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Hydrologic Visibility of Weather Radar Systems Operating in Mountainous Regions: Case Study for the Ardèche Catchment (France)

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ABSTRACT

A simulation procedure has been developed for use in predetermining the expected quality of rain-rate estimates that a given weather radar system operating in a mountainous region may obtain over a given hydrologic catchment. This first application of what is referred to as the "hydrologic visibility" concept focuses on the quantification of the rain-rate error resulting from the effects of ground clutter, beam blockage, and the vertical profile of reflectivity (VPR). The assessment of the impact of the space-time structure of the radar error in terms of discharge at the catchment outlet is also investigated using a distributed hydrologic model. A case study is presented for the Ardèche catchment in France using the parameters of two S-band weather radars operated by Météo-France at Nîmes and Bollène. Radar rain-rate error generation and rainfall-runoff simulations are performed using VPR and areal rainfall time series representative of the Cévennes rain climatology. The major impact of ground clutter on both rainfall and runoff estimates is confirmed. The "hydrologic compositing procedure," based on the selection of the elevation angle minimizing the rain-rate error at a given point, is shown to be preferable to the "pseudo-CAPPI" procedure based on radar-range considerations only. An almost perfect ground-clutter reduction (GCR) technique is simulated in order to assess the effects of beam blockage and VPR alone. These error sources lead to severe and slight rain underestimations for the Nîmes and Bollène radars, respectively, over the Ardèche catchment. The results, indicating an amplification of the errors on the discharge parameters (peak discharge, runoff volume) compared to the areal rainfall error, are of particular interest. They emphasize the need for refined corrections for ground clutter, beam blockage, and VPR effects, in addition to the optimization of the radar location and scanning strategy, if hydrologic applications are foreseen.

1. Introduction

From a meteorological point of view, mountains induce a wide range of mesoscale phenomena, including the generation and intensification of precipitation. From a hydrologic point of view, mountainous topography produces shorter response times and higher streamflow volumes compared to those of flatland regions. For these reasons, real-time monitoring of rainfall is essential in mountainous regions to provide information for heavy precipitation warnings and the assessment of the hydrologic impact of such rain events, using real-time rainfall–runoff models (Binder and Schar 1996). Compared to conventional raingauge networks, ground-based weather radar systems offer a number of advantages in the real-time monitoring context. However, in such mountainous regions, the measurement of rainfall by radar is very complex, and the quality of radar estimates varies greatly, depending on the location. The interaction of electromagnetic waves with relief (ground clutter and screening effects) and the vertical structure of atmospheric reflectivity (bright band, partial beam filling at cloud tops) explain a large part of this spatial variability (Joss and Waldvogel 1990; Andrieu et al. 1997).

The aim of the present paper is to develop a physically based simulation procedure that can be used to predetermine the expected quality of rain-rate estimates that a given weather radar system may obtain over a given region in space, typically a hydrologic catchment. We refer to this quality as the "hydrologic visibility" hereafter. For a known reference rain field, the first step is

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to simulate measured reflectivities within a given detection domain. Subsequently, the radar data processing can be simulated, and the radar-derived rainfall estimates can be compared with the reference rainfall. We believe that such a simulation approach is useful to complement both radar hydrology case studies (e.g., Andrieu et al. 1997; Creutin et al. 1997) and more comprehensive radar-rain gauge evaluations in mountainous regions (e.g., Joss and Lee 1995; Joss et al. 1998; Chèze and Helloco 1999; Young et al. 1999; Vignal and Krajewski 2001). It could, in particular, be used to gauge the required efforts in terms of radar siting and networking over a given mountainous region. Previous work has been devoted to the determination of ground clutter and screening effects based on digital terrain models (DTMs) (e.g., Delrieu et al. 1995; Gabella and Perona 1998). The "hydrologic visibility" simulation will first focus on the impact of both the relief and the vertical structure of rain in terms of error on the rain rate and on the resulting discharge estimates at the catchment outlet, the information relevant for hydrologic applications. Other well-known sources of error, such as Z-R relation uncertainty, attenuation, or anomalous propagation effects, are ignored in this preliminary approach.

In section 2, a formulation of the radar rain-rate error is proposed under various simplifying assumptions. Section 3 is devoted to the presentation of the study area, the Ardèche catchment (2240 km²), located in a mediumelevation mountainous region (Cévennes-Vivarais) of France and subject to flash flooding. The reference rainfall dataset consists of the time series of vertical profiles of reflectivity (VPR) and the corresponding areal rainfall time series for two Cévennes rain events. In section 4, the rain-rate error simulation procedure is implemented to compare the performance of various scanning strategies and radar data processing methods using the parameters of two existing S-band radar systems operated by Météo-France at Nîmes and Bollène. In section 5, the radar error propagation effects in terms of discharge are considered for one of the Ardèche subcatchments (Vogüé, 635 km²) using a distributed hydrologic model (TO-PODYN). Our conclusions are reported in section 6.

