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Rainstorm characteristics derived from weather radar images

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Abstract. In order to define the spatial and temporal characteristics of rainstorms, multiple time series of weather radar images over The Netherlands and Belgium are analysed. The velocity of rainfall events and the direction of movement are determined using the cross-correlation technique and statistical distributions are calculated. After developing a technique to discriminate single rainstorms within a radar image, some spatial characteristics of rainstorms are determined. Therefore different methods to define the dimension of a rainstorm are proposed and worked out. A statistical analysis revealed that the dimensions of rainstorms in the direction of the rainfall movement are significantly different from the dimensions in the direction perpendicular to the rainfall movement. This information can later be applied in a stochastic rainfall model which accounts for spatial variability.

1 Introduction

Last decades several studies have shown that hydrological models give better results when the spatial variability of the rainfall input is taken into account (e.g. Krajewski et al., 1991; Obled et al., 1994; Willems and Berlamont, 1999). When performing a long-term hydrological simulation using uniform rainfall over the catchment, the peak discharges will be overestimated since in reality the largest rainfall intensities will not be found over the whole catchment at the same time. As a consequence a rainfall generator, which preserves the spatial organisation of rainfall patterns, is necessary for simulating long time series of spatial rainfall. Weather radar images are a perfect source for obtaining the amount of spatial rainfall information that is needed for building a spatial rainfall generator, considering their spatial and temporal resolution. The objective of this study is to have a more accurate description of some rainfall characteristics at mesoscale. Not only the velocity of rainfall events and the direction in which they move are studied thoroughly, but also the dimensions of rainstorms are considered. Therefore a clear definition of a rainstorm is first formulated. The statistical distributions of the rainfall characteristics that are determined in this study can directly be used as an input for a stochastic spatial rainfall generator.

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2 Description of the data

The data used for this study are pCAPPI (pseudo Constant Altitude Plan Position) radar images provided by the KNMI (Royal Meteorological Institute of the Netherlands). The Netherlands, the western part of Germany and the northern part of Belgium are covered with these images. The radar images are parallel to the meridian of Greenwich, with a 200 × 200 pixel grid of pixelsize 2.4 × 2.4 km^2. Twenty time series of radar images, with a 15-minutes time lag between two consecutive images, a minimum of 45 images and a maximum of 96 images per series, were selected within the period 1998–2000. To include possible seasonal variation, rainfall events were chosen throughout the year and only days with a high total amount of rainfall were selected. All the selected rainfall events are part of frontal weather systems.

3 Movement of rainfall events

For the calculation of the motion vector of rainfall events, the cross-correlation technique, first published by Zawadski (1973), is used. The motion vector is determined by the (k_x, k_y)-displacement which gives the highest cross-correlation $\rho\,(k_x, k_y)$ in a Cartesian coordinate system defined by the X- and Y-axes (respectively East–West and North–South direction). An important advantage in using this method to calculate the velocity and direction of movement is that very small spatial lags (k_x, k_y) can be used. The smallest lag used in this study equals 0.1 pixel length.

Out of the 20 series of radar images, 1603 pairs of consecutive images could be selected. On each of these pairs the translation method was used to calculate the velocity of the rainfall event U_{xy} (km.h^{-1}) and the direction of the rain-

Table 1. Statistical information (mean m, standard deviation s, minimum min, maximum max and fitted distribution) of some characteristics of the 934 studied rainstorms. A square root transformation of the data is indicated with a $\sqrt{}$-subscript for the distribution parameters

