A 10-year radar-based climatology of rainfall

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I. INTRODUCTION

Weather radars give quantitative precipitation estimates (QPE) over large areas with high spatial and temporal resolutions not achieved by conventional rain gauge networks. Now that long radar data sets become available (e.g. Allen and DeGaetano, 2005; Germann et al., 2006), radar data could also be utilized for climatological applications. This study (Overeem et al., 2008) describes the derivation of a 10-year radar-based precipitation climatology for the Netherlands. Using rain gauges, a vertical profile of reflectivity (VPR) and a spatial adjustment are applied to the 24-hour radar-based precipitation depths. The daily adjustment is also applied to sub-daily accumulations. The verification of the radar-based accumulations with an independent gauge network confirms the quality of the data set. Finally, the radar data are used to obtain exceedance probabilities and maximum rainfall depths.

II. RADAR AND RAIN GAUGE DATA

A. Radar data

Radar reflectivity data were obtained from the two C-band Doppler weather radars in the Netherlands, which are operated by KNMI and located in De Bilt (52.10° N, 5.18° E, 44 m above MSL) and Den Helder (52.96° N, 4.79° E, 51 m above MSL), see Figure 1. Every 5 minutes the radars, which have a 3-dB beamwidth of 1°, performed 4 azimuthal scans of 360° around a vertical axis at beam elevation angles of 0.3°, 1.1°, 2.0° and 3.0°.

From 1998 to 2007, pseudo-CAPPI images, for which ground clutter was removed, are available with a temporal resolution of five minutes at a 2.4-km horizontal resolution. Figure 2 displays the volume coverage pattern with the height of the four elevations as a function of range from the radar, where the bold line denotes the pseudo-CAPPI. Next, the reflectivities $Z$ (mm$^6$ m$^{-3}$) of the pseudo-CAPPI images were converted to rainfall intensities $R$ (mm h$^{-1}$) with the fixed Z-R relationship (Marshall et al., 1955),

$$ Z = 200R^{1.6} $$

With 0.5 dBZ classes this resulted in 97 possible levels of rainfall intensities ranging from 0.1 to 100 mm h$^{-1}$. Subsequently, 1-hour rainfall accumulations were constructed from the 5-min rainfall intensities if at least 10 out of 12 images were available. The range of the radar accumulation images was limited to 200 km. The data from the Den Helder radar were only used for the period February 2001-2007 and selected

Fig. 1. Maps of the Netherlands with in the upper panel the locations of the weather radars in De Bilt and Den Helder, their 200-km range (circles), and the 33 automatic rain gauges (squares) and in the lower panel the locations of the 326 manual rain gauges.
of QPE from radar observations, however is less successful at long ranges. In this section a VPR adjustment is proposed, which also improves the quality of rainfall accumulations far from the radar. Subsequently, a spatial adjustment is applied.

A. VPR and bias adjustment per radar

The VPR adjustment method uses rain gauges to remove the mean-field bias and to adjust for reflectivity values which change with height. For each radar-gauge pair with at least 0.5 mm of rainfall the ratio of the accumulated 24-hour 8 UTC rainfall from the manual rain gauge and its corresponding radar pixel is calculated. An adjustment “factor” $f_{\text{raw}}$ in dB is defined for each of these pairs as:

$$f_{\text{raw}}(i_n, j_n) = 10 \cdot 10^{\log \left( \frac{G(i_n, j_n)}{R_{\text{raw}}(i_n, j_n)} \right)}$$

with $G(i_n, j_n)$ the amount of rain for rain gauge $n$, $R_{\text{raw}}(i_n, j_n)$ the amount of rain for the corresponding radar pixel ("raw" denotes unadjusted data), and $(i_n, j_n)$ the image coordinates of rain gauge $n$.