2. Theory

The interpretation of the radar measurements in terms of rainfall is complex since it depends 1) on the rainfall variability at all scales (elementary scales of the raindrops, radar resolution volume, storms), 2) on the detection domain (defined mainly by the surrounding relief), and 3) on the parameters of the radar system employed. A further difficulty comes from the need to transform the reflectivity measured aloft into a rain-rate estimate at ground level. The aim in the present section is to derive a theoretical expression for the error produced when the measured reflectivity factor $Z_m(r_0, \theta_0, \phi_0)$ (mm⁶ m⁻³) is used in the calculation of the rain rate. If a standard *Z*–*R* power-law relationship with *Z*

= aR^b is used for the conversion, and if the true rain rate at a reference level h_{REF} (e.g., the ground level) is denoted $R_{\text{REF}}(x_0, y_0)$ (mm h⁻¹), the relative error RE, used hereafter as a quality index, is defined as

$$\operatorname{RE}(r_0, \ \theta_0, \ \phi_0) = \frac{[Z_m(r_0, \ \theta_0, \ \phi_0)/a]^{1/b}}{R_{\operatorname{REF}}(x_0, \ y_0)} - 1, \quad (1)$$

where (r_0, θ_0, ϕ_0) designate the spherical coordinates of a point M_0 in the atmosphere at which the radar signal contributed by various scattering elements (hydrometeors, mountains) is sampled. The Cartesian coordinates (x_0, y_0, h_0) of M_0 , with respect to an arbitrary origin, will also be used in the following derivations.

In the next three subsections, the expression for the measured reflectivity factor $Z_m(r_0, \theta_0, \phi_0)$ is derived for the general case of the presence of a weather target and a mountain target within the radar resolution volume. The resulting relative errors on the rain rate are discussed in the last two subsections.

a. Measured reflectivity and total backscattered power

The measured reflectivity can be related to the total backscattered power $P(r_0, \theta_0, \phi_0)$ (W) received at the weather radar site from a contributing region of the atmosphere centered at M_0 using the weather radar equation

$$Z_m(r_0, \theta_0, \phi_0) = P(r_0, \theta_0, \phi_0) r_0^2 / C, \qquad (2)$$

where *C* is the weather radar constant.

If independent scattering is assumed between rain and mountain targets, the power $P(r_0, \theta_0, \phi_0)$ can formally be expressed as the sum of the corresponding back-scattered powers P_R and P_M :

$$P(r_0, \theta_0, \phi_0) = P_R(r_0, \theta_0, \phi_0) + P_M(r_0, \theta_0, \phi_0).$$
(3)

Based on weather radar theory, as developed for instance by Doviak and Zrnic (1993), the following unified mathematical formulation can be proposed for these two powers:

$$P_{R}(r_{0}, \theta_{0}, \phi_{0}) = \frac{P_{t}\lambda^{2}}{(4\pi)^{3}} \iint_{V} \int \frac{I(r, \theta, \phi)W_{0}(r, \theta, \phi)\eta(r, \theta, \phi)}{r^{4}} dV \quad (4)$$

and

$$P_{M}(r_{0}, \theta_{0}, \phi_{0}) = \frac{P_{t}\lambda^{2}}{(4\pi)^{3}} \iint_{S(V)} \frac{I(r, \theta, \phi)W_{0}(r, \theta, \phi)\sigma^{0}(r, \theta, \phi)}{r^{4}} dS,$$
(5)

where (r, θ, ϕ) designate the spherical coordinates of a point *M* in the atmosphere, and *P*₁ and λ are the transmitted power (W) and the wavelength (m) of the radar,

respectively. For the weather target, the reflectivity $\eta(r, \theta, \phi)$ (m² m⁻³) is the backscattering cross section of the hydrometeors per unit volume. Similarly, the backscattering coefficient $\sigma^{0}(r, \theta, \phi)$ (m² m⁻²) is the backscattering cross section of the mountain surface per unit area.

In both equations, the function $W_0(r, \theta, \phi)$ is used to weight the contribution of the scattering elements contained in an elementary volume (or distributed over an elementary surface) centered at point *M* to the power sampled at M_0 . Details concerning this function, which is the product of the two-way power gain of radiation pattern $G_0^2 f^4(\theta_b, \phi_b)$ and a radial weighting function $|W(r_b)|^2$ (with $r_b = r - r_0$, $\theta_b = \theta - \theta_0$, and $\phi_b = \phi - \phi_0$), are available in Delrieu et al. (1995). The Gaussian approximations used hereafter, and the resulting definition of the *m*-dB radar resolution volume V_m , are also reviewed in the aforementioned reference.

The function $I(r, \theta, \phi)$ in (4) and (5) describes the power interception that may occur between the radar antenna and the target of interest. The interception may result from (i) the presence of partial or total masks due to the relief and/or (ii) cloud and rain attenuation effects. The function $I(r, \theta, \phi)$ can, therefore, be written as

$$I(r, \ \theta, \ \phi) = L_s(r, \ \theta, \ \phi) L^2(r, \ \theta, \ \phi), \tag{6}$$

where $L_s(r, \theta, \phi)$ is the screening factor, which takes the value 0 if there is a mask between the radar and the point centered at (r, θ, ϕ) , and 1 if not. The function $L^2(r, \theta, \phi)$ is the two-way attenuation factor, which takes values between 1 (no attenuation) and 0 (complete attenuation).

b. Rain-backscattered power with interception and vertical heterogeneity of precipitation