	m	s	min	max	Distribution
Area $[\mathrm{km}^2]$	87178	35707	8456	202568	N($\mu_{\sqrt{}} = 288.90, \sigma_{\sqrt{}} = 60.96$)
Perimeter $[\mathrm{km}]$	3654	1174	1022	6989	N($\mu_{\sqrt{}} = 59.63, \sigma_{\sqrt{}} = 9.90$)
x_1 $[\mathrm{km}]$	382	90	79	480	-
y_1 $[\mathrm{km}]$	405	75	94	480	-
x_2 $[\mathrm{km}]$	328	117	81	609	W($\alpha = 367.47, \beta = 3.06$)
y_2 $[\mathrm{km}]$	314	111	53	563	W($\alpha = 351.66, \beta = 2.99$)
x_3 $[\mathrm{km}]$	410	104	124	618	W($\alpha = 450.01, \beta = 4.43$)
y_3 $[\mathrm{km}]$	392	89	126	599	W($\alpha = 425.71, \beta = 5.12$)

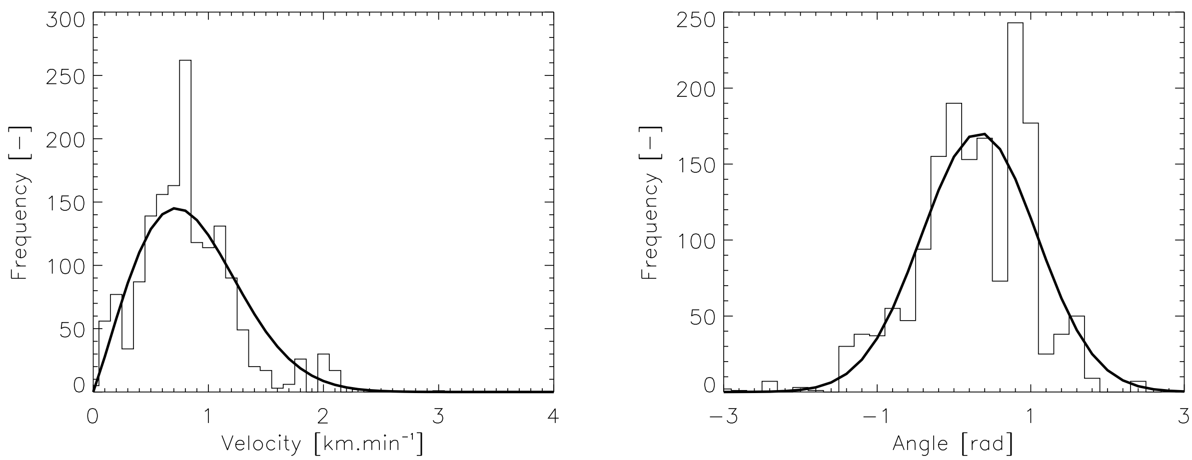

Fig. 1. Statistical distributions of the velocity and the direction of movement calculated with 1603 pairs of radar images.

fall movement θ (rad), which is taken relative to the eastern direction. A histogram of the original and transformed data was made for each characteristic and tested for different bell-shaped theoretical probability density functions (pdf's). Herefore the normal distribution, denoted as N(μ,σ), the Weibull distribution, W(α,β) and the Gamma distribution, G(k), were considered. The different transformations that were applied to the original data were the square root-transformation, the $\log$-transformation and the inverse of the data. To estimate the parameters for the distributions the least squares approach was used.

The velocity of the studied rainfall events varied between 1.8 and 185.3 km.h^{-1}, with a mean of 51.78 km.h^{-1}. Statistical analysis (Kolmogorov-Smirnov analysis and QQ-plots) of the histogram of rainfall velocity lead to the selection of a Weibull distribution characterised with a scale parameter α equal to 0.98 and a shape parameter β equal to 2.10, as the most optimal probability distribution function (Fig. 1). Transformation of the data did not improve the results.

The direction in which the rainfall event is moving varied between -2.88 and 2.90 radians, with a mean of 0.327 radians. The best fit for the distribution of this rainfall movement characteristic is found to be normal distribution with a mean μ equal to 0.33 radians and a standard deviation σ of 0.75 radians. This means that the rainfall systems move mainly in the E–NE direction.

