

Rainstorm characteristics in temperate areas derived from multiple time series of weather radar images

**GABRIELLE J. M. DE LANNOY, INGE L. M. DE JONGH,
NIKO E. C. VERHOEST & FRANCOIS P. DE TROCH**

*Laboratory of Hydrology and Water Management, Ghent University, Coupure links 653,
B-9000 Ghent, Belgium*

inge.dejongh@rug.ac.be

Abstract To define the spatial and temporal characteristics of rainstorms, 20 time series of weather radar images over northwestern Europe were analysed. The velocity of rainfall events and the direction of movement were determined for 1632 radar images using the cross-correlation technique. A technique was developed to discriminate single rainstorms within a radar image. After calculating the area and perimeter of these rainstorms, different methods to define the dimensions of rainstorms were proposed. Statistical calculations revealed that the dimensions of rainstorms in the direction of the rainfall movement were significantly different from the dimensions in the direction perpendicular to the movement. Rainstorms are composed of several rain cells which are clustered together. In order to describe the occurrence of cell clusters, a new technique was used for localizing cluster centres within a rainstorm. The positions of the cluster centres along and across the rainfall movement follow a Poisson distribution.

Key words cross-correlation; rain cell clusters; rainfall movement; weather radar

INTRODUCTION

Several studies over the last decades 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 & Berlamont, 1999). When performing a long-term hydrological simulation using uniform rainfall over the basin, the peak discharges will be overestimated since in reality the largest rainfall intensities will not be found over the whole basin at the same time. As a consequence a rainfall generator, which preserves the spatial organization 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 and the localization of clusters within a rainstorm are considered. Therefore a clear definition of a rainstorm has to be formulated first. 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 (e.g. Willems, 2001).

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 Greenwich meridian, with a 200×200 pixel grid of pixel size $2.4 \times 2.4 \text{ km}^2$. 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 selected rainfall events are parts of frontal weather systems.

METHODS

Rainfall movement

For the calculation of the motion vector of rainfall events, the cross-correlation technique, first published by Zawadski (1973), was used. The motion vector is determined by the (k_x, k_y) displacement which gives the highest cross-correlation in a Cartesian coordinate system defined by the X_1 - and Y_1 -axes (east–west and north–south directions, respectively).

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 rainfall 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 (pdfs). Therefore the normal distribution $N(\mu, \sigma)$, the Weibull distribution $W(\alpha, \beta)$ 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.

Determination of a rainstorm

A new concept, namely the *APratio* (km), is introduced:

$$APratio = \frac{\sum_{\text{rainy areas}} Area_i}{\sum_{\text{rainy areas}} Perimeter_i} \quad (1)$$

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 small 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. 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. 1). 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.

Rainstorm dimensions

To determine the dimension of a rainstorm, three different methods are proposed. Therefore two coordinate systems are defined. The first system uses the east–west (X_1) and north–south (Y_1) directions in the image, while the axes in the other system are chosen parallel (X_{23}) and perpendicular (Y_{23}) to the direction of movement of the rainstorm. Using different criteria, three rectangles can be built for every rainstorm (Fig. 2). The lengths of their sides gives an estimation for the size of the rainstorm. Two methods build the smallest possible rectangle around the rainstorm with sides parallel to coordinate axes: method 1 uses the X_1, Y_1 system, while method 3 uses the X_{23}, Y_{23} system. Method 2 builds its rectangle using the intersection points of the rainstorm with the X_{23}, Y_{23} coordinate system.

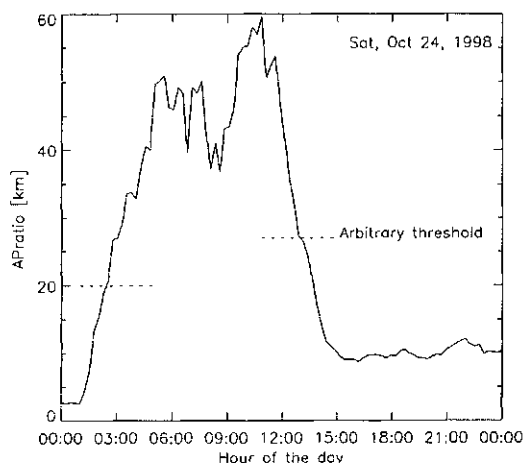


Fig. 1 The evolution of the $APratio$ on 24 October 1998 determined using 96 radar images. Images with an $APratio$ below the dotted lines are supposed to have a rainstorm in development or decay and are not subjected to any further analysis.