Let us first consider the rain-backscattered power (4). As a classical assumption, we consider the Rayleigh approximation to be valid for the hydrometeors of interest and use the equivalent radar reflectivity factor, denoted hereafter as Z, instead of the reflectivity η . As in Andrieu et al. (1995), a further important assumption in the present work is that the equivalent reflectivity factor field can be broken into two independent terms:

$$Z(r, \theta, \phi) = Z_{\text{REF}}(x, y)z(h), \qquad (7)$$

where (x, y, h) denotes the Cartesian coordinates of point M. The variable $Z_{\text{REF}}(x, y)$ represents the reflectivity factor at the reference level h_{REF} . The variable z(h), the VPR, represents the variations of the reflectivity factor as a function of altitude and is assumed to be horizon-tally invariant. It can be shown (Pellarin 2001) that the weather radar equation (4) then yields the following expression for $P_R(r_0, \theta_0, \phi_0)$ if the horizontal variations of the reflectivity factor field are assumed to be small at the scale of the radar resolution volume:

$$P_{R}(r_{0}, \theta_{0}, \phi_{0}) = C \frac{Z_{\text{REF}}(x_{0}, y_{0})z_{a}(r_{0}, \theta_{0}, \phi_{0})}{r_{0}^{2}}.$$
 (8)

The function $z_a(r_0, \theta_0, \phi_0)$ is defined as $z_a(r_0, \theta_0, \phi_0)$

$$= \left[\frac{8 \ln 2}{\pi \psi_3^2} \iint_{\theta,\phi} I(r_0, \ \theta \ \phi) f^4(\theta_b, \ \phi_b) \times z(r_0 \cos \theta) \sin \theta \ d\theta \ d\phi\right].$$
(9)

This function can be viewed as a correction term for the classic weather radar equation that accounts for the radar beam characteristics, the interception between the radar and the resolution volume, and the vertical heterogeneity of the reflectivity factor field.

Let us recall that the radar constant can be expressed as

$$C = \frac{P_t G_0^2 \pi^3 |K|^2 c \tau \psi_3^2}{1024 \ln 2l_r \lambda^2},$$
 (10)

where G_0 is the power gain of the antenna along the beam axis, $|K|^2$ is a constant depending on the complex index of refraction of the hydrometeors, c is the speed of light (3 10⁸ m s⁻¹), τ is the pulse duration (s), ψ_3 is the 3-dB beamwidth, and l_r is the finite bandwidth loss factor (Doviak and Zrnic 1993).

c. Mountain-backscattered power

Assuming the range extent of the radar resolution volume to be small with respect to range r_0 , the following expression can be proposed for the mountain-backscattered power:

$$P_{M}(r_{0}, \theta_{0}, \phi_{0}) = C' \frac{\Sigma^{0}(r_{0}, \theta_{0}, \phi_{0})}{r_{0}^{4}}, \qquad (11)$$

where *C'* is the radar constant for a surface target [*C'* = $P_t \lambda^2 G_0^2 / (4\pi)^3$]. The total backscattering area (m²), defined as

$$\Sigma^{0}(r_{0}, \theta_{0}, \phi_{0})$$

$$= \iint_{S(V)} I(r_{0}, \theta, \phi) |W(r_{b})|^{2} f^{4}(\theta_{b}, \phi_{b}) \sigma^{0}(r, \theta, \phi) dS,$$
(12)

is the integral of the backscattering coefficient over the illuminated area S(V) weighted by the angular and radial weighting functions and the interception function *I*. The principle of the numerical determination of mountain returns using a digital terrain model is extensively described by Delrieu et al. (1995).

It is convenient to define the *apparent* reflectivity factor $Z_M(r_0, \theta_0, \phi_0)$ of the mountain target, since radar measurements are interpreted using the weather radar equation. The variable $Z_M(r_0, \theta_0, \phi_0)$ (mm⁶ m⁻³) is related to the total backscattering area by the following expression: • The (a, b) coefficients and the radar constant C are assumed to be error-free. Additional error terms could eas-

$$Z_{M}(r_{0}, \theta_{0}, \phi_{0}) = \frac{C'}{C} \frac{\Sigma^{0}(r_{0}, \theta_{0}, \phi_{0})}{r_{0}^{2}}.$$
 (13)

d. Resulting theoretical errors on the rain rate

1) RAIN RETURNS ALONE

Let us first consider the case of radar returns without any mountain contribution [i.e., $P_M(r_0, \theta_0, \phi_0) = 0$ in (3)]. From (2) and (8), the measured reflectivity can be written as

$$Z_m(r_0, \theta_0, \phi_0) = Z_{\text{REF}}(x_0, y_0) z_a(r_0, \theta_0, \phi_0), \quad (14)$$

and the rain-rate relative error (1) can be expressed as

$$\operatorname{RE}(r_0, \,\theta_0, \,\phi_0) = [z_a(r_0, \,\theta_0, \,\phi_0)]^{1/b} - 1.$$
(15)

2) MIXED RAIN-MOUNTAIN RETURNS

Combining (2), (3), (8), (11), and (13) yields the following expression for the measured reflectivity factor when rain and mountain contributions are mixed for a given radar resolution volume:

$$Z_m(r_0, \ \theta_0, \ \phi_0) = Z_{\text{REF}}(x_0, \ y_0) z_a(r_0, \ \theta_0, \ \phi_0) + Z_M(r_0, \ \theta_0, \ \phi_0).$$
(16)