4 Rainstorm characteristics

4.1 Determination of a rainstorm

A new concept, namely the APratio (km) (Eq. 1) is introduced. Based on the temporal evolution of the APratio, a technique was developed to reject images which contain rainy systems in development or decay. When a rainstorm is growing (or dissipating), several little rainy areas can be detected in the image. This results in a relatively low APratio, since the total perimeter is much larger compared to the situation where the same rainy area is part of one connected system. So every image with a high APratio represents a rainy system which is fully developed.

$$\mathrm{APratio} = \frac{\sum_{rainy\ areas} \mathrm{Area}\ \mathrm{A_i}}{\sum_{rainy\ areas} \mathrm{Perimeter}\ \mathrm{P_i}} \qquad (1)$$

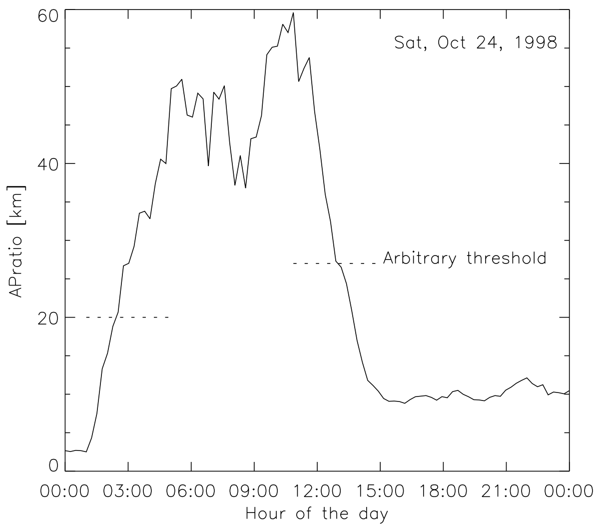

Fig. 2. The evolution of the APratio on 24 October 1998, determined using 96 radar images. Images with an APratio below the dotted lines are supposed to have a rainstorm in development or decay and are not subjected to any further analysis.

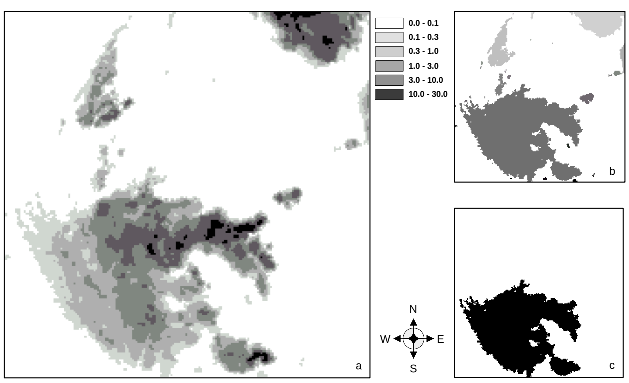

Fig. 3. Radar image from 5 July 1999 at 04:15 LT. (a) The original image with 8 rainfall classes (mm.h^{-1}). (b) The different rainy areas within the image. (c) The largest rainy area in the image, the rainstorm.

The area and the perimeter for the different rainy groups in every image of the time series are determined, the APratio is calculated and its evolution is plotted (e.g. Fig. 2). The next step includes the determination of arbitrary thresholds for the APratio, above which the rainy area can be considered to be fully developed. These thresholds are different for every time series of radar images and are mainly based on the visual interpretation of the plot. Only images with an APratio above these thresholds are further used in this study. Finally, in every radar image that is retained, the largest rainy area is selected as the rainstorm (Fig. 3). From the 1632 available radar images, only 934 were considered to visualise a rainstorm as it is defined above.

