AN and MN it is important to compare both networks and to understand differences in precipitation measurements obtained with both networks. This report describes this comparison and may serve as background information for the design of the precipitation networks in the Netherlands and elsewhere.

1 Introduction

1.1 Problem description

Like many other meteorological institutes in the world, KNMI operates two precipitation networks side by side: an automatic network (AN) and a manual network (MN). Traditionally, MNs have been used as reference networks providing daily precipitation sums, while ANs have been used to obtain precipitation intensity with high temporal resolution. Following former WMO recommendations, KNMI corrected the AN precipitation such that their 0800-0800 UTC precipitation sums (on an hourly basis) agreed with the 0800 UTC measurement of the manual rain gauges positioned next to the automatic gauge¹. In 1981 this practice was abandoned, because there was an increase in the number of automatic rain gauges and these gauges were at positions (e.g. airfields) where manual observations were not feasible.

It is well known that precipitation measurements are affected by losses (WMO, 1984) resulting in undercatch. The most important loss results from wind induced errors. These may amount to about 10% for rainfall and 50% for snow. Other losses are e.g. due to wetting² of internal walls of the collector and the container when it is emptied and due to evaporation³. For automatic raingauges additional losses may occur due to e.g. the operation of a heating element at low temperatures. It is estimated that MN in the Netherlands measures on average about 5% too little precipitation (wind and wetting error), which equals about 50 mm/year (Braak, 1945; Warmerdam, 1981). It is further observed that AN measures about 5% less precipitation than MN (Overeem, 2009) resulting in a total undercatch of about 10%. WMO (2008) states in its requirements an achievable measurement uncertainty for daily precipitation sums of 5% or 0.1 mm (whatever the largest absolute amount). It is clear that AN does not meet this requirement.

Internationally, there is a trend to expand ANs and to decrease, or even to dismantle, MNs. Given the large error of ANs, however, the suitability of these networks for climate monitoring purposes may be questioned. Detailed comparisons are therefore needed between MNs and ANs. Although we have a rough indication of the differences between AN and MN for the Netherlands, a detailed comparison is still lacking.

1.2 Scope and objectives

The main objective of this study is to quantify and understand the differences in precipitation amounts between AN and MN in the Netherlands. The study is further meant to support (changes in) the design of those networks in the Netherlands and elsewhere and to guide possible instrumental improvements.

The comparison is restricted to the 2001-2013 period and MN is used as a reference. Although MN is not an absolute reference, it is used here as such. Inhomogeneities due to e.g. stations relocations are not quantified, they are considered here as an integral part of the uncertainty in the precipitation of the network.

¹ Until 1970 the measuring time was 7:40 UTC.

² The wetting error occurs when precipitation adheres to the inside walls of the gauge and evaporates (or sublimates) without being recorded.

³ The evaporation error is generally small or negligible for gauges with protected containers, such as those used in the present study.

Chapter 2 describes both networks and defines the methodology. Chapter 3 presents results of the comparison and an exploration of factors that may affect the differences between AN and MN . Chapters 4 and 5 present a discussion, a summary and conclusions and recommendations.

2 Data and methods

In this chapter we first describe the two precipitation networks AN and MN. The layout of the networks, the metadata and the instruments are presented. A selection of 31 station pairs is used for the comparison as described in the methods section. Metadata about relocations is presented in Appendix A.

2.1 Data

2.1.1 *Automatic Network*

Figure 1 shows the location of the automatic weather stations (AWS) and the manual rainfall stations in the Netherlands. The rain gauges of AN are installed at 32 of the 35 AWS locations in the Netherlands. They are mostly situated in open areas. Precipitation is measured using the so-called KNMI rain gauge (see e.g. Wauben, 2004, for a drawing and details). This electric gauge is of a floating type and measures precipitation with a time resolution of 12 seconds. The funnel and reservoir are heated for temperatures $\leq 4^{\circ}\text{C}$ in order to melt solid precipitation. The gauge has a calibration interval of 14 months. Currently, precipitation values are archived at 1-min, 10-min and 1-hour time steps. The hourly data is validated by the validation division and is used in this research. The hourly data is publically available via the KNMI website.

The majority of the automatic rain gauges are placed in a so-called English setup (see Figure 2). The setup consists of a pit surrounded by a circular wall with a diameter of 3 m and a height of 40 cm. 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 soil 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. This reduces the errors induced by wind field deformations due to the presence of the sensor itself. The slope and surroundings are covered with grass. The English setup is intended to have no wind-induced loss. A 1-year comparison study of Braak (1945), however, showed a 2.7% annual loss of the English setup (with the largest losses in the winter half-year) with respect to a reference setup with no wind error (comparable to the WMO reference gauge). The study took place in De Voorst, the Netherlands, and was performed with two identical manual gauges measured each morning at 8:00 local time.

The English setup is slowly abandoned and today almost half of the rain gauges are now situated in an Ott windscreen (see Figure 3). The Ott screen has a height and diameter of 1 m. For the stations that are currently equipped with an Ott screen, Table 1 presents the introduction dates. The reason for the transition to Ott screens is that the English setup is rather costly to build and requires additional maintenance. At some locations problems occur due to high ground water levels and/or poor drainage. The English setup is also sensitive to debris, since leaves, grass and sand are easily blown into the precipitation gauge and may cause instrument failures. Wauben (2004) compared the English set-up with the set-up using an Ott screen in De Bilt and found an annual mean (extra) loss of the Ott screen, compared to the English set-up, of 1.5%. In the windy season the differences may be up to 6%.

2.1.2 *Manual Network*

The MN is maintained since 1850. The number of rain gauges gradually increased in the period 1850–1950 and an almost constant network size since 1946. Currently there are about 325 rain gauges (see Figure 1 for the station locations) with an average distance of 9.9 km. The gauges are mostly located in sheltered locations



Figure 1: Map of automatic weather stations (red dots) and manual precipitation stations (black dots) in the Netherlands (situation of December 2010).

(gardens of houses, near farms, etc.). Figure 4 shows an example of a rain gauge. The rain gauges are operated by voluntary observers. Each morning the 24 h (0800–0800 UTC) amount of precipitation is measured and since 1995 digitally transferred to KNMI by telephone.

Little is known about the site and type and position of the rain gauges used in the 19th century. In 1903, a standardization was carried out with the introduction of a standard rain gauge. The rim of this rain gauge was at 1.50 m above ground level and the orifice area was 400 cm². Owing to an extensive study of Braak (1945) on



Figure 2: KNMI automatic rain gauge in English set-up.



Figure 3: KNMI automatic rain gauge in an Ott screen.



Figure 4: Example of a manual rain gauge (with the rim at 0.4 m).

Table 1: Automatic weather stations with a KNMI automatic rain gauge in an Ott windscreen.

No	Station	Station no.	Ott screen since
1	Wijk aan Zee	257	2 May 2001
2	Cabauw	348	27 October 2001*
3	Schiphol	240	2 March 2004
4	Stavoren	267	6 May 2005
5	Maastricht	380	7 October 2005
6	Rotterdam	344	27 September 2006
7	De Kooy	235	26 April 2007
8	Herwijnen	356	8 March 2008**
9	De Bilt	260	25 September 2008
10	Eelde	280	18 May 2009
11	Valkenburg	210	2 September 2009
12	Westdorpe	319	24 November 2011
13	Leeuwarden	270	13 September 2012
14	Hupsel	283	24 October 2013
15	Heino	278	30 October 2013
16	Marknesse	273	17 April 2014

*Exact date is given date \pm 11 days

**Exact date is given date \pm 4 days

the wind-induced error of precipitation measurements, KNMI started lowering the height of the rain gauges to 0.40 m above ground level in 1946. Braak made an estimate of the wind-induced error for all precipitation stations in the Netherlands, which was on average 5.5% for precipitation measurements at 1.50 m. In January 1947, about 65% of the gauges had been lowered to the height of 0.40 m. The remainder of the gauges was gradually lowered in the next 6 years. Reduction of the measurement height to 0.40 m about halved the wind-induced error (Buishand and Velds, 1980). The precipitation data were not corrected for this error. From 1962 onwards KNMI introduced a new type of rain gauge with an orifice area of 200 cm² while the height of the rim remained at 0.40 m above ground level. The effect of this change on the measured precipitation amounts is probably negligible⁴.

Probably since 1953 the daily precipitation measurements have been subjected to extensive quality control on a routine basis. Suspect values are traced by comparing the daily measurements with those from neighboring stations and could often be recovered after consulting the observer. In addition, multi-day precipitation amounts are distributed across individual days using measurements of neighboring stations and, more recently, radar rainfall. Before 1953 the location of the precipitation stations was inspected infrequently and metadata for that period is scarce. From 1953 onwards, stations are visited on average once every 2 years by station inspectors and reports of the visits have been archived at KNMI. The data is publically available via the KNMI website.

⁴ Several comparisons have been undertaken of the 200 cm² and 400 cm² gauges. The results are, however, not unequivocal. Denkema (1980 and 1981) presented the results of parallel measurements in De Bilt and the Foppenpolder in Maasland. His results indicated that the 200 cm² gauge measures about 1% less precipitation than the 400 cm² gauge. In contrast, Warmerdam (1981) described a parallel measurement near Hupsel and found up to 3% more precipitation for the 200 cm² gauge compared to the 400 cm² gauge. Earlier research, mentioned by Braak (1945), indicated that precipitation amount increases with the magnitude of the surface area of the gauge, supporting the findings of Denkema.

2.2 Methodology

The precipitation data has been used as it is distributed to the public and used in KNMI products. This means that no corrections have been made e.g. for station relocations and instrumental changes like the gradual change from English setup to the use of the Ott screen for AN.

2.2.1 Selection of period and station pairs

We considered the 13-year period 2001-2013. In this period most of the stations have complete data. To compare AN and MN, we selected stations pairs consisting of an AN station and the most nearby MN station. The automatic weather stations IJmuiden, Vlieland and Woensdrecht in Figure 1 have no automatic rain gauge and for Wijk aan Zee the first 4 months are missing. Those four stations are not included in the analysis. Figure 5 shows the locations of the 31 selected AN locations. Table 2 presents the basic metadata of the 31 station pairs including the distance between the stations. Information about relocations is presented in Appendix A. Relocations usually cause a change in environment of the gauge and thus the wind error.



Figure 5: Positions of the 31 automatic rain gauges that have been compared with the most nearby manual rain gauge (see Table 2). The strikethrough stations have no automatic rain gauge or have not enough data.

Table 2: Metadata of the 31 station pairs used in the study (beginning of 2014). The x-y coordinates are for the Dutch coordinate system with its origin 120 km southeast of Paris (x positive to the East and y positive to the North). For privacy reasons x-y coordinates are rounded to the nearest integer. The distances between the stations are based on the non-rounded values.