This gives the following expression for the rain-rate error:

$$\operatorname{RE}(r_{0}, \theta_{0}, \phi_{0}) = \left[z_{a}(r_{0}, \theta_{0}, \phi_{0}) + \frac{Z_{M}(r_{0}, \theta_{0}, \phi_{0})}{Z_{\operatorname{REF}}(x_{0}, y_{0})} \right]^{1/b} - 1. \quad (17)$$

Compared to (15), the mountain return contribution to the rain-rate error appears in the form of an additive term composed of the apparent mountain reflectivity factor normalized by the rain reflectivity factor. As would be expected, the impact on the estimation of rain rate depends on the relative values of the mountain and rain returns.

e. Comments

Several hypotheses were necessary in the previous developments:

- The assumption of a horizontally invariant VPR is certainly realistic only after some temporal averaging and over limited regions in space.
- Equations (15) and (17) are established under the assumption that a unique set of (a, b) coefficients can be used in the Z-R relationship over the detection domain. This is a conventional, though probably crude (especially for cold clouds), assumption made in many operational radar data processing systems.

- The (*a*, *b*) coefficients and the radar constant *C* are assumed to be error-free. Additional error terms could easily be included in the error formulation to account for these effects. For the sake of conciseness, corresponding simulations will not be presented in this article.
- Equation (3) relies on the assumption of independent scattering of the mountain and the weather targets. This assumption, reasonably well supported by the work devoted to the "mountain reference technique" (Delrieu et al. 1999; Serrar et al. 2000), is thought to be acceptable at least for simulation purposes.
- Note also that in the following numerical calculations, a "curved-spherical" coordinate system, corresponding to the 4/3 earth's radius model (Doviak and Zrnic 1993), is used for the propagation path of the electromagnetic waves. The simulation of anomalous propagation effects is beyond the scope of the present paper.

3. Study area

a. The Ardèche catchment and the ARAMIS radar network

The Ardèche catchment (2240 km² at Sauze Saint Martin) is located in the Cévennes-Vivarais region at the southern edge of the French Massif Central (Fig. 1). This medium-elevation mountainous region is subject to intense long-duration rain events during autumn. The 10-yr recurrence rainfall is, for instance, greater than 50 and 250 mm for 1- and 24-h durations, respectively, over a large part of the region (Bois et al. 1997). Special attention will be paid in section 5 to one of the Ardèche subcatchments (Ardèche at Vogüé, 635 km²). This catchment has been selected by Météo-France, Electricité de France, and the Laboratoire d'Etude des Transferts en Hydrologie et Environment (LTHE) Surface Hydrology Group for an operational evaluation of flash flood prediction tools (Datin 1998; Saulnier and Datin 2002). The hydrologic sensitivity of the region with respect to flash flooding was the reason for installing two weather radar systems in Nîmes and Bollène. The main parameters of these radar systems of the Météo-France ARAMIS radar network are listed in Table 1. The Nîmes S-band radar offers rather satisfactory coverage for most of the catchments in the southern part of the region (the Cèze, Gardons d'Anduze, d'Alès, Vidourle, and Hérault Rivers), which are located within the 40-80-km radar range. However, the coverage of the Ardèche catchment, located at ranges between 60 and 110 km, is unsatisfactory, especially in the upper subcatchments. The S-band radar in Bollène, newly installed in 2000, is expected to appreciably improve coverage in the northern part of the region, and especially the Ardèche catchment within its 20-60-km range. The narrow 3-dB beamwidth (1.28°) of the Bollène radar system is a very positive feature in terms of radar measurement quality in such a mountainous area. The operational scanning strategy of these two radar systems



FIG. 1. Presentation of the study area. A digitized terrain model of the Cévennes–Vivarais region is presented together with the locations of the three radars (with 40-km range markers) operated by Météo-France in that area. The S-band Nîmes and Bollène radars are operated for the hydrometeorological surveillance of the downstream Rhône River tributaries (such as the Cévennes–Vivarais watersheds), while the C-band Sembadel radar is dedicated to the surveillance of the upper Loire catchment. The Ardèche catchment, delineated by a thick black line, is representative of the Cévennes–Vivarais basins, which are prone to flash flooding during autumn. Two contours are drawn corresponding to the Vogüé catchment (635 km²) and the Sauze Saint Martin catchment (2240 km²). Also represented with a thin line is the contour of the Gardon d'Anduze catchment (550 km²); see section 3b.

is composed of three plan position indicators (PPIs) scanning every 5 min at preselected elevation angles. A "pseudo–constant altitude PPI" (CAPPI) procedure is used in operational mode by Météo-France for the production of the 5-min rain-rate maps. The highest-elevation data are considered within the $[0 - r_1]$ -km range, the medium-elevation data within the $[r_1 - r_2]$ -km range, and the lowest-elevation data for ranges greater than r_2 . The corresponding elevation angles and range values are listed in Table 1.