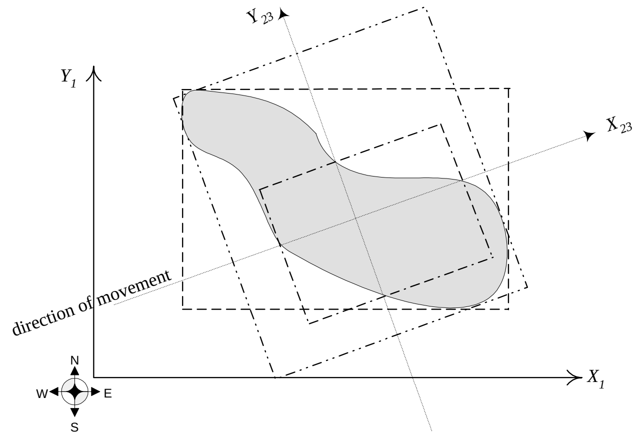

Fig. 4. Schematic overview of the three methods to determine the extension of a rainstorm. The different rectangles give the maximum size of the rainstorm for method 1 (dash-dash), method 2 (dash-dash-dot) and method 3 (dash-dot-dot).

4.2 Area and perimeter of a rainstorm

The first characteristics that are calculated for the rainstorms are the total area (km^2) and the perimeter (km). The results of this analysis are summarized in Table 1. We can state that the area of the rainstorm lies in the range 10^3–10^4 km^2, which means that we study large mesoscale synoptic areas (LMSA's) following the classification of rainfall structures by Austin and Houze (1972). Statistical analyses revealed that the distribution of the area and the perimeter calculated using all the 934 processed rainstorms can be approached by a normal distribution after a square root transformation of the data.

4.3 The dimension of a rainstorm

To determine the dimension of a rainstorm, three different methods are proposed.

– **Method 1.** The dimension of the rainstorm is measured using the East–West and North–South directions of the image, this means in a coordinate system with $\mathrm{X}_1, \mathrm{Y}_1$ axes (Fig. 4). The smallest rectangle that can be build around the rainstorm, with sides parallel to the sides of the image will determine the dimensions of the rainstorm. The lengths of the rectangle sides, which are expressed as x_1 and y_1, give an estimation for the size of the rainstorm.

– **Method 2.** A new coordinate system (X_{23},Y_{23}) is defined. The directions of the axes are chosen parallel (X_{23}) and perpendicular (Y_{23}) to the direction of movement of the rainstorm (Fig. 4). By using the intersections of the rainstorm with the X_{23} and Y_{23} axes a new rectangle can be formed of which the length of the sides give an estimation for the size of the rainstorm. It depends on the shape of the studied rainstorm whether the whole rainstorm will be included in the rectangle

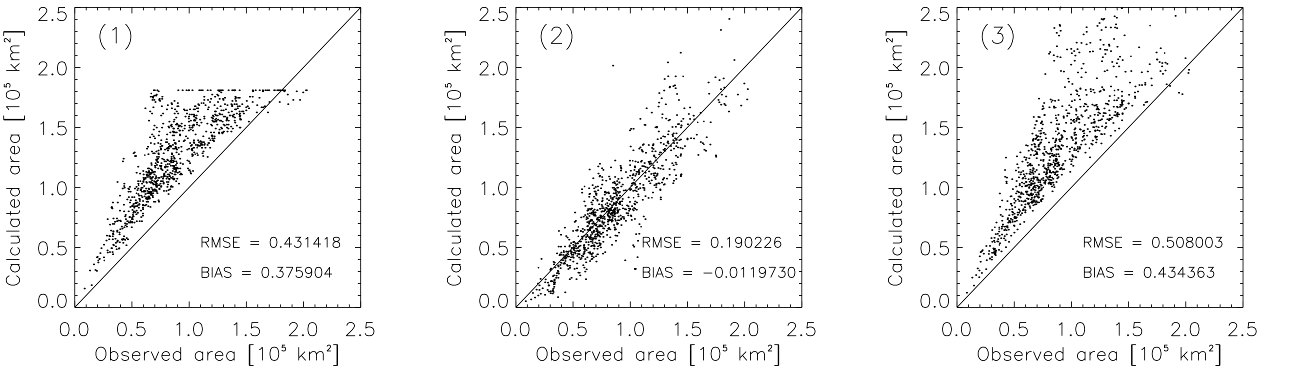

Fig. 5. Comparison between the observed and the calculated area (a circular shape) of the 934 rainstorms, using the 3 different methods to determine the dimension of the rainstorm.

or not. The dimension of the rainstorm will now be expressed as x_2 in the direction of the movement and as y_2 in the direction perpendicular to the direction of the movement.