Automatic network (AN)				Manual Network (MN)				Dist.(km)
Stat	Name	x (km)	y (km)	Stat	Name	x (km)	y (km)	
210	Valkenburg	089	465	474	Valkenburg	090	465	0.44
235	De Kooy	114	549	25	De Kooy	115	547	2.21
240	Schiphol	114	481	458	Aalsmeer	113	475	5.89
249	Berkhout	127	517	222	Hoorn	131	519	3.65
251	Hoorn (Tersch.)	152	601	26	Formerum	149	600	2.79
260	De Bilt	141	457	550	De Bilt	141	457	0.23
267	Stavoren	155	546	80	Stavoren	153	544	2.23
269	Lelystad	164	497	369	Lelystad	165	497	0.39
270	Leeuwarden	180	582	85	Leeuwarden	178	581	1.88
273	Marknesse	189	524	317	Marknesse	187	523	2.29
275	Deelen	189	453	591	Deelen	190	454	1.44
277	Lauwersoog	209	603	171	Anjum	205	600	5.06
278	Heino	214	494	340	Heino	214	495	0.55
279	Hoogeveen	235	530	332	Hoogeveen	229	525	8.10
280	Eelde	235	571	161	Eelde	234	571	1.09
283	Hupsel	242	454	688	Hupsel	241	454	1.18
286	Nieuw Beerta	273	580	143	Finsterwolde	269	581	3.42
290	Twenthe	258	477	670	Twenthe	259	476	2.31
310	Vlissingen	030	385	733	Vlissingen	032	387	2.23
319	Westdorpe	048	361	770	Westdorpe	048	360	0.72
323	Wilhelminadorp	051	394	749	Wilhelminapolder	051	395	0.86
330	Hoek v Holland	068	445	477	Hoek v Holland	070	445	1.98
344	Rotterdam	090	442	473	R'dam-W-Haven	089	434	7.59
348	Cabauw	123	442	561	Benschop	124	446	3.56
350	Gilze-Rijen	124	397	843	Gilze-Rijen	123	397	1.16
356	Herwijnen	138	430	830	Herwijnen	138	426	3.68
370	Eindhoven	154	385	919	Eindhoven	152	386	2.61
375	Volkel	177	408	920	Volkel	176	406	1.91
377	Ell	181	356	970	Stramproy	178	355	3.26
380	Maastricht	181	324	973	Beek	185	326	4.04
391	Arcen	211	391	923	Arcen	211	389	1.91

2.2.2

Calculation of derived variables

Differences in precipitation between AN and MN are likely affected by meteorological variables like wind speed, rainfall intensity (related to drop size), and precipitation type (snow or rain). To study these dependencies, the hourly data of AN stations was aggregated to 0800–0800 UTC daily data. In this way, these daily values corresponded with the 0800–0800 UTC daily precipitation amounts of MN.

For AN, hourly precipitation amount is available with 0.1 mm resolution and hourly precipitation duration with 0.1 hour resolution. For each day we calculated for the AN stations: (a) precipitation sum, (b) precipitation duration, (c) mean precipitation intensity on rain hours from (a) and (b), (d) mean wind speed on rain hours, and (e) mean temperature on rain hours.

For wind speed the mean hourly values have been used as measured at AN stations (usually at 10 m height). Temperature is measured at 1.5 m.

Depending on the situation, precipitation differences between AN and MN may be described by both percentage differences (PD) and absolute differences (AD). PD is defined as:

$$PD = 100 \frac{P_{AN} - P_{MN}}{P_{MN}}$$

where P_{AN} is the precipitation of the AN and P_{MN} of the MN. AD is defined as:

$$AD = P_{AN} - P_{MN}$$

The results are presented using MN as a reference.

3 Results

In this chapter we first compare the annual and seasonal mean precipitation differences between AN and MN. Second, we discuss the difference in the number of wet days of both networks. Third, the probability distributions of the daily precipitation amounts are compared to study the effect of precipitation amount on the differences between AN and MN. Fourth, we explore the effects of temperature, precipitation intensity and wind speed on the network differences. Finally, the effect of rounding errors is discussed.

3.1 Annual mean precipitation differences

Figure 6 shows the time series of the mean annual precipitation amounts of AN and MN. As expected, the mean precipitation amounts for MN are larger than those for AN. For AN the mean annual precipitation for the 2001-2013 period equals 812.8 mm and for MN 868.4 mm. The mean difference is thus 55.5 mm.

Figure 7 shows the annual percentage difference (PD) between AN and MN of the precipitation amounts shown in Figure 6. The annual PD varies between -5.0% in 2007 and -9.2% in 2013. The mean PD equals -6.4%. Testing the series for homogeneity using the Buishand-test⁵ (Buishand, 1982), shows a statistically significant (5% level) step change of 2% in 2009. In the period 2001-2008 the mean PD equals -5.6% and from 2009-2013 -7.6%.

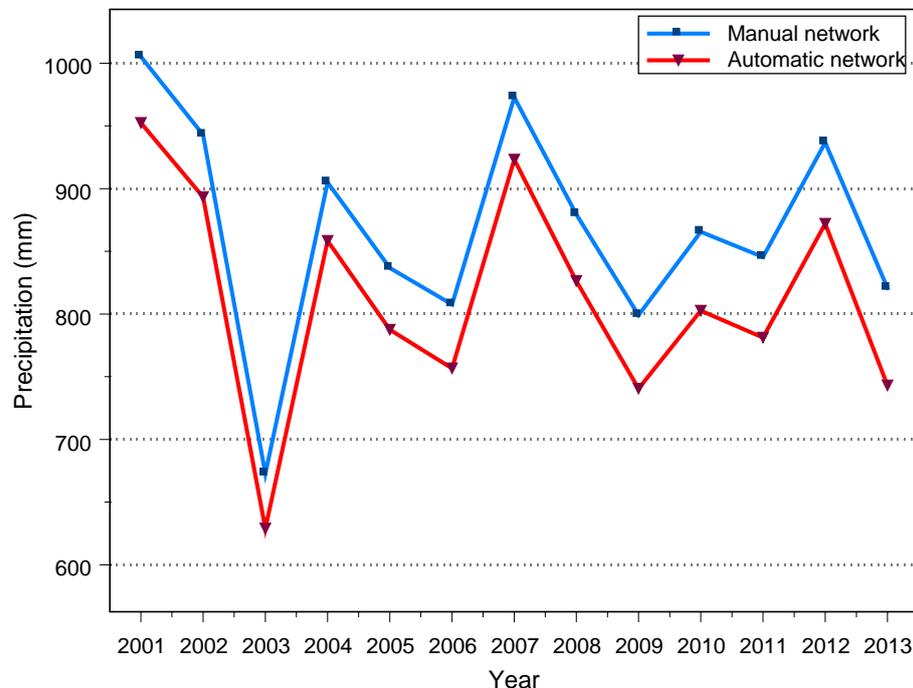


Figure 6: Mean annual precipitation amounts for the AN and the MN in the period 2001-2013 (average of the amounts of the 31 stations defined in Table 2).

⁵ The version used here is the so-called cumulative deviations test. It uses the maximum of the absolute values of the adjusted partial sums.

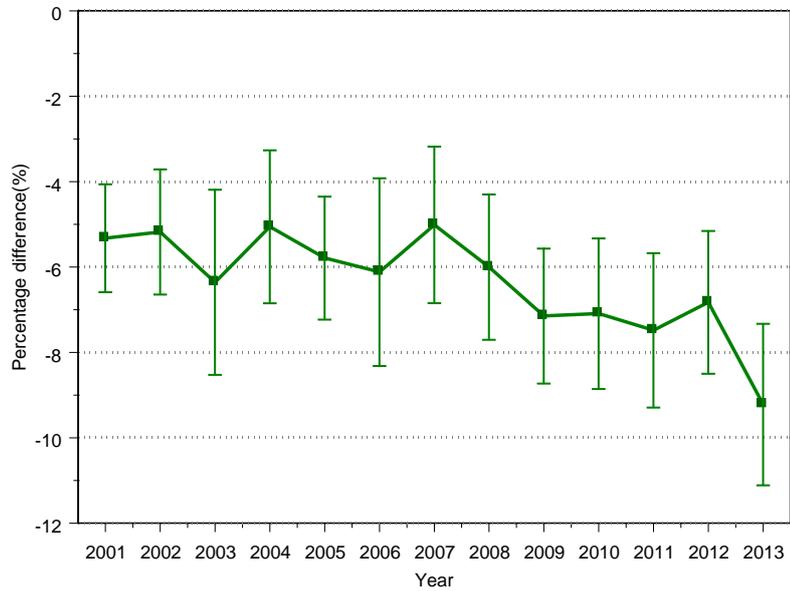


Figure 7: Percentage differences between the annual precipitation amounts of the AN and the MN in the 2001-2013 period. The error bars give the $2 \times SE$ values.

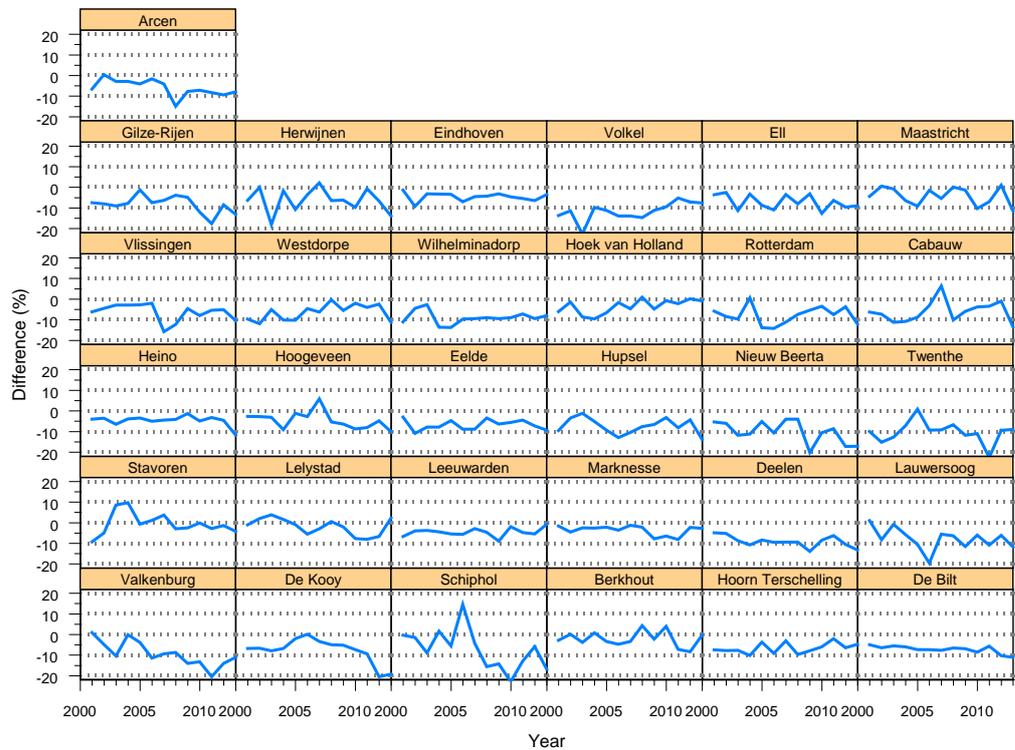


Figure 8: Percentage differences between the annual precipitation amounts of the AN and the MN in the 2001-2013 period for the individual stations.

The annual PD for all 31 station pairs separately is shown in Figure 8. The figure shows that there are large differences between the pairs. The changes in the individual series cannot easily be linked to stations relocations or the introduction of the Ott screen. There is, however, a weak correlation ($r = 0.4$) between the

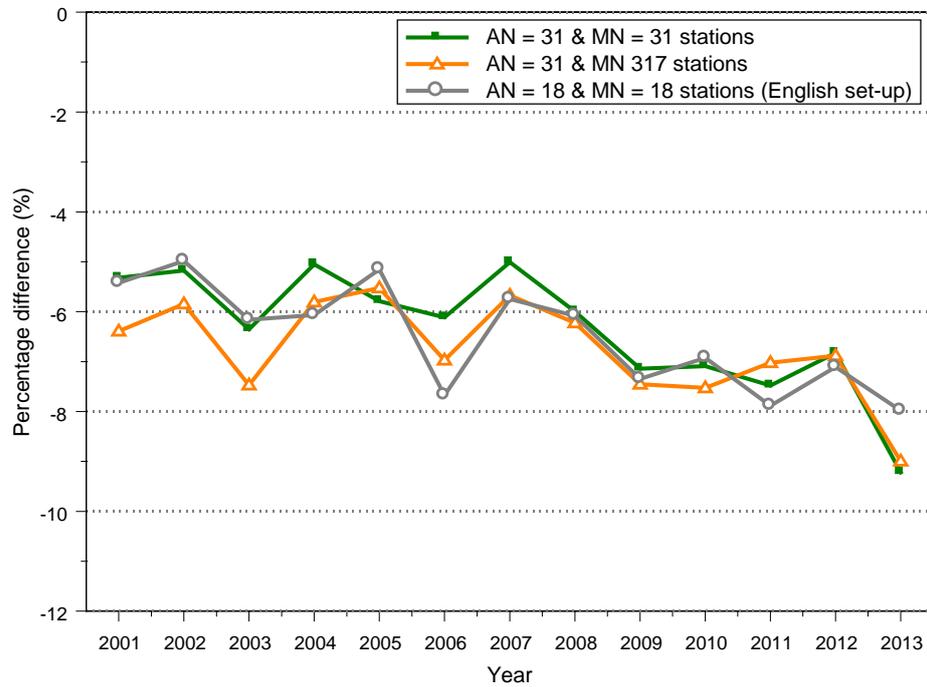


Figure 9: Percentage differences between the annual precipitation amounts of the AN and the MN in the 2001-2013 period for (a) the 31 station pairs (as in Figure 7), (b) with all available MN stations, and (c) using only station pairs with English set-up.

interannual variability of PD of each station pair and the distance between the AN station and the corresponding MN station.

It is of interest to know the reason for the observed step change in Figure 7. Figure 9 therefore shows two extra curves in addition to the one presented in Figure 7. The orange curve shows PD for the case where the annual mean values for the MN are calculated from all 317 manual stations with complete data. The shape of the curve is similar to the original curve for the 31 stations pairs. The step change in 2009 is still statistically significant and amounts to 1.4% which is slightly smaller than for the 31 stations pairs. Apparently, the step change is not sensitive to the selection of MN stations.

The gray curve in Figure 9 shows PD for the case where only the 18 stations are considered that have an English set-up throughout the 2001-2013 period (see Table 1)⁶. Again the shape of the curve is similar to the original curve for the 31 stations pairs and the step change in 2009 is statistically significant and amounts 1.5%. Obviously, the step change is also not caused by the change of the English set-up to the set-up with an Ott screen. This could somewhat be expected because Table 1 shows that the change of the English set-up to the Ott screen happens gradually and not stepwise.

Another reason that could explain the step change is instrumental failure of the automatic rain gauges. It is reported that an increasing number of instruments has problems with the heating device (within the calibration term of 14 months). The

⁶ For the stations Hupsel and Heino we made an exception because they have less than 3 months of data with an Ott screen in the period of interest.

heating device should turn of automatically at temperatures > 4°C but this not always occurs. This results in extra wetting losses.

As an alternative to the step change, the trend in the data in Figure 7 can also be explained by a linear trend, where the noise around the fit results from natural variation. In that case, there is a highly significant linear trend of -0.246%/year ($t=-4.4$). The trend (not shown) gives a change of the annual mean PD between 2001 and 2013 of -4.88 to -7.84%, a change of 3.0%.

3.2 Seasonal mean precipitation differences

Figure 10 shows for AN and MN the annual cycle of monthly mean precipitation. The figure shows that there is a strong seasonal variation with the smallest precipitation

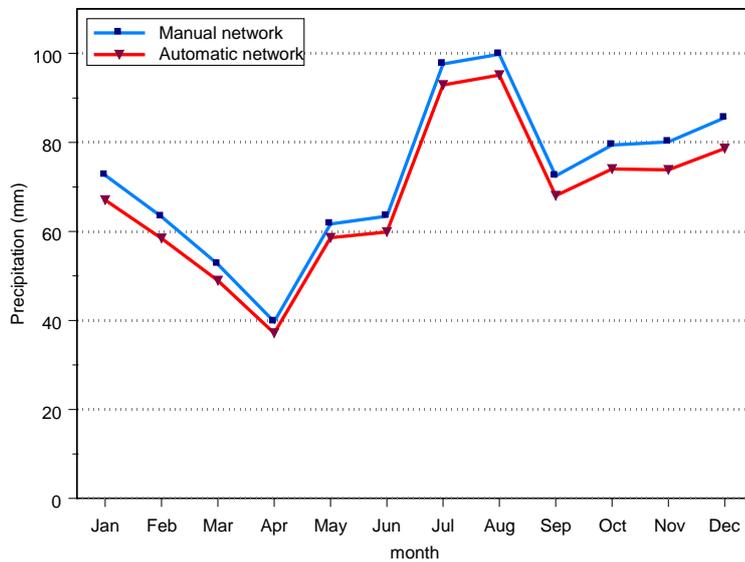


Figure 10: Mean monthly precipitation amounts for the AN and the MN in the period 2001-2013 (average of the amounts of the 31 stations defined in Table 2).

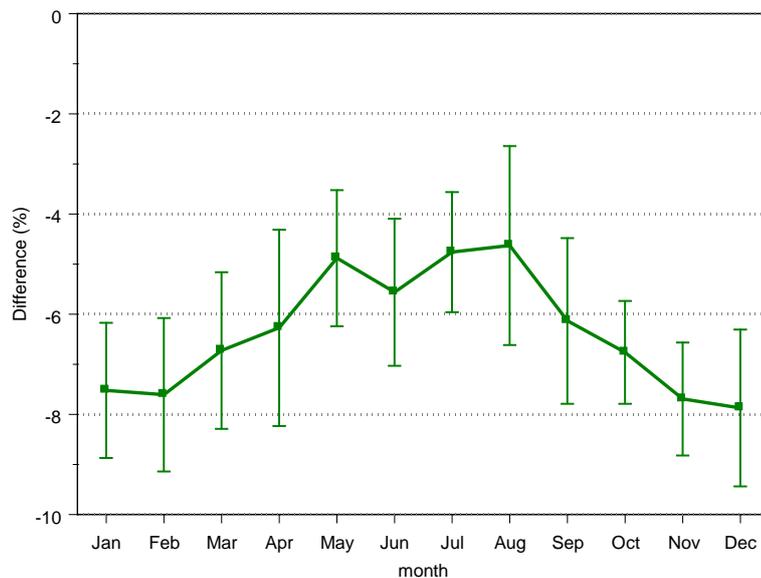


Figure 11: Percentage differences between the monthly precipitation amounts of the AN and the MN in the 2001-2013 period. The error bars give the $2 \times SE$ values.

amounts in April (≈ 40 mm) and the largest in July-August (≈ 100 mm). In all months the mean precipitation amounts for MN are larger than those for AN.

PD in Figure 11 shows a clear seasonal cycle and ranges between -7.7 in winter (DJF) and -5.0% in summer (JJA).

Differences between rain gauges are often seasonally dependent because of e.g. the seasonal dependence of wind speed and precipitation intensity. Here the operation of the heating element in winter may also contribute to the observed seasonal differences. In the remainder of the chapter this will be discussed further.

3.3 Differences in number of wet days

The number of wet days is an important variable in e.g. climate change studies. Changes in measurement systems may affect this variable. Figure 12 shows PD of the number of wet days as a function of the wet-day threshold (0.1, 0.2, ..., 1.5 mm). For each threshold, PD was calculated per year and averaged per station. Thereafter the mean of the 31 station averages and its standard error (SE) were calculated. As expected, AN has less wet days than MN. For low thresholds (< 0.3 mm) the SE of PD is large. For thresholds ≥ 0.3 mm the SE remains almost constant and the mean PD equals about -4%.

Figure 13 shows the annual cycle of PD for the average number of wet days for the 0.8 mm threshold. The annual mean number of wet days for this threshold equals 144 and the monthly mean varies between 8.7 (April) and 14.9 (December) (using the MN data). Figure 13 shows a clear seasonal cycle with PD ranging between -5.6% in winter (DJF) and -3.0% in summer (JJA). There is thus a clear difference in the number of wet days of AN and MN, which may be the result of only small absolute precipitation differences on days with relatively small precipitation amounts.

A detailed look at the number of days with a precipitation amount of 0.1 mm reveals that manual observers have some difficulty in measuring such small daily amounts

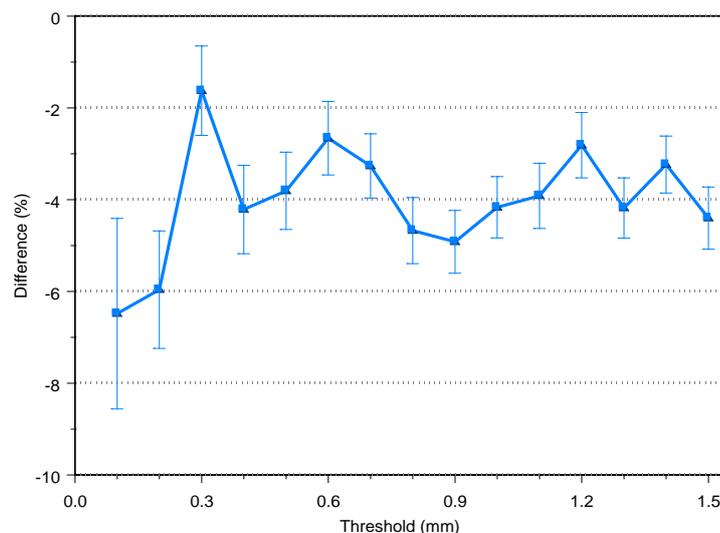


Figure 12: Percentage differences between the mean number of wet days of the AN and the MN as a function of the wet-day threshold in the 2001-2013 period. The error bars give the $2 \times SE$ values.

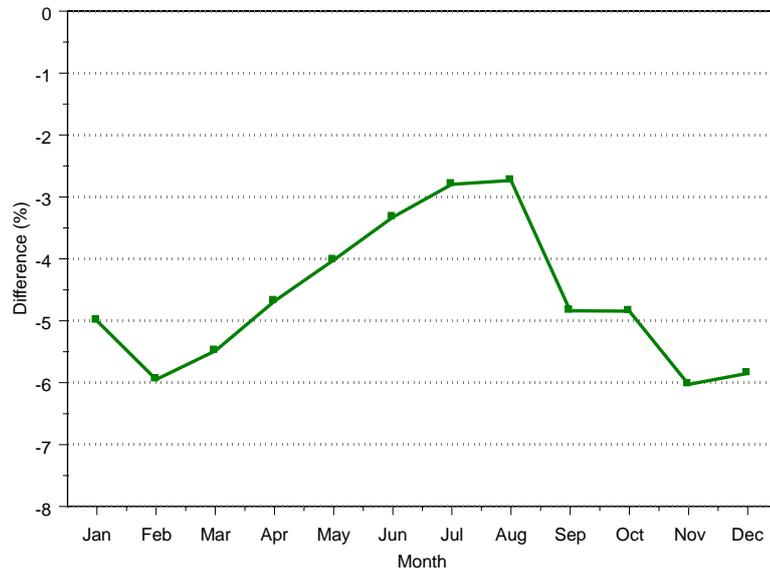


Figure13: Percentage differences between the average monthly number of wet days of the AN and the MN in the 2001-2013 period for a wet-day threshold of 0.8 mm.

objectively. AN stations measure on average 12.1 days/year with 0.1 mm amounts with a spatial standard deviation (SSD) of 0.99 days/year. The SSD remains almost constant for higher thresholds. In contrast, the observers at the MN station measure on average 14.6 days/year with 0.1 mm amounts with a much larger SSD of 8.68 days/year.

For higher thresholds, SSD decreases rapidly and for thresholds > 0.5 mm it becomes almost equal to the SSD of the AN. For the complete manual network (317 stations) the annual mean number of days with 0.1 mm precipitation ranges between 0 and 44 without a clear spatial pattern. It seems that the measurement of small precipitation amounts (< 0.5 mm/day) by the MN observers could be improved.

The underestimation of the number of wet days by AN with respect to MN is a potential inhomogeneity that limits the interchangeability of AN and MN stations.

3.4 Probability distribution of daily amounts

It is of interest to compare the probability distributions of the daily precipitation amounts. Comparing the percentiles of these distributions gives the relationship between the magnitude of the daily amounts and PD and AD.

As an example, Figure 14 shows the percentiles of daily precipitation amounts of the manual and automatic gauge in De Bilt. All daily values are considered. The figure starts with the 56th percentile because lower percentiles are zero or too small to give meaningful results. The figure shows that for De Bilt the percentiles of the manual gauge are always larger than those of the automatic gauge. For the automatic and manual gauges, e.g. the 56th percentile equals 0.3 and 0.5 mm, respectively, yielding a PD of 40% for that percentile.

Figure 15 shows PD between the percentiles of the automatic and manual gauge in De Bilt. PD increases nonlinearly with increasing percentile and ranges between about -36% for the 56th percentile and -3% for the 98th percentile (values on the

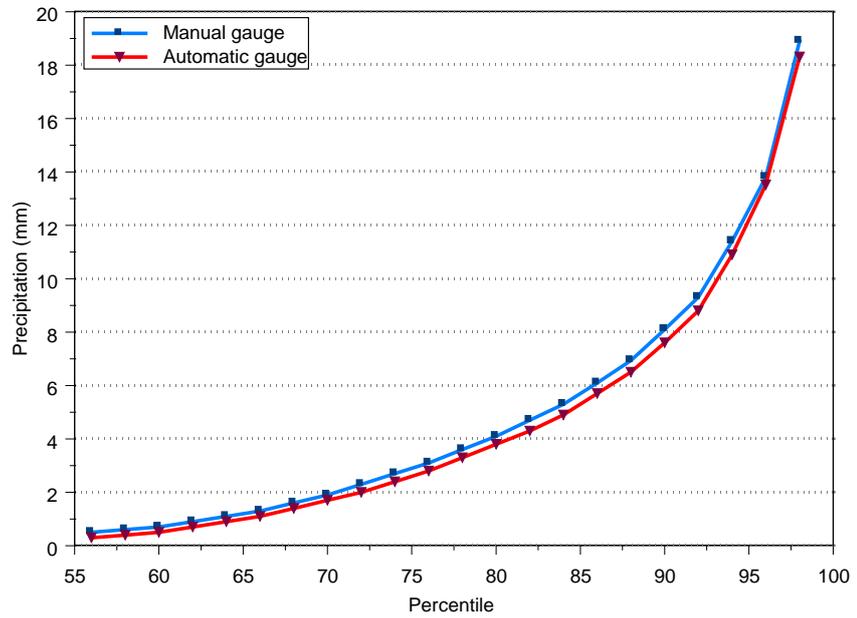


Figure 14: Percentiles of daily precipitation amounts of De Bilt (2001-2013) for the manual and automatic gauge.

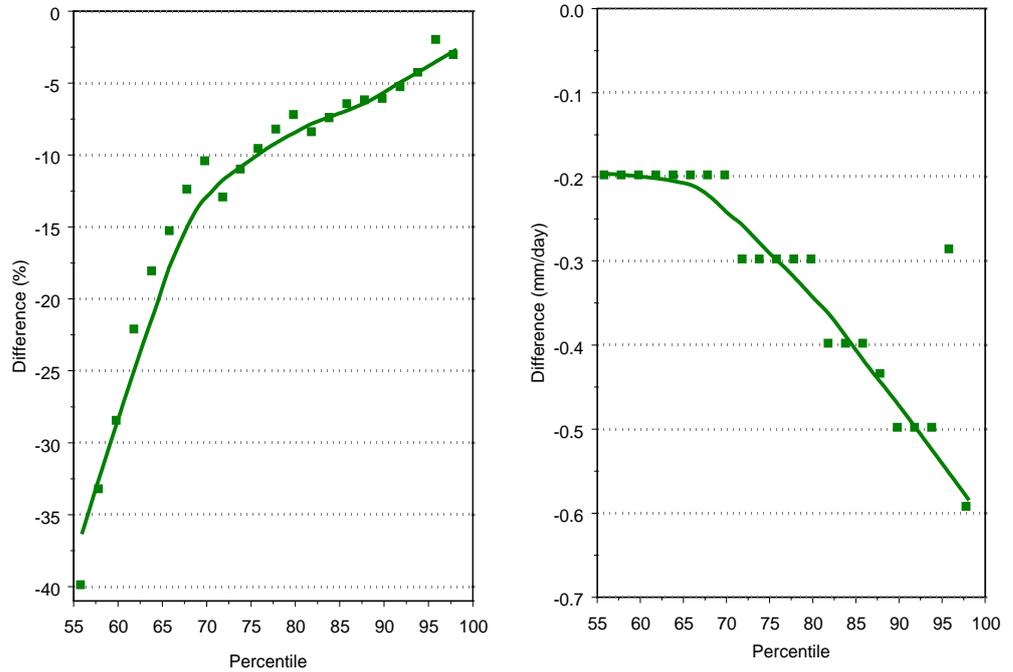


Figure 15: Differences between percentiles of daily precipitation amounts of the automatic and manual gauge in De Bilt (2001-2013). The smooth line represents a loess smooth (Cleveland, 1979). The left figure shows the percentage difference and the right one the absolute difference in mm/day.

smooth line). AD decreases about linearly with increasing percentile and range between -0.2 mm/day for the 56th percentile and -0.6 mm/day for the 98th percentile.

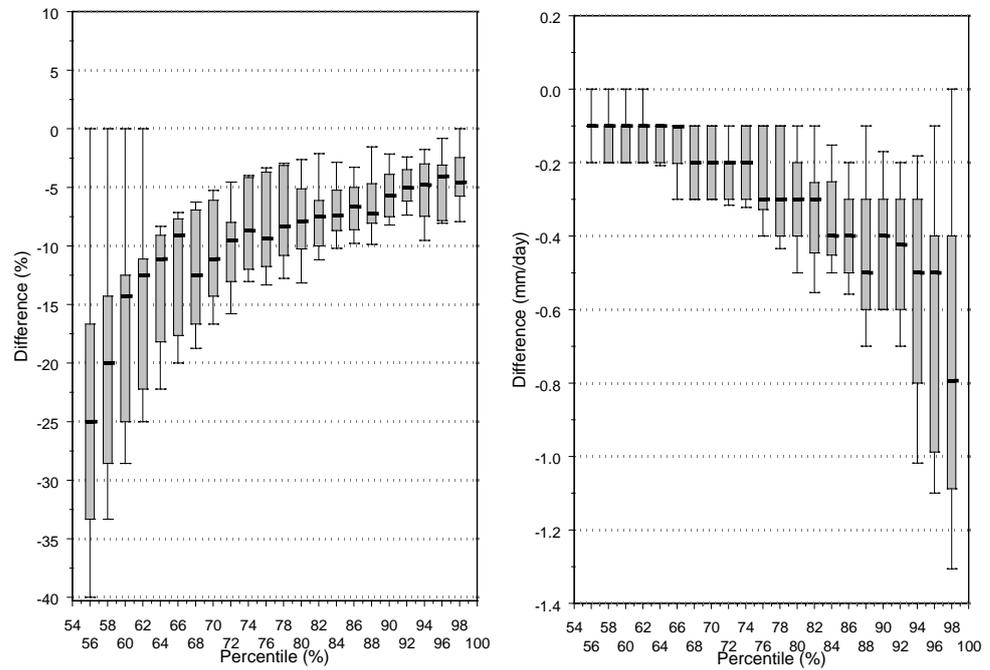


Figure 16: Boxplot of differences between percentiles of daily precipitation amounts of AN and MN stations (2001-2013). Each box represents the differences of the 31 station pairs. The left figure shows the percentage difference and the right one the absolute difference in mm/day. Here and in subsequent figures, each box is bounded by the 25th and 75th percentile and the whiskers extent to the 5th and 95th percentile and the bold dashed line in each box is the median. Note that here the percentiles on the x-axis have a different meaning than those of the boxplot.

Figure 16 shows boxplots of PD and AD for different percentiles, where each box summarizes the values of the 31 station pairs. For the small percentiles, there is a large variation between PD of stations pairs while for the AD this occurs for the large percentiles. The former is probably partly related to the difficulties of MN observers to objectively measure small amounts, while the latter is related to the local nature of extreme precipitation events (especially in summer). The median values show the same behavior as the results for De Bilt in Figure 15. The median PD increases nonlinearly with increasing percentile and ranges between about -25% for the 56th percentile and -5% for the 98th percentile. As for De Bilt, AD decreases about linearly with increasing percentile and ranges between about -0.1 mm/day for the 56th percentile and -0.8 mm/day for the 98th percentile.

PDs between the annual maximum daily rainfall amounts are shown in Figure 17. The figure shows a large variation between the station pairs. The median PD values for each year are, however, almost always negative and vary between -6.8% (2012) and 2.8% (2005). On average, the annual maxima of AN are 3.2% smaller than those of MN. AD (not shown) equals on average -0.9 mm/day.

The probability distributions of AN and MN stations are thus clearly different. The results show that there is not a straightforward relation that translates the one network into the other.

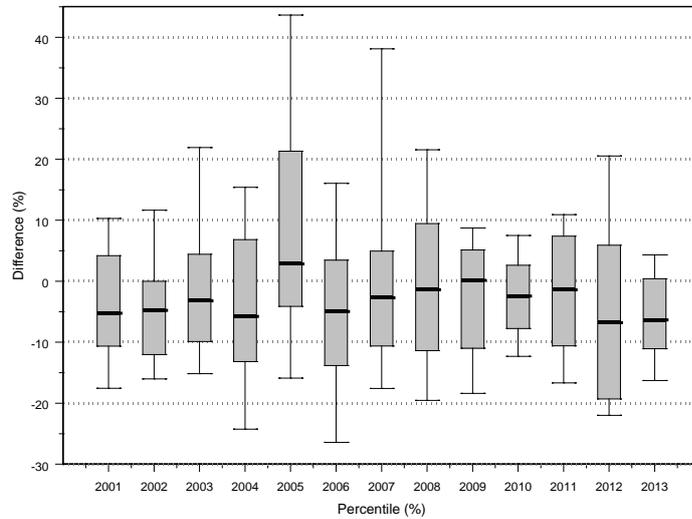


Figure 17: Boxplot of percentage differences between annual maximum daily precipitation amounts of AN and MN stations (2001-2013). Each box represents the percentage differences of the 31 station pairs. The bold dash in each box represents the median.

3.5 Effect of weather variables on precipitation differences

3.5.1 Temperature

Figure 18 shows the relationship of PD and AD with temperature (T). For each day, T represents the mean T on hours with precipitation > 0 mm. T-categories were defined using cut points at 0,1,2,...,20°C. PD and AD were then calculated for each station pair and T-category. Thereafter, the mean T, the station mean PD and AD and their $2 \times SE$ values were calculated for each T-category.

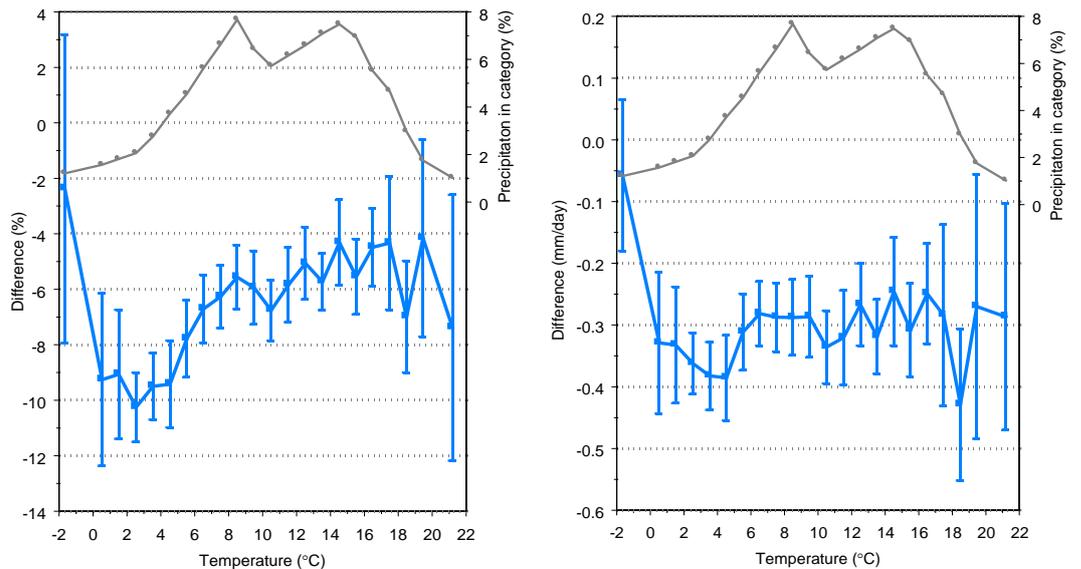


Figure 18: Differences between the mean precipitation amounts of the AN and the MN as a function of temperature in the 2001-2013 period. The error bars give the $2 \times SE$ values. The gray line gives the % of total precipitation in a category. The left figure shows the percentage difference and the right one the absolute difference in mm/day.

For $T > 7^{\circ}\text{C}$ the figure shows an almost constant PD of about -5% with increasing SE towards the higher end of the T-range. For $T \leq 7^{\circ}\text{C}$ PD becomes more negative with decreasing T. The SE increases towards the lower end of the T range. Note that for snow ($T < 0^{\circ}\text{C}$), PD is closest to zero (although it has a large SE).

The large negative values of PD for $T \leq 7^{\circ}\text{C}$, down to about -10% for $T=2.5^{\circ}\text{C}$, may partly be caused by the seasonality of meteorological factors that affect precipitation errors. Examples of such factors are wind speed and precipitation intensity. However, the strong change of PD for T between 4 and 7° suggest an instrumental reason as well. The most likely reason is the heating of the automatic rain gauge. The AD are relatively large between 0 and 7°C. The reason that for snow PD and AD are closest to zero, may be that snow that is melted in the automatic gauges (by the heating element) will be measured, whereas snow in manual rain gauges may partly blow out of the gauge before the once daily measurements. Apparently, when compared to MN, this partly compensates for the effect of the heating device at AN stations.

Although the heating device of the KNMI automatic rain gauge would only be needed for $T < 1^{\circ}\text{C}$ it is designed to operate for $T \leq 4^{\circ}\text{C}$. For $T < 2^{\circ}\text{C}$ the heating is constant and between 2 and 4°C it decreases linearly to zero. In practice the heating device may sometimes also operate for T between 4 and 7°C (Bijma, 2008). The heating may thus cause relatively large amounts of precipitation to evaporate from the funnel wall for $T < 7^{\circ}\text{C}$, increasing the wetting error. Long lasting precipitation event are likely to be most affected.

3.5.2 *Precipitation intensity*

Precipitation intensity (P_{int}) may be an important factor influencing the precipitation differences between AN and MN. The drop size determines to a large extent P_{int} and, consequently, the potential wind error. P_{in} may also affect the potential wetting error, being larger for small P_{int} .

We calculated P_{int} for each AN station and for each day as the daily precipitation amount divided by the daily rainfall duration (yielding P_{int} in mm/hour). For each day we calculated an average daily P_{int} for the Netherlands as a whole from the 31 automatic stations (for each day using only the stations with $P_{\text{int}} > 0$). These daily values have been used to create P_{int} categories. P_{int} can thus be considered as the average precipitation intensity for the Netherlands (for the stations where precipitation occurred).

Figure 19 shows the relationship of PD and AD with P_{int} . P_{int} -categories were defined using cut points at 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.6, 2.0, 2.5, 3.0, 5.0 mm/hour. PD and AD were then calculated for each station and P_{int} -category. Thereafter, the mean P_{int} , the station mean PD and AD and the $2 \times \text{SE}$ values were calculated for each P_{int} -category.

The figure shows a nonlinear relationship of PD with P_{int} . For large values of P_{int} (> 3 mm/hour), PD stabilizes around -2.5%. PD is strongest negative for small values of P_{int} (i.e. long precipitation duration for the same amount of precipitation). The graph for AD shows that AD becomes stronger negative with increasing P_{int} up to about $P_{\text{int}} = 2.0$ mm/hour. For $P_{\text{int}} > 2.0$ mm/hour AD fluctuates around -0.3 mm/day with large standard errors.

3.5.3 *Wind speed*

Figure 20 shows the relationship of PD and AD with wind speed (FH). For each day, FH was calculated from AN stations as the mean wind speed on hours with

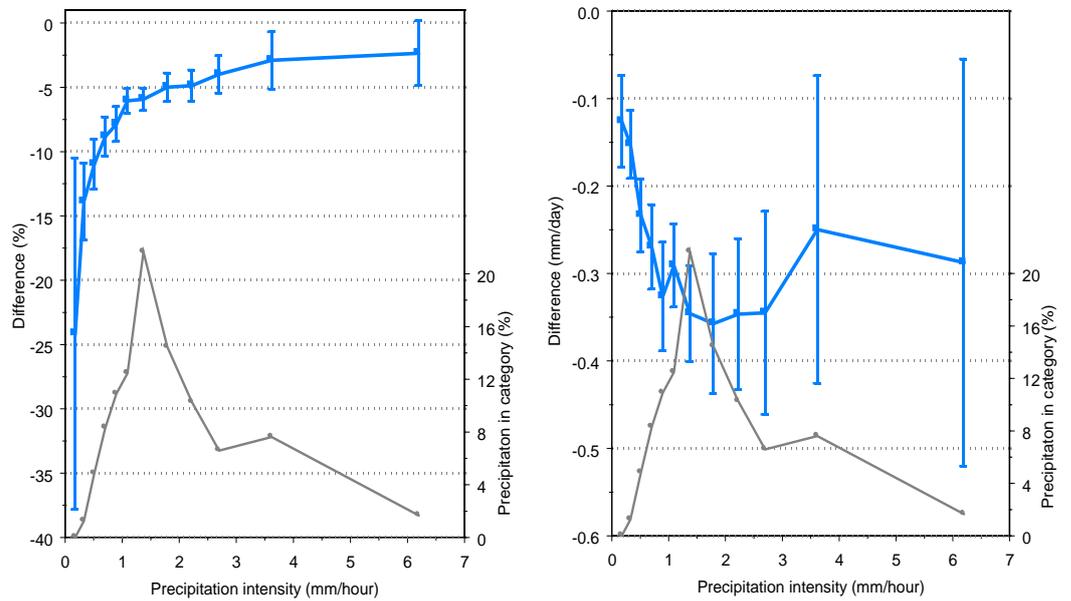


Figure 19: Differences between the mean precipitation amounts of the AN and the MN as a function of precipitation intensity in the 2001-2013 period. The error bars give the $2 \times SE$ values. The gray line gives the % of total precipitation in a category. The left figure shows the percentage difference and the right one the absolute difference in mm/day.

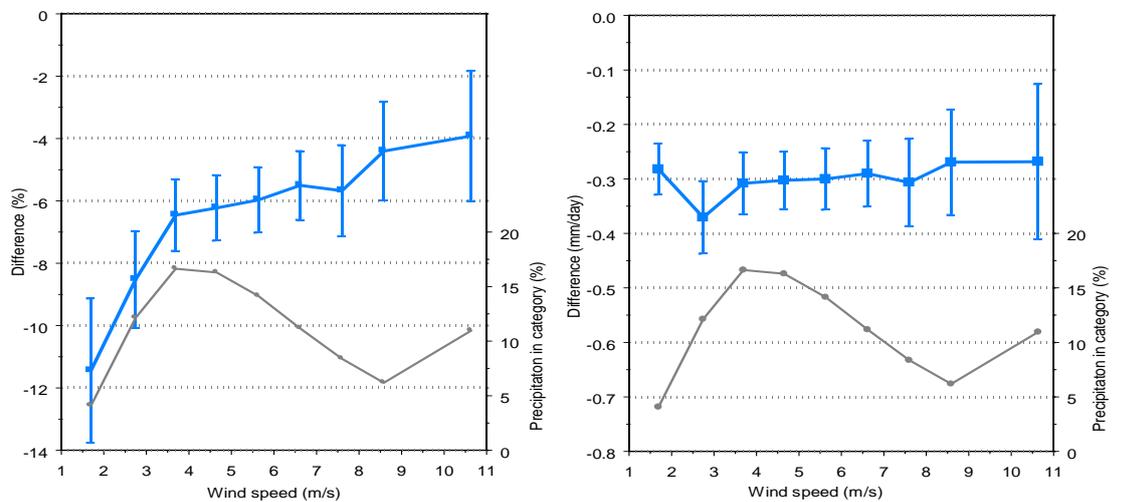


Figure 20: Differences between the mean precipitation amounts of the AN and the MN as a function of wind speed in the 2001-2013 period. The error bars give the $2 \times SE$ values. The gray line gives the % of total precipitation in a category. The left figure shows the percentage difference the right the absolute difference in mm/day.

precipitation > 0 mm. FH-categories were defined using cut points at 2,3,...,9 m/s. PD and AD were then calculated for each station and FH-category. For each FH-category the mean FH, the station mean PD and AD and the $2 \times SE$ values were calculated.

The figure shows a relatively constant PD of -6 to -4% for FH \geq 4 m/s. For FH < 4 m/s, PD decreases to about -11%. The gray line shows that most of the

precipitation is the range where $-8 \leq PD \leq -5\%$. The values for AD show an almost constant difference of -0.3 mm/day for all values of FH.

In general, wind induced errors are the most important reason for differences in precipitation amounts between rain gauges. Here it seems that, on average, the effect of FH is small or similar for AN and MN. Apparently, FH is not the main explaining factor for PD and AD.

3.5.4

Combined effects

Figure 21 explores the relationship of PD and AD with T for 15 combinations of P_{int} and FH (as presented at the top of each panel). PD and AD were calculated for each P_{int} and FH combination without distinguishing between stations. The $2 \times SE$ values were not calculated here. P_{int} increases from left to right and FH from top to bottom.

As expected, the largest negative PDs are found for small P_{int} while FH has only a small effect. Also the relationship with T (as shown in Figure 18) is most evident for small P_{int} . PD becomes almost zero at high FH, especially for $P_{int} > 1.6$ mm/hour. For $P_{int} > 1.6$ mm/hour, there is no clear effect of FH on the PD-T relationship. Note that for $P_{int} > 3.0$ mm/hour, PD for the low temperatures are missing. This is a result of the strong annual cycle of P_{int} (mean P_{int} in DJF equals 0.76 mm/hour and in JJA 2.02 mm/hour). Note also that for $T < 0^\circ\text{C}$ (snow), PD mainly depends on FH, with PD ranging from negative for $FH \leq 4.0$ m/s to strongly positive for $FH > 8.0$ m/s. The latter may be caused by the effect of snow blown out of the manual gauges. This effect is stronger at large wind speeds. The lower graph shows that AD is mostly between -0.4 and 0.0 mm/day. Again the effect of snow for $FH > 8.0$ m/s is clearly visible.

The results so far, suggest that precipitation amount and P_{int} are important factors for explaining the precipitation differences between AN and MN. Figure 22 shows AD as a function of precipitation amount for several P_{int} categories for both winter (DJF) and summer (JJA). Precipitation amount is defined here as the mean of the daily values of the AN and MN gauge for each station pair. The figure shows some interesting facts. In DJF AD becomes stronger negative with increasing precipitation amount and decreasing P_{int} . AD can be as large as about -1.8 mm/day for the category with the largest precipitation amounts and the lowest P_{int} values. In general AD becomes closer to zero with decreasing precipitation amount and increasing P_{int} . The graph for JJA shows the same pattern but the magnitude of AD is only about half that of the DJF graph and the relationship of AD with P_{int} is not as obvious as for DJF.

The large difference between the DJF and JJA graphs in Figure 22 might (partly) be explained by the operation of the heating device. For the same precipitation amount, precipitation duration increases with decreasing values of P_{int} . Increased duration of precipitation implies that the funnel wall remains wet for longer periods, increasing the wetting error by the artificial heating of the heating device. In JJA the heating device does not operate and cannot explain the negative AD values. It might be that the undercatch of AN with respect to MN in JJA is related to an increased wetting error for AN. AN stations are positioned in open areas whereas MN stations are in sheltered locations. Consequently, wind speeds are larger and exposure time to direct sun light is longer at AN stations compared to MN stations, resulting in larger wetting errors. This undercatch becomes larger with increased precipitation duration.

3.6

Effect of rounding errors

A possible source of error in AN data may be the rounding of hourly precipitation values. The validated hourly data are rounded to one decimal and distributed to the public as -1 values for hours with precipitation > 0 and < 0.05 mm (trace precipitation). For practical purposes (like calculating the daily amounts in AN), the

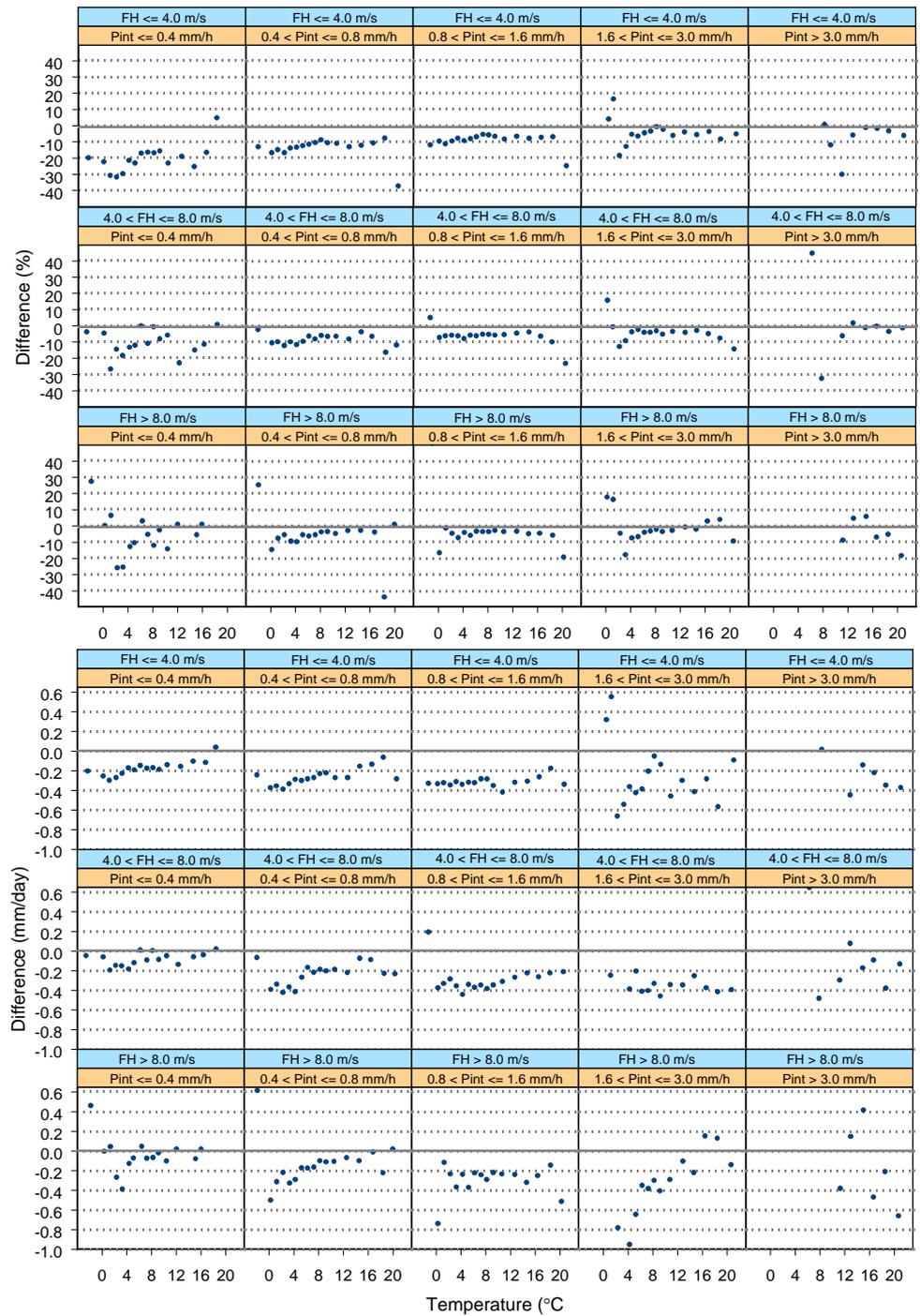


Figure 21: Differences between the mean precipitation amounts of the AN and the MN as a function of temperature in the 2001-2013 period for 5 categories of precipitation intensity (Pint) and 3 categories of wind speed (FH). The gray line presents the zero difference and is drawn as a reference. The top figure shows the percentage difference the lower the absolute difference in mm/day.

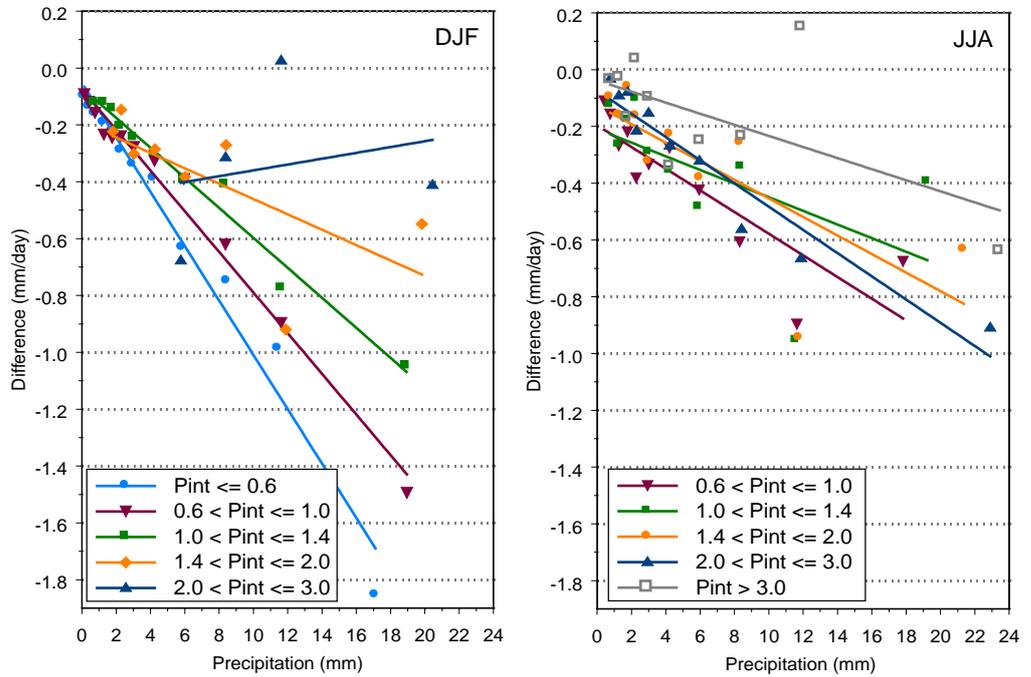


Figure 22: Absolute differences between the mean precipitation amounts of the AN and the MN as a function of precipitation amount in the 2001-2013 period for 5 categories of precipitation intensity (Pint) for winter (DJF) and summer (JJA). The straight lines are least-squares fits.

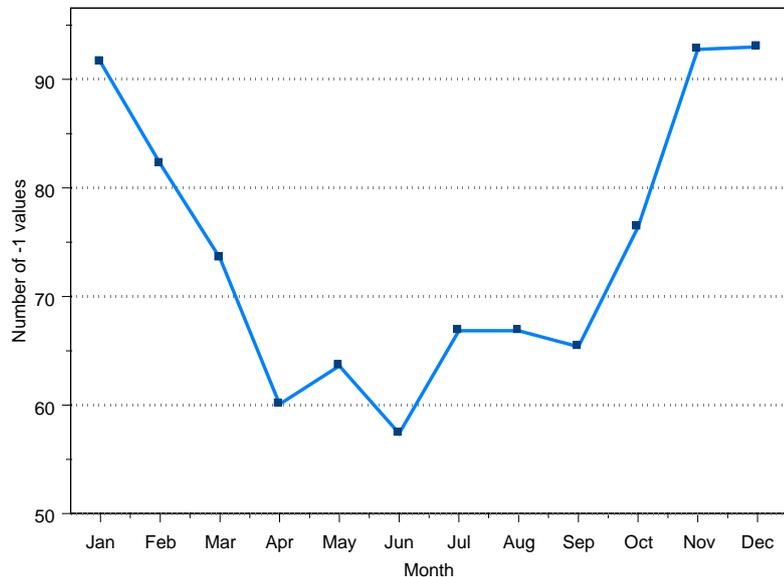


Figure 23: Mean monthly number of -1 values (precipitation < 0.05 mm) in the hourly precipitation data of De Bilt (2001-2013).

-1 values are set to zero. For the present study it is of interest to know the magnitude of the error introduced by the rounding.

Figure 23 shows the seasonal cycle of the number of -1 values for De Bilt. The annual number of -1 values in the 2001-2013 period (not shown) varies between

730 (2003) and 1064 (2001) without any visible trend. The mean annual number of -1 values equals 890.

For the De Bilt we used the non-rounded 10-min data (not operationally available) for the 2011-2013 period to estimate the effect of rounding. From these values we calculated non-rounded hourly precipitation amounts and compared these with the published hourly amounts (after removing missing and suspect values). There is an average error of 0.007 mm per -1 value. This means $890 \times 0.007 = 6.2$ mm/year is missing because of the rounding. The average annual precipitation from the automatic rain gauge in De Bilt equals 859 mm, so the error due to rounding equals 0.72%.

If we consider the non-rounded values for all hours, instead of only the -1 values, only 4.1 mm/year is missing, reducing the error due to rounding to 0.43%.

The magnitude of the error introduced by rounding is thus small but not negligible. It can easily be accounted for by postponing the rounding and allowing more digits in the database.

4 Discussion

The results in this report for the 2001-2013 period show that AN measures about 5-8% less precipitation than MN. Because MN has an undercatch of about 5% (combined wind and wetting error), the total undercatch of AN equals about 10-13%. The precipitation data in this study has been used as it is distributed to the public and used in KNMI products. Although e.g. relocations may affect the results for individual stations, it is unlikely that they bias the general finding of the study (see e.g. Figure 9, where the AN is compared with 317 MN stations).

From 2009 onwards, there is a statistical significant increase in the precipitation loss of AN. It is hard to say whether this is a step change or whether it is part of a trend. The increased loss may probably partly be explained by the slow transition to the Ott screen at AN stations and partly by an increase, in recent years, in the number of reported problems with the heating elements of automatic gauges.

Apart from the transition to Ott screens and possible problems with heating elements, there still is a difference between AN and MN of about 5-6%. Although differences in catch of rain gauges can often be explained by differences in wind error, this is probably only partly the reason here. Two factors should be considered. First, MN stations are mostly located in sheltered locations (gardens of houses, near farms, etc.) while AN stations are mostly located in open areas (because of the necessity to measure undisturbed wind speed). This should result in larger a catch at MN stations than at AN stations. The second factor is the situation of the instrument. MN stations have the rim of the gauges installed at 0.4 m above the ground level (without a wind shield) while AN stations have the gauge installed in an English set-up. This should result in a larger catch at AN stations than at MN stations. The effect of both factors probably partly outweigh each other.

The gauges in the English set-up are affected by wind speed. Braak (1945) showed for a windy location in De Voorst a wind error of about 2.7% for the English set-up compared to the WMO reference. This error increases with about 1.5% when the English set-up is replaced by a setup with an Ott screen with the rim at 1.0 m above the ground surface (Wauben, 2004). Although the latter result is for the De Bilt and the first for De Voorst, it may tentatively be estimated that the total wind error of the automatic gauge in the Ott screen equals about $2.7 + 1.5 = 4.2\%$. This is only slightly larger than the estimated wind error for MN of about 3%.

Kuik (2001) compared in a 1-year experiment for De Bilt the automatic rain gauge in the English setup with 2 manual rain gauges placed next to it with the gauge rim installed at 0.4 m above ground level. Both gauges were thus subject to the same sheltering. The manual gauges measured 3.4% more precipitation than the automatic rain gauges. Kuik stated that the reason for the difference was not clear. In the present study we compared automatic rain gauges with the most nearby manual gauge. Manual rain gauges are mostly situated in more sheltered areas than the automatic gauges. Therefore, it is not surprising that in this study we found that manual gauges measure more than 3.4% more precipitation than the corresponding automatic gauges.

The results in the present report suggest that the differences in catch between AN and MN partly originate from differences in wetting errors from the surface of the funnel. The undercatch of AN compared to MN occurs in all seasons and for all magnitudes of daily precipitation amounts. The relative undercatch equals about 25% for small daily amounts (56th percentile) and 5% for the large daily amounts

(98th percentile). The absolute undercatch shows an almost linear relationship with percentile of the daily amount and ranges between about 0.1 mm/day (56th percentile) and 0.8 mm/day (98th percentile). Especially in winter (DJF), the undercatch of automatic gauges compared to manual ones strongly depends on precipitation duration and may be as large as 1.8 mm/day for a wet day with > 10 mm of rainfall and low precipitation intensity. The functioning of the heating element of the automatic gauge may be important here.

In general it is desirable to minimize the undercatch of a network. Although the undercatch of MN is difficult to reduce, there are several possibilities to reduce the undercatch of AN to become closer to that of MN. First, the recommendations in Bijma (2008) could be implemented. This solves, among others, the problem of the heating element. Second, the implementation of the Ott screen could be stopped (the English setup clearly has a smaller wind error than the setup with the Ott screen). If this is not possible, the wind error of the setup with the Ott screen can somewhat be reduced by lowering the height of the rim of the gauge from 1.0 to 0.7 m above ground level (this reduces the wind speed at rim height by about 10%). Third, the difference between AN and MN can be reduced by about 0.5% by postponing the rounding of the precipitation amounts of AN and allowing more digits in the database.

The above measures will probably not be sufficient to reduce the undercatch of AN to the level of MN. Some research is needed to investigate the small losses, like wetting. For instance, it might be of interest to investigate whether there are differences in adhesion of water to the funnel wall of manual and automatic gauge and whether there are differences in drying time of the gauges in the field.

The measuring of small amounts (< 0.5 mm/day) by MN observers can be improved. The large spatial variability of the number of days with small amounts suggests that these amounts are not objectively measured (see also Buishand, 1977)⁷. Additional instruction of the observers might be needed here. The effect of the inadequate measurement of small MN amounts on the results in the present study is probably restricted to an increase of the uncertainty range of the results for small amounts. There is no indication of a systematic effect.

Precipitation networks and climate monitoring

There are three main sources of error that affect the suitability of precipitation networks for climate monitoring purposes: (1) relocations or changes in the local environment of the gauges, (2) changes in instruments and methods⁸, and (3) weather-dependent measurements errors (e.g. wind-induced undercatch). For individual stations, the effect of relocations or changes in the local environment may be large because of their impact on both the wind error and the wetting error. However, as long as the changes are not systematic, their effect on a network as a whole is probably small. In the present study, AN stations are located in open areas and MN stations in enclosed areas. For the study period, there are no systematic changes in this practice. In addition, for the Netherlands, Buishand et al. (2012) homogenized the precipitation series of MN and found only minor differences between trends calculated from the homogenized and non-homogenized network. Changes in instruments and methods generally introduce inhomogeneities in existing precipitation series, although they may sometimes decrease the

⁷ P.46, Fig.6.1

⁸ Methods apply e.g. to instrumental set-up (e.g. height of the gauge rim above ground level, use of a wind screen), software settings and calibration of the instruments, regulations concerning: (a) measurement of snow, (b) distribution of multi-day amounts, (c) validation, and (d) dealing with missing values.

measurement errors. Correcting for these inhomogeneities is often not feasible or restricted to only the lower order moments. Whereas MNs usually have a long continuity of instruments and methods, this continuity is hard to guarantee with ANs. This is demonstrated in the present study where in the short period 2001-2013 a discontinuity occurred: gradual transition from the English set-up to the set-up with an Ott screen for about half of the AN stations. This introduced a weather-dependent error (Wauben, 2004) that is difficult to correct. In addition, KNMI recently started searching for a commercially available automatic precipitation gauge to replace the current operational automatic gauge. It is known that all available gauges have their own specific errors (Wauben, 2006; WMO, 2009) and each gauge change will introduce a new inhomogeneity. Weather-dependent errors hamper the detection of long-term precipitation change because the relevant weather variables themselves may be subject to long-term changes. For example, an increase in wind speed increases the wind error of precipitation causing an artificial decrease in precipitation. Another example is the increase in temperatures. This affects e.g. the fraction of precipitation falling as snow. Because the wind error for snow is almost an order of magnitude larger than for rain, any change in this fraction results in an artificial change in precipitation. In addition, increased temperatures decrease the frequency of the operation of the heating device (as for the AN gauges in the present study), thus decreasing the wetting error in winter. For the Netherlands, AN exhibits a much larger undercatch than MN and is probably most affected with respect to its ability to signal long-term precipitation change.

5 Summary, conclusions and recommendations

Summary and conclusions

This report compares the automatic precipitation network (AN) in the Netherlands with the manual network (MN) in the 2001-2013 period. At 31 locations the hourly precipitation values of AN are aggregated to daily (0800-0800 UTC) values and are compared with the daily precipitation values of the most nearby MN station measured at 0800 UTC. The influence of temperature, wind speed and precipitation intensity is explored using for each AN station the daily mean values of these variables on rain hours.

The main conclusion of the study is that AN measures annually 5-8% less precipitation than MN, with an average of 6.4% for the whole 2001-2013 period. This corresponds to about 0.3 mm per wet day. Because MN has an undercatch of about 5% (combined wind and wetting error), the total undercatch of AN equals about 10-13%. This is much larger than the WMO requirement of 5% (achievable measurement error).

The other conclusions can be summarized as follows:

1. There is a statistical significant increase of about 2% of the undercatch of AN with respect MN in the 2001-2013 period. It is unclear whether this is a step change in the annual values in 2009 or a long-term trend. The cause of the increase in undercatch is probably a result of a combination of (a) the slow transition at AN stations of the English setup to a setup with an Ott screen and (b) an increase, in recent years, of problems with the heating elements of automatic gauges at AN stations resulting in an increased wetting loss.
2. The undercatch of AN with respect to MN varies seasonally and equals on average 7.7% in winter (DJF) and 5.0% in summer (JJA).
3. AN underestimates the number of wet days with respect to MN by about 4%. In DJF the underestimation equals 5.6% and in JJA 3.0%.
4. For MN there is an unrealistically large spatial variability in the number of days with small precipitation amounts (< 0.5 mm/day). This suggests that MN observers have difficulties with objectively measuring these amounts. Additional instruction of the observers is recommended.
5. The undercatch of AN with respect to MN strongly depends on precipitation amount. On average the undercatch varies between 25% (≈ 0.1 mm/day) for the 56th percentile of the probability distribution of the daily amounts (including the days with 0 precipitation) and 5% (≈ 0.8 mm/day) for the 98th percentile. The 56th and 98th percentiles correspond to a daily precipitation amount of about 0.4 and 17 mm, respectively. For the annual maximum precipitation amounts the undercatch equals on average 3.2% (≈ 0.9 mm/day).
6. The undercatch of AN with respect to MN is studied as a function of temperature, wind speed, and rainfall intensity. The results suggest that the undercatch for a specific day mainly depends on the precipitation amount and intensity (and thus the precipitation duration). In DJF the undercatch can be as large as 1.8 mm/day for the category with the largest precipitation amounts and the lowest precipitation intensity values. In general the undercatch becomes smaller with decreasing precipitation amount and increasing intensity. For JJA the undercatch as a function of these variables is about half of the DJF values.

7. The relatively large values of the undercatch of AN for temperatures $\leq 7^{\circ}\text{C}$ and the comparison of results for DJF and JJA, suggest that the heating device of the AN gauges amplifies the wetting error.
8. For snow ($T < 0^{\circ}\text{C}$), the undercatch of AN with respect to MN is close to zero. This is probably a result of the melting of snow by the automatic rain gauges. Snow that is melted will be measured, whereas snow in manual rain gauges may blow out of the gauge. This almost completely compensates for the other errors of AN with respect to MN.
9. Braak (1945) found for the Voorst that the English setup has a wind error of 2.7%. This error increases by about 1.5% when the rain gauge is transferred from the English setup to a setup using an Ott screen (Wauben, 2004). MN stations have on average a wind error of about 3% (Braak, 1945). They are, however, usually subject to more sheltered conditions than AN stations. Kuik (2001) found for De Bilt that two manual gauges measured 3.4% more precipitation than an automatic gauge in an English setup at the same location. It can thus tentatively be deduced that the major part of the undercatch of AN with respect to MN is not related to difference in wind error.
10. Conclusion (9) is confirmed by the finding in the present study that the undercatch of AN with respect to MN is almost independent of wind speed (about 0.3 mm/day for each wind speed class).

Recommendations

The following recommendations can be stated:

1. Keep a representative set of MN stations in the future for climate monitoring purposes, since they have long and stable records and serve as a reference, though not absolute. Today AN cannot satisfy those needs. The total undercatch of AN amounts to 10-13%. This is much larger than the WMO requirement of 5% (achievable measurement error) and leaves too much room for potential inhomogeneities in case of changes in instruments and methods. It is unlikely that commercially available automatic precipitation gauges will solve this issue in the near future.
2. Reduce the undercatch of AN by about 0.5% by postponing the rounding of the precipitation amounts of AN and allowing more digits in the database.
3. Reduce the undercatch of AN by implementing the recommendations in Bijma (2008). This solves, among others, the problem of the heating element.
4. Reduce the undercatch of AN by stopping the implementation of the Ott screen (unless the situation is not suitable for an English set-up). Alternatively, the wind error of the setup with the Ott screen can somewhat be reduced by lowering the height of the rim of the gauge from 1.0 to 0.7 m above ground level (this reduces the wind speed at rim height by about 10%).
5. Study the differences in wetting errors for the automatic and manual gauges for laboratory conditions and in the field.
6. Use the WMO reference set-up for future parallel experiments, e.g. when a new precipitation gauge is selected or evaluated. The gauges of interest should be compared in their normal set-up with the same gauges in a WMO reference pit. Also include the manual gauge (both in the WMO reference pit and in its normal set-up) in such an experiment. The WMO reference pit situates the rain gauge such that the rim of the gauge is at ground level surrounded by a roster (see e.g. Braak, 1945, and WMO, 2009). This eliminates the wind error.

7. Provide the voluntary observers of MN with information/guide lines regarding the measurement of small precipitation amounts (< 0.5 mm/day) to solve the large spatial standard deviations of these events.

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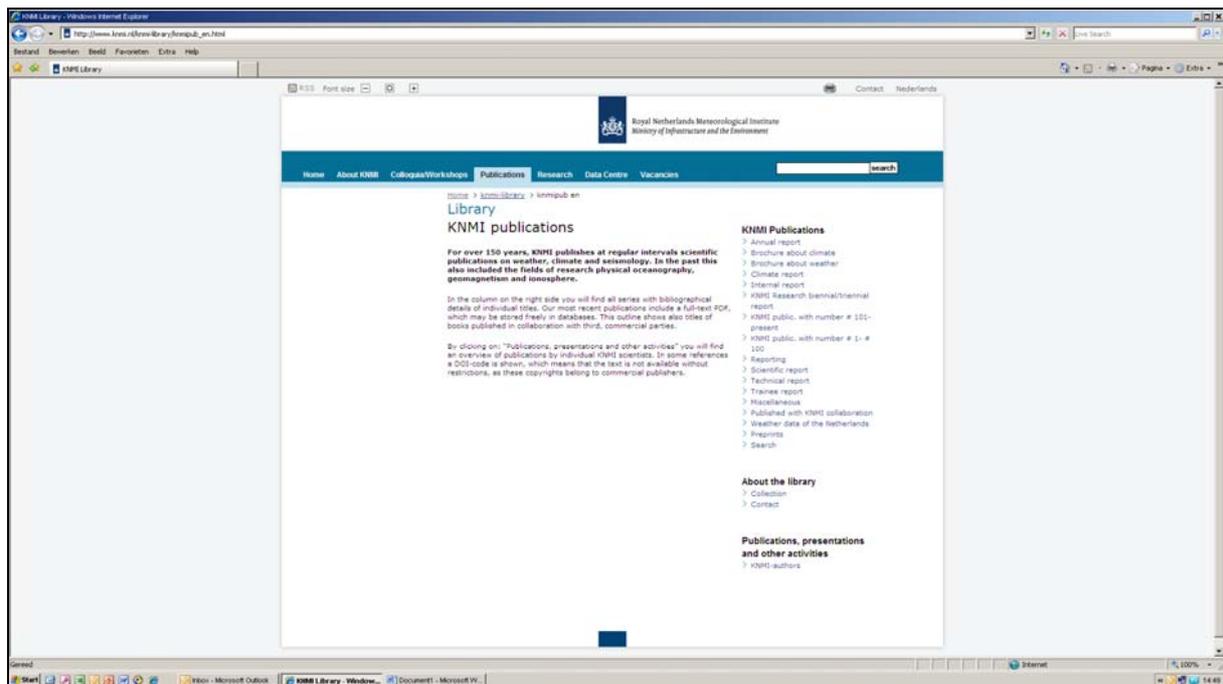
Appendix A. Station and instrument relocations

Automatic network (AN)		Manual Network (MN)	
Stat	Name	Stat	Name
210	Valkenburg • 02-09-2009 (885 m)	474	Valkenburg • 20-02-2001 (200 m) • 27-11-2005 (5 m)
235	De Kooy	25	De Kooy • 10-02-2004 (1100 m) • 14-11-2006 (46 m)
240	Schiphol • 02-03-2004 (4 km)	458	Aalsmeer • 01-11-2007 (58 m) • Feb 2009 (a few meters)
249	Berkhout	222	Hoorn • 26-04-2013 (2 km)
251	Hoorn (Tersch.)	26	Formerum
260	De Bilt • 25-09-2008 (200 m)	550	De Bilt
267	Stavoren	80	Stavoren • 27-03-2003 (125 m)
269	Lelystad	369	Lelystad
270	Leeuwarden	85	Leeuwarden
273	Marknesse	317	Marknesse • 06-05-2004 (600 m) • 18-07-2005 (1250 m) • 24-11-2007 (800 m) • 18-06-2008 (2 km)
275	Deelen	591	Deelen
277	Lauwersoog	171	Anjum
278	Heino	340	Heino • 05-06-2013 (323 m)
279	Hoogeveen	332	Hoogeveen • 01-07-2004 (tens of m) • 11-09-2005 (tens of m) • 28-09-2005 (1750 m)
280	Eelde	161	Eelde • 22-04-2005 (450 m)
283	Hupsel	688	Hupsel • 25-03-2004 (2 m)
286	Nieuw Beerta	143	Finsterwolde • 11-10-2007 (1 m)
290	Twenthe	670	Twenthe
310	Vlissingen	733	Vlissingen
319	Westdorpe	770	Westdorpe • 17-07-2001 (20 m) • 05-06-2007 (4 m)
323	Wilhelminadorp	749	Wilhelminapolder • 25-04-2001 (800 m) • 10-12-2003 (ca 1500 m) • 10-01-2013 (430 m)
330	Hoek v Holland	477	Hoek v Holland • 13-04-2001 (6 m)
344	Rotterdam • 28-09-2006 (600 m)	473	R'dam-W-Haven
348	Cabauw	561	Benschop • 01-05-2003 (2 m)

350	Gilze-Rijen	843	Gilze-Rijen
356	Herwijnen	830	Herwijnen <ul style="list-style-type: none"> • 13-01-2004 (1200 m)
370	Eindhoven	919	Eindhoven <ul style="list-style-type: none"> • 13-01-2005 (1450 m)
375	Volkel	920	Volkel <ul style="list-style-type: none"> • 17-04-2005 (7 m) • 25-08-2009 (688 m) • 17-08-2011 (3 m)
377	Eil	970	Stramproy <ul style="list-style-type: none"> • 30-07-2007 (5 m)
380	Maastricht <ul style="list-style-type: none"> • 01-11-2005 (1770 m) 	973	Beek <ul style="list-style-type: none"> • 30-04-2007 (50 m)
391	Arcen	923	Arcen

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