b. Reference rainfall

The knowledge of VPR climatologies is very important in radar meteorology. Some results are proposed in the literature based on long-term volumetric radar data (e.g., Joss et al. 1998; Vignal and Krajewski 2001) or on vertically pointing radar observations (Fabry and Zawadzki 1995). In the present study, the mean VPR time series derived from the dataset collected during the Cévennes 1986-88 radar experiment (Andrieu et al. 1997; Creutin et al. 1997) were considered to be the most representative information available for the Cévennes rain events. The ANATOL S-band radar (250-kW peak power, 4-m antenna, 1.8° beamwidth at half-power point) used during the experiment was set up at an altitude of 1030 m MSL and operated with a two-elevation scanning strategy (1.1° and 3.1°). A procedure was developed for the inversion of the VPRs from the reflectivity ratio curves established as a function of range (Andrieu and Creutin 1995; Andrieu et al. 1995). Time series of the hourly averaged VPRs obtained during two rain events, namely the 13-15 November 1986 and the 4-6 October 1987 rain events with 38 and 33 h of observation, respectively, are pre-

	MELODI	MTO2000
Location	Nîmes-Manduel	Bollène
x coordinate (km, Lambert II)	774.516	793.658
y coordinate (km, Lambert II)	1869.690	1927.770
Altitude (m)	77.5	327.0
Transmitter-receiver		
Peak power (kW)	600	600
Frequency (Ghz)	2.8	2.8
PRF (Hz)	330	250
Pulse width (μs)	2	2
Minimum detectable signal (MDS) (dBm)	-103	-113
Dynamic range (dB)	80	80
Antenna		
Diameter (m)	4.0	6.2
Beamwidth at half-power point (°)	1.8	1.28
Power gain (dB)	40.0	42.5
Scanning strategy	3 PPIs every 5 min	3 PPIs every 5 min
Rotation speed (° s^{-1})	5	5
Elevation angles (°)	2.6, 1.3, 0.6	1.8, 1.2, 0.8
Pseudo-CAPPI compositing ranges (km)	$r_1 = 20$	$r_1 = 35$
	$r_2 = 80$	$r_2 = 75$

TABLE 1. The Météo-France radar parameters.

sented in Figs. 2a and 2b, respectively. Also plotted in these figures are the time series of the corresponding hourly areal rainfall calculated over the Gardon d'Anduze watershed (550 km²; see Fig. 1). The areal rainfall data will be considered in section 5 for the assessment of the hydrologic impact of the radar rain-rate errors. A concise view of the VPR data is given in Fig. 2c showing the average VPR and the envelope of the hourly VPRs. The reference level h_{REF} is the radar altitude (1030 m MSL), and it is assumed that the function z(h) is equal to 1 below h_{REF} . Furthermore, since the ratio curves could not be calculated within the 5-km radar range because of sidelobe contamination in that area, the VPRs could not subsequently be estimated within the first 200 m above the radar site. Consequently, actual variations of the VPR only appear above an altitude of about 1200 m. Note that the gradient of the mean VPR is about 2.8 dB km⁻¹ between 1200 and 3000 m MSL. It then reaches a value of about -20 dB km^{-1} between 3000 and 4000 m MSL. The variability of the VPR over the 71 h is relatively high, with a variation of about 2000 m in the "echo top." Brightband effects, reaching a maximum value of about 3 dB at an altitude of 2800 m MSL, are present for a period of about 10 h during the 4-6 October 1987 rain event. The assumption of z(h) = 1 below 1200 m MSL is certainly a significant limitation of the available VPR data. However, the more comprehensive results presented by Vignal and Krajewski (2001) suggest that the variation of the average VPR may be rather limited within such an altitude range.

4. Application of the hydrologic visibility concept to the Ardèche catchment: Quality of the rainrate estimation

The aim of the present section is a first application of the hydrologic visibility concept to the Ardèche catchment using the parameters of the two S-band weather radars operated by Météo-France at Nîmes and Bollène. After a description of the implementation conditions, an illustration of the simulation results is given prior to a discussion of the performance obtained for the two radars with various scanning strategies, compositing procedures, and data processing techniques.

a. Implementation and illustration of the simulation results

In the case of rain returns alone, a major simplification, resulting from the decomposition of the reflectivity factor according to (7), is that the rain-rate theoretical error (15) is *apparently* independent with respect to the horizontal variations of the reflectivity factor field. This is of course only "apparent" since the interception function $I(r, \theta, \phi)$ and, more precisely, the attenuation factor $L^2(r, \theta, \phi)$ obviously depend on the 3D reflectivity factor field. Furthermore, in the case of mixed rain-mountain returns, $Z_{\text{REF}}(x_0, y_0)$ appears explicitly in the formulation of the rain-rate error (17).

In order to avoid the description of the horizontal variability of the reflectivity factor field:

- We will assume in the following that attenuation effects are negligible; that is, $L^2(r, \theta, \phi) = 1$ in (6). This is a reasonable assumption for the S-band radars considered herein.
- A fixed value, denoted Z_{REF} and assumed to be constant in space, will be used to parameterize $Z_{\text{REF}}(x_0, y_0)$. A climatological mean at the reference level h_{REF} associated with the VPR could be considered for this purpose. Of course, the sensitivity of the simulations to the Z_{REF} parameter will have to be assessed.



FIG. 2. Display of the hourly (left) vertical profile of reflectivity and (right) areal rainfall time series for the two Cévennes rain events of (a) 13–15 Nov 1986 and (b) 4–6 Oct 1987. The areal rainfall was measured with radar and rain gauge data over a Cévennes catchment of 550 km². (c) A concise view of the VPR data with the display of the average VPR and the envelope of the 71 VPRs. The VPR and areal rainfall data actually define the "reference rainfall" used herein in the hydrologic visibility simulation procedure.