– **Method 3.** Again the coordinate system with the X_{23} and Y_{23} axes is used, but now the dimension of the rainstorm is defined by creating the smallest rectangle possible around the rainstorm with its sides parallel to the coordinate system (Fig. 4). The length of the rectangle sides (x_3 and y_3) determine the dimension of the studied rainstorm.

The statistical characteristics of the rainstorm dimensions are summarized in Table 1 for the 3 proposed methods. Again theoretical distributions are fitted to the observed distributions of the different x and y variables, except for the distributions obtained with method 1. Because the histograms of x_1 and x_2 are truncated at 480 km (the maximum width of the radar image) we did not fit pdf's for these variables. For the four other variables (x_2, x_3, y_2 and y_3) a Weibull distribution gave the best fit, with shape parameters in the range 2.99 to 5.12 and scale parameters varying between 352 and 450 (Table 1).

To test whether the dimensions of the rainstorm are significantly different in x- and y-direction, a non-parametric Mann-Whitney test was performed on the x_2,y_2 and the x_3,y_3 data, respectively. A significant difference was found between the dimensions of the rainstorm in the direction of the rainfall movement and the direction perpendicular to the direction of movement ($P < 0.05$). This result was obtained for both methods 2 and 3.

Since the dimension of the rainstorms can be used to determine the areal extent of the rainstorm in a spatial rainfall model (e.g. Willems, 2001), it is tested which method can give the most accurate calculation of the rainstorm area. Therefore the observed rainstorm area is compared with the area that is calculated using the dimensions determined with the different methods. The shape of the rainstorm can be approached by a circle or an ellipse. For every rainstorm the area of two circles and one ellipse are calculated. The first circle has a diameter equal to the smallest dimension in x- and y-direction and the second one has a diameter equal to the average of the x- and y-dimensions. The area of the ellipse is calculated using the determined x- and y-dimensions. To have an objective measure to conclude which situation gives the best result, the RMSE (Root Mean Square Error) and the bias are calculated.

From Fig. 5 it is obvious that method 1 and method 3 tend to give an overestimation of the rainstorm area, which is confirmed by the rather large positive bias. A small bias and RMSE are only reached with method 2, when calulating the area of an ellipse or of a circle with a diameter equal to the average of the x- and y-dimensions. The results for the circle are slightly better compared to the results for the ellipse.

5 Conclusions

The cross-correlation technique has been used successfully to determine the velocity and the direction of movement of rainfall events. Statistical analysis revealed that the velocity of rainfall events follows a two-parameter Weibull distribution and that the distribution of the direction of rainfall movement can be approached by a normal distribution.

A technique to discriminate single rainstorms within radar images has been optimized making use of the total area and the total perimeter of all rainy areas in the radar image. Only images with a fully developed rainstorm were selected for further analysis of rainstorm characteristics. Three methods to determine rainstorm dimensions were proposed. By comparing the real rainstorm area with the area calculated from the rainstorm dimensions, we found that the dimensions of the rainstorm are best determined using a coordinate system based on the direction of movement. The rainstorm dimensions are defined by the intersection points of the coordinate system and the rainstorm. The distributions of the dimensions in x- and y-direction follow both a two-parameter Weibull distribution. Statistical analysis revealed that the dimensions of the rainstorms in x- and y-direction are significantly different.

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