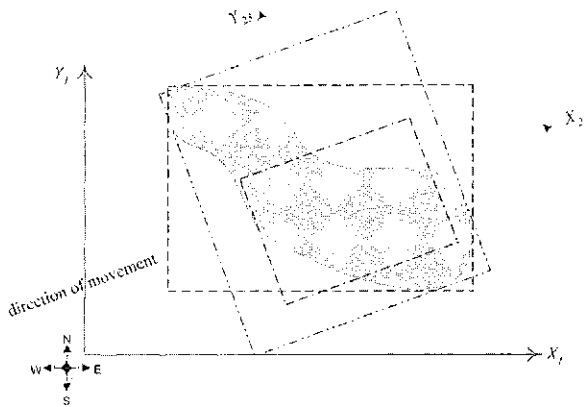


Fig. 2 Schematic overview of the three methods to determine the extension of a rainstorm. The different rectangles give the maximum size of the rainstorm for method 1 (—), method 2 (---) and method 3 (-·-·).

Rain cell clusters

Within a rainstorm, small areas with a high rainfall intensity can appear. These areas are rain cells for which earlier research could already conclude that they are clustered together (Bacchi *et al.*, 1991). Due to the spatial resolution of the radar images used in this research, the individual rain cells cannot be detected accurately, so only rain cell clusters will be considered. To simplify the analysis, we assume that the location of the cluster centres can be used as the location of the clusters. In order to locate the cluster mass centres in the radar image, the level slicing technique is used to define rain cell clusters. The connected areas which have a rainfall intensity above a preset threshold and have a minimum area of 46 km^2 (i.e. 8 pixels) are considered to be rain cell clusters. For each cluster, the threshold used depends on the rainfall intensity within the cluster. After the delineation of the clusters, the centre of each cluster is determined.

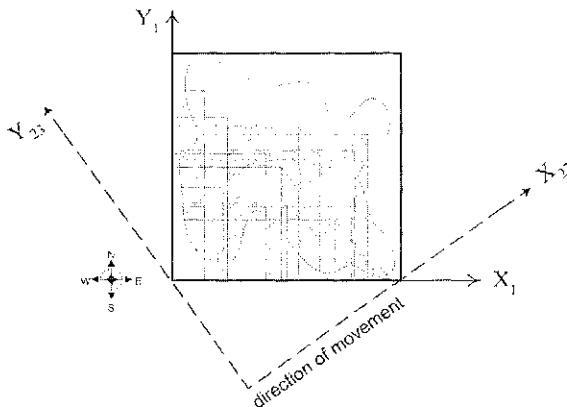


Fig. 3 Schematic overview of the 1-D method to calculate the Poisson parameter λ : after projection of the cluster centres, the intercluster distances are calculated.

We assumed that the spatial distribution of clusters is a homogeneous Poisson distribution with only parameter λ , which means that the intercluster distance follows an exponential distribution with a probability density function that is given by $f_x = \lambda e^{-\lambda x}$. The parameter λ is calculated using a one-dimensional (1-D) and a two-dimensional (2-D) method.

For the 1-D method, the cluster centres are projected on a straight line and the intercluster distances are calculated. The histogram of the intercluster distance is plotted and an exponential distribution is fitted whereby the Poisson parameter λ is directly found. We used four different lines to project the centres on: the X_1 , Y_1 , X_{23} and Y_{23} coordinate axes (Fig. 3). In this way it could be tested if there is a difference in cluster density for the different directions in the image.

In the 2-D method a pixel in the image is selected, a square is created around that pixel and the cluster centres within the square are counted. This procedure is repeated for increasing areas of the squares and for all pixels within the rainstorm. Finally, a plot of the number of counted cluster centres against the area of the used square is created (Fig. 4). The first part of the plot is linear and the slope of the trend line equals the λ -parameter, which represents the number of clusters per unit area.