The following linear regression equation is used to model $f_{\text{raw}}$ as a function of the height $\Delta h$ of the lowest beam elevation above the 800-m pseudo-CAPPI height:

$$f_{\text{raw}}(i_n, j_n) = b + a \cdot \Delta h(i_n, j_n) + \epsilon(i_n, j_n)$$

where $\epsilon(i_n, j_n)$ denotes a residual. The VPR adjustment factor (dB) is defined as:

$$F_{\text{VPR}}(i, j) = b + a \cdot \Delta h(i, j)$$

with $(i, j)$ the pixel image coordinates, and is applied to each pixel in the radar domain. The lowest elevation reaches the 800-m height ($\Delta h = 0$) at a range of 80 km, as shown in Figure 2. For ranges shorter than 80 km $\Delta h$ is set to 0. Subsequently, the VPR adjusted 24-hour accumulations from both radars are composited.

B. Spatial adjustment of composites

A spatial adjustment (Brandes, 1975; Michelson and Koistinen, 2000) is performed on the adjusted rainfall accumulation composites from the previous section. The adjustment follows from a distance-weighted interpolation (Barnes, 1964) of the logarithms of the ratio of the accumulated daily rainfall from the manual gauge and the corresponding value from the VPR adjusted radar composite ($f_{\text{VPR}}^c$). This results in the spatial adjustment factor $F_{\text{spat}}^c$ (dB):

$$F_{\text{spat}}^c(i, j) = \frac{\sum_{i_n=1}^{N} f_{\text{VPR}}^c(i_n, j_n) \cdot w_g(i, j)}{\max_{i_n=1}^{N} w_g(i, j) \cdot \delta_0}$$

with

$$f_{\text{VPR}}^c(i_n, j_n) = 10 \cdot 10^{\log \left( \frac{G(i_n, j_n)}{R_{\text{VPR}}^c(i_n, j_n)} \right)}$$

and

$$w_g(i, j) = \exp[-d_n^2(i, j)/\sigma^2]$$

where $\sigma$ ($= 12$ km) determines the smoothness of the $F_{\text{spat}}^c$ field, $d_n(i, j)$ is the distance between manual rain gauge $n$ and

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Fig. 2. Volume coverage pattern displaying the height of the four beam elevations with respect to antenna level as a function of range from the radar. The bold line denotes the pseudo-CAPPI image, the gray shaded areas indicate the 1$^\text{st}$-beam for the lowest and highest elevation.
the accumulations are obtained for every clock-hour. If ∑_{n=1}^{N} w_p(i,j) < k_0 because all valid gauges are located far from (i,j), the denominator of Eq. 5 is set to k_0 = 0.5 and F'_{pot}(i,j) is reduced.

C. Sub-daily composites

The VPR and spatial adjustment factor fields of the daily composite are employed to the raw composites of 1-hour rainfall depths. Subsequently, 1-hour rainfall depths are used to construct depths for durations D of 2, 4, 8, 12 and 24 hour for each clock-hour if the data availability is at least 83.3%. Next, from these accumulations only radar pixels over the land surface of the Netherlands are selected, covering an area of approximately 35 600 km².

IV. CHARACTERIZATION AND VERIFICATION OF ADJUSTED ACCUMULATIONS

A. Seasonal cycle of the VPR gradient

Although the VPR radar-gauge adjustment is statistical, the estimated VPR gradients can be related to the type of rainfall. Figure 3 shows the VPR gradient a from Eq. 4 as a function of the year for the radar in De Bilt. The negative gradients in winter are notably attributed to partial overshooting of precipitation due to the dominance of stratiform rainfall, which is shallow. In summer, convective rainfall occurs more frequently, which has a larger vertical extent and strong reflectivity cores aloft causing positive VPR gradients. The VPR gradient in dBR km⁻¹ can be converted to a gradient in dBZ km⁻¹ using Eq. 1, thus the values differ a factor 1.6. In winter and in summer typical values of respectively -8 to 0 dBZ km⁻¹ and -2 to 4 dBZ km⁻¹ are found in Figure 3.

B. Verification with independent rain gauges

The 10-year data set of radar-derived composited rainfall accumulations is verified with the independent automatic rain gauge network for D = 1, 2, 4, 8, 12 and 24 hour, where the accumulations are obtained for every clock-hour. The residuals, i.e. the differences between the radar and gauge derived rainfall, are calculated for each radar-gauge pair. The bias in the mean 24-hour rainfall depth is reduced from -0.77 mm for the raw data to -0.02 and 0.04 mm for respectively the VPR and spatial adjustment methods. The residual standard deviation decreases from 2.59 mm (raw) to 1.87 mm (VPR adjustment) and 1.43 mm (spatial adjustment). An important part of these standard deviations is likely to be caused by representativeness errors. For example, the standard deviation of the differences between 24-hour 8 UTC rainfall depths from manual and automatic gauges within a 2.4-km radius for the period 1998-2007 is already 1.06 mm.