Figure 3 provides an illustration of the simulation results obtained between azimuth angles of 260° and 335° NE for the Bollène radar system in the region of the Ardèche catchment. The left-hand column refers to simulations for an elevation angle of 0.8° , and the right-hand column refers to an elevation angle of 2.0° . The top graphs show the maps of the rain-rate errors obtained when the interactions between the electromagnetic waves and the relief are considered alone. The variable z(h) was set to 1, regardless of h, in the code imple-

mentation. The Z_{REF} parameter was set to a value of 30 dBZ for this run. Concerning the backscattering coefficient at S band, the estimate $\overline{\sigma}_0(\alpha) = -0.098 \alpha$ – 12.8 (dB) was derived from the data proposed by Moore in Skolnik (1990, chapter 12). In that expression, α , in degrees, represents the angle of incidence of the electromagnetic waves on the mountain surfaces. The topleft graph in Fig. 3 clearly shows the dramatic impact of ground clutter in terms of rain-rate estimation for the 0.8° elevation angle, with values of the rain-rate error greater than 400% for about 20% of the catchment area. Note also that a significant part of the beam is blocked by the first mountain ridge, at a range of about 15 km from the radar, leading to a rain-rate underestimation reaching -10% over most of the ground-clutter-free parts of the Ardèche catchment. Mount "Dent de Rez" (azimuth 300°N, range 24 km) produces an even more severe blockage, leading to a rain-rate error of about -40%. The top-right graph shows the considerable benefit obtained in terms of ground clutter and mask reduction when the elevation angle is increased to a value of 2°. The middle graphs in Fig. 3 show simulations performed with the average Cévennes VPR presented in Fig. 2c with screening and ground-clutter effects neglected. The interception factor $I(r_0, \theta, \phi)$ and the apparent reflectivity of the mountains $Z_{M}(r_{0}, \theta_{0}, \phi_{0})$ are set to 1 and 0, respectively, in these simulations. Obviously, due to the decrease of VPR with altitude, the rain-rate error RE is equal to 0 or less (corresponding to an underestimation) and decreases with range. Compared to the top graphs, the situation is now reversed, with a much better rain-rate estimation over the Ardèche catchment for the low elevation angle. Finally, the bottom graphs in Fig. 3 provide the results obtained when both the VPR and the relief-related effects are taken into account, showing a complex spatial structure of the rain-rate error. At the scale of the radar resolution volume, possible compensations may occur between overestimating (e.g., ground clutter, eventual bright bands) and underestimating effects (interception, decrease of the VPR with the altitude).

b. Assessment criteria at the catchment scale

Two quality criteria will be considered to assess the radar performance at the catchment scale. The average of the absolute value of the rain-rate error (1) is defined, in percent, as

$$\overline{\mathrm{RE}}| = \frac{100}{N} \sum_{i=1}^{N} |\mathrm{RE}(i)|, \qquad (18)$$

where *N* is the number of 1-km^2 pixel elements used for the discretization of the catchment. The $|\overline{\text{RE}}|$ criterion could mean that, on the average, the rain rate is over- or underestimated by $|\overline{\text{RE}}|$ % at any point of the catchment for the considered radar configuration.

A direct average of the error, denoted \overline{RE} , in percent, is also computed as



FIG. 3. Illustration of the hydrologic visibility simulation procedure. The case of the S-band MTO2000 radar system located in Bollène is considered over the azimuthal sector corresponding to the Ardèche catchment. The left- and right-hand columns correspond to simulations performed for elevation angles of 0.8° and 2°, respectively. The top graphs refer to the rain-rate errors RE (%) resulting from electromagnetic wave–relief interactions alone (ground clutter and masks), the middle graphs to the rain-rate errors resulting from the average VPR alone, and the bottom graphs to the combined effects of the two sources of error.



FIG. 4. Evolution of the average of the absolute value of the rainrate error calculated over the Ardèche catchment (Sauze Saint Martin) as a function of the elevation angle. The sensitivity of the simulation procedure to the parameter Z_{REF} is tested using three values (20, 30, and 40 dBZ). These curves indicate that, depending on the elevation angle, ground clutter has both a tremendous and a hardly quantifiable impact in terms of rain-rate estimation. However, the optimal elevation angle value is defined to within $\pm 0.2^{\circ}$.

$$\overline{\text{RE}} = \frac{100}{N} \sum_{i=1}^{N} \text{RE}(i), \qquad (19)$$

because this criterion is equal to the areal rainfall error in case of a uniform rain rate over the catchment.

In order to quantify and generalize the results given in Fig. 3, the dependance of the |RE| criterion on the elevation angle has been calculated for the Bollène radar over the Ardèche catchment (Fig. 4). Three values of Z_{REF} (20, 30, and 40 dBZ) were considered to illustrate the sensitivity of the procedure to this parameter. As expected, the presence of ground clutter greatly affects the |RE| criterion with a significant increase, whatever the Z_{REF} value, as the elevation angle decreases. Obviously, since ground clutter disappears, the sensitivity of the rain-rate error calculation to the Z_{REF} parameter diminishes for high elevation angles. The optimum elevation angle lies between 1.8° and 2.2° , with an average rain-rate error increasing from 24% to 35% when the Z_{REF} parameter is taken to be equal to 40 and 20 dBZ, respectively.

c. Performance obtained for various radar locations, scanning strategies, compositing procedures, and data processing techniques

The actual operational scanning strategies (see Table 1) of the two radar systems are considered in the following simulations. The hypothetical operation of a MELODI radar system at Bollène is also considered, in order to evaluate the expected benefit related to the use of the bigger antenna of the MTO2000 radar system. Compositing issues, that is, combining radar measurements performed at various elevation angles to obtain the best possible rain-rate field, are also addressed. Two compositing procedures are considered:

- the pseudo-CAPPI procedure, used in operational mode by Météo-France, for which the choice of the elevation angle is range-dependent only (see Table 1); and
- 2) the "hydrologic procedure" by which, for each point of the area of interest, the elevation angle leading to the minimum error on the rain-rate is selected among the available elevation angles. Note that the optimal elevation angle is chosen on the basis of the average VPR profile displayed in Fig. 2c.

Furthermore, a ground-clutter rejection (GCR) technique based on the pulse-to-pulse fluctuations of the radar signal is presently implemented within the Météo-France radar systems. Given the major impact of the related errors (e.g., Figs. 3 and 4), we have considered the possibility of modeling a GCR technique in our simulations. For this purpose, the Météo-France GCR attenuation relation was adjusted using dry-weather ground clutter collected with and without GCR. The corrected ground-clutter values $Z_M^{GCR}(r_0, \theta_0, \phi_0)$ are given by the following relations:

- If $Z_M(r_0, \theta_0, \phi_0) \le 42$ dBZ, then $Z_M^{GCR}(r_0, \theta_0, \phi_0) = Z_M(r_0, \theta_0, \phi_0) 30$ (dBZ).
- If $Z_M(r_0, \theta_0, \phi_0) > 42$ dBZ, then $Z_M^{GCR}(r_0, \theta_0, \phi_0) = Z_M(r_0, \theta_0, \phi_0) 35$ (dBZ).

These values are used instead of $Z_M(r_0, \theta_0, \phi_0)$ in (17) to evaluate the rain-rate error. We may outline that such a GCR model is very crude and probably very optimistic regarding the actual performance of GCRs during rainy conditions both for ground-cluttered and ground-clutter-free areas.

The simulation procedure was implemented with the full VPR time series presented in Fig. 2. Table 2 provides the results obtained in terms of the average value of the $|\overline{RE}|$ and the RE criteria, along with the 10% and 90% quantiles (denoted $|\overline{RE}|$, \overline{RE} , q10, and q90, respectively) of the statistical distribution of $|\overline{RE}|$ calculated over the 71 available VPRs for the various radar configurations listed above.

Concerning the MELODI radar system at Nîmes, an overall average underestimation of about 47% can be attributed to range, mask, and VPR effects. Depending on the VPR, a fluctuation of this error in the range (10%-65%) is observed. For this radar system, ground-clutter effects are weak over the Ardèche catchment: ground clutter close to Mount Lozère induces a slight increase of the |RE| criterion and a decrease of the RE criterion, reflecting the compensation of overestimating and underestimating effects. Note that the hydrologic compositing procedure (with GCR off) is as efficient as the GCR model in the reduction of this error in such a case.

Concerning the MTO2000 radar installed at Bollène,

	MTO2000 radar at Bollène (MELODI radar at Bollène)					MELODI radar at Nîmes			
Ardèche catchment (2240 km ²) Criteria	RE ^a (%)	q10 ^ь (%)	q90 ^ь (%)	RE° (%)	RE (%)	q10 (%)	<i>q</i> 90 (%)	RE (%)	
GCR off									
Pseudo-CAPPI composite	322.2 (240.3)	316.7 (234.2)	330.4 (249.2)	298.0 (210.7)	66.5	44.6	79.9	-28.5	
Hydrologic composite	32.4 (69.6)	26.2 (64.1)	41.6 (76.6)	5.8 (40.4)	46.8	10.4	64.9	-46.7	
GCR on									
Pseudo-CAPPI composite Hydrologic composite	16.8 14.5	7.6 7.3	31.2 25.7	-16.9 -13.7	48.6 46.7	26.4 9.6	62.3 65.1	$-48.6 \\ -46.7$	

 TABLE 2. Performance of the Bollène and the Nîmes S-band radars over the Ardèche catchment (values in parenthesis are at 2240 km² at Sauze Saint Martin).

||RE|| represents the average value over the 71 VPRs of the |RE|| criterion calculated at the catchment scale using (18).

^b q10 and q90 represent the 10% and 90% quantiles, respectively, of the statistical distribution over the 71 VPRs of the $\overline{|\text{RE}|}$ criterion calculated at the catchment scale using (18).

e RE represents the average value over the 71 VPRs of the RE criterion calculated at the catchment scale using (17).

the pseudo-CAPPI simulation with GCR off clearly demonstrates the dramatic impact of the ground clutter over the Ardèche catchment, with average overestimations at the catchment scale of greater than 300%. The hydrologic compositing procedure provides a very significant improvement with an $|\overline{RE}|$ criterion of 32.4%. Almost perfect compensation between overestimations and underestimations yields an \overline{RE} criterion of 5.8%. When the GCR technique is applied, both the pseudo-CAPPI and the hydrologic compositing procedure criteria are very significantly improved (with a slight superiority shown by the hydrologic compositing procedure). An overall underestimation of about -14% to -16% remains as a result of mask and VPR effects.

The numbers in parentheses listed in Table 2 for the "GCR off" simulations at Bollène refer to the hypothetical case of the use of a MELODI radar at that location instead of the implemented MTO2000 radar. At first glance, the results obtained are paradoxical since the MELODI rain-rate errors are smaller than the MTO2000 errors for the pseudo-CAPPI simulation, while an improvement would have been expected as the result of the use of a larger antenna. A detailed analysis confirms this finding: at the ranges corresponding to the Ardèche catchment (30-80 km), the MTO2000 mountain returns are actually more intense than the MELODI returns at the low elevation angle as the result of the better energy concentration around the beam axis. The situation is reversed close to the radar, owing to the broader antenna pattern of the MELODI radar system. It is very interesting to note that the hydrologic visibility procedure is able to take advantage of the smallest beamwidth with an $|\overline{RE}|$ criterion reduced from 69.6% to 32.4%; here again, the good ground-clutter filtering capability of this compositing technique is illustrated.

As a complement to the results listed in Table 2, Fig. 5 (top graphs) presents the maps of the selected ele-

vation angles for the two compositing procedures. The spatial distribution of the average value and the 10% and 90% quantiles of the rain-rate error calculated over the 71 VPRs in the "GCR off" simulation case are presented as well. These figures clearly show that the criteria listed in Table 2 only provide a partial assessment of the radar rain-rate errors characterized by a discontinuous behavior in space (ground-clutter effects versus range-dependent effects). Note that the use of a more complex elevation angle pattern for the hydrologic compositing procedure (right column) actually leads to more uniform rain-rate error maps compared to the pseudo-CAPPI compositing procedure (left column). The time variability of the rain-rate errors illustrated with the maps of the q10 and q90 quantiles is also high, mostly in the ground-clutter-free areas at long range.

5. Impact of the rain-rate errors in terms of discharge at the Vogüé catchment outlet

The space-time structure of the radar errors illustrated in Fig. 5 is thought to have a very important impact on the discharge at catchment outlets. To assess this point, the TOPODYN hydrologic model has been used to simulate reference and radar-derived discharges at the outlet of one of the Ardèche catchments (Ardèche at Vogüé, 635 km²).

a. Description of the hydrologic model used

The hydrologic model used herein is based on the well-known topography-based TOPMODEL (Beven and Kirkby 1979; Beven et al. 1995; Beven 1997), which is one of the first attempts to model a distributed hydrologic response with the concept of variable contributing areas, introduced by Cappus (1960) and Dunne and Black (1970). This model was developed with the

aim of providing a physically realistic set of modeling concepts, needing only a small number of parameters. Basically, TOPMODEL predicts, at each time step, the spatial distribution of the water content of each digital terrain model (DTM) pixel of the catchment. The water content is calculated as a function of the spatial distribution of an index of hydrologic similarity and of the mean overall water storage. Initially (Beven and Kirkby 1979), the index of hydrologic similarity was a pure topographic index κ expressed as $\kappa = \ln(a/\tan\beta)$ with a the drainage area per unit length (m) of hillslope and $\tan\beta$ (-) the topographic local slope used as an approximation of the hydraulic gradient of the perched hillslope water table. The overall water storage, or storage deficit, is derived from a water balance assessment at each time step [see Beven et al. (1995) for full details]. Because the concept of contributing areas was recognized to be the preponderant runoff generation process over the Ardèche catchments (Datin 1998), the TOP-MODEL approach was chosen in this study to investigate the effect of radar rain-rate errors on flood prediction.

However, TOPMODEL assumes that rainfall is uniform in space, which is a reasonable assumption for the small catchments ($<100 \text{ km}^2$) for which it was first developed. In the present region, rainfall may have a strong spatial variability (Bois et al. 1997). A specific version of TOPMODEL, called TOPODYN, was therefore developed (Datin 1998) with two main new features. First, it offers an improvement in the water balance assessment, ensuring a more accurate mass balance conservation (Saulnier and Datin 2002; Habets and Saulnier 2001). Second, the spatial variability of the rainfall is taken into account explicitly by means of a dynamic index of hydrologic similarity defined as

$$\lambda_{i,i} = \ln\left(\frac{a_{i,i}R_{i,i}}{\tan\beta_i}\right),\tag{20}$$

with

$a_{i,t}$ (m)	=	the drainage area per unit length
		of hillslope,
$\tan\beta_i$ (-)	=	the topographic local slope, and
$R_{i,t}$ (m h ⁻¹)	=	the hillslope recharge of the
		perched water table.

As opposed to TOPMODEL, which considers a uniform hillslope recharge $\overline{R}_{i,t}$ the hillslope recharge $R_{i,t}$ of the water table can now change in space as the spatial variability of rainfall is taken into account. For a given time step, some parts of the catchment may receive no rain. The lateral subsurface downslope flow on these "dry" parts of the