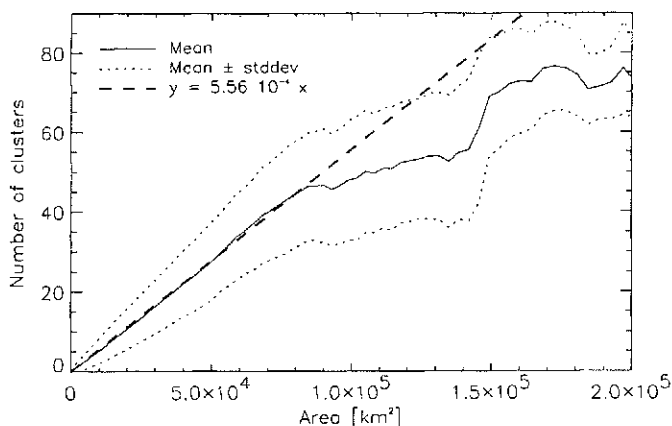


Fig. 4 Determination of the Poisson parameter λ using the 2-D method, where λ is the slope of the trend line in the linear part of the graph.

RESULTS

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 led to the selection of a Weibull distribution characterized 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. Via transformation of the data a better fit to the theoretical pdfs could not be achieved.

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 a 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.

From the 1632 available radar images, only 934 were considered to represent a rainstorm as it is defined in this work. Once the rainstorms are defined, the total area and the perimeter of each rainstorm can be calculated (Table 1). Statistical analyses revealed that the distribution of the area and the perimeter, calculated using all the 934 processed rainstorms can be best approached by a normal distribution after a square root transformation of the data.

For the three proposed methods the statistical characteristics of the rainstorm dimensions are summarized in Table 1. 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 y_1 are truncated at 480 km (the maximum width of the radar image) we did not fit pdfs 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.

To test whether the dimensions of the rainstorm are significantly different in x - and y directions, 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.

The results of the analysis of the cluster centres are summarized in Table 2. Using the 2-D method we obtained an idea about the cluster density within the rainstorm but no conclusions could be made about how these clusters are spatially organized. There the 1-D method offers a solution: it can be noticed that the clusters seem to be more distributed along the direction of the rainstorm movement compared with the distribution of the clusters in the direction perpendicular to the rainfall movement.

Table 1 Statistical information of some rainfall characteristics.

Characteristic	Mean	Standard deviation	Fitted distribution
<i>1603 pairs of radar images:</i>			
Velocity (km min ⁻¹)	0.863	0.412	W($\alpha = 0.98, \beta = 2, 10$)
Direction angle (rad)	0.327	0.755	N($\mu = 0.33, \sigma = 0.75$)
<i>934 rainstorms:</i>			
Area (km ²)	87178	35707	N($\mu_{\sqrt{}} = 288.90, \sigma_{\sqrt{}} = 60.96$)
Perimeter (km)	3654	1174	N($\mu_{\sqrt{}} = 59.63, \sigma_{\sqrt{}} = 9.90$)
x_1 (km)	382	90	-
y_1 (km)	405	75	-
x_2 (km)	328	117	W($\alpha = 367.47, \beta = 3.06$)
y_2 (km)	314	111	W($\alpha = 351.66, \beta = 2.99$)
x_3 (km)	410	104	W($\alpha = 450.01, \beta = 4.43$)
y_3 (km)	392	89	W($\alpha = 425.71, \beta = 5.12$)

W($\alpha =, \beta =$): Weibull distribution with scale parameter α and shape parameter β

N($\mu =, \sigma =$): Normal distribution with mean μ and standard deviation σ . A square root transformation of the data is indicated with a $\sqrt{\quad}$ -subscript.

Table 2 Calculated Poisson parameters λ for the spatial distribution of the cell cluster centres.

	Coordinate axis:			
	X_1	Y_1	X_{23}	Y_{23}
1-D method (cluster centres km^{-2})	0.199	0.211	0.135	0.145
2-D method (clusters km^{-2})	5.56×10^{-4}			

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. Three methods to determine rainstorm dimensions were proposed. Statistical analysis revealed that the dimensions of the rainstorms in x - and y -directions both follow a two-parameter Weibull distribution and are significantly different.

Using a level slicing technique rain cell clusters could be detected in the radar images. After the application of a 1-D and a 2-D method it could be proved that the spatial distribution of rain cell cluster centres follows an homogeneous Poisson distribution. A good interpretation of the spatial distribution of clusters can be made when using the results of the two proposed methods.

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