Next, for each duration the residuals are ranked in increasing order and the values belonging to the 25th, 50th (median) and 97.5th percentiles are determined and plotted in Figure 4. For the raw radar data the 95-percentile interval of the residuals is rather wide, and the distribution is negatively skewed implying that with respect to rain gauges the underestimates are more severe than the overestimates. Note that also values of (near) zero rainfall are used to construct Figure 4, which occur so frequently that the median is close to zero.

The 95-percentile interval decreases significantly for the VPR adjustment and the spatial adjustment method and the asymmetry of the distribution of the residuals has disappeared. Similar results are obtained for durations < 24 hour, although the 95-percentile interval is reduced only slightly for D = 1-8 hour.

In conclusion, the daily adjustments perform well on both daily and sub-daily accumulations and remove the systematic underestimation of precipitation by radar.

V. EXAMPLES OF RADAR RAINFALL CLIMATOLOGY

A. Empirical exceedance probabilities

Based on the radar data set, empirical exceedance probabilities of rainfall are calculated. Using the rainfall depths from all radar pixels located above the land surface of the Netherlands, rainfall frequencies are calculated for classes of 1 mm.

Subsequently, exceedance frequencies are calculated, which are scaled with the sum of all frequencies, so that empirical exceedance probabilities of rainfall depths are obtained, which are shown in Figure 5. For example, for the spatially adjusted radar data a 24-hour 8 UTC rainfall depth of 100 mm has an exceedance probability of approximately 8.4 · 10⁻⁶ implying that on average this rainfall depth is exceeded approximately once in 1.2 · 10⁵ days (≈ 328 year) in 1 arbitrary radar pixel. These exceedance probabilities are spatial averages over the Netherlands which are assumed to be independent of season. Deviations from these averages are probably limited, because the Netherlands is a relatively small and flat country.
Figure 5 shows that the exceedance probabilities of 24-hour 8 UTC rainfall from the adjusted radar data (VPR and spatial adjustment methods) are in good correspondence with those based on the manual rain gauges, while the use of raw radar data results in much lower exceedance probabilities. So, adjustment of radar data with rain gauges is a prerequisite to obtain reliable exceedance probabilities of rainfall.

Figure 6 gives the exceedence probabilities for 1, 2, 4, 8, 12 and 24-hour radar rainfall sums over the period 1998-2007, based on the spatial adjustment method.
exceeded on average approximately once in $1.2 \cdot 10^3$ clock-hours ($\approx 49$ days).

B. Maximum rainfall depths

Now that the exceedance probabilities have shown a good correspondence with those from manual rain gauges, the spatial distribution of rainfall maxima is investigated. Figure 7 displays the maximum 24-hour 8 UTC rainfall sums from interpolated manual rain gauge data (a) and spatially adjusted radar data (b) for the period 1998-2007 and demonstrates a reasonable resemblance between both. For the radar data also the maximum one-hour rainfall sums are plotted (c), which is, at an acceptable spatial resolution, usually not possible for rain gauge data. The maximum one-hour rainfall sum shows a strong spatial variation with values ranging from 10 to 74 mm.

VI. OUTLOOK

The derivation and verification of one of the longest radar data sets described in the literature has been discussed. A first analysis shows good prospects for employing this data set in climatological applications. The following step in the use of this radar rainfall climatology is to calculate probabilities of extreme rainfall, e.g. used in the design of hydraulic structures. This would enable us to study the statistics of extreme areal rainfall for durations $< 24$ hour, which is difficult to achieve with rain gauges.

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Fig. 7. Maximum rainfall depths over the period 1998-2007 based on 24-hour 8 UTC accumulations from a) manual rain gauge data and b) spatially adjusted radar data. Figure c) is based on the one-hour spatially adjusted radar accumulations. The figures for the manual gauges are based on daily depths interpolated with continuous curvature splines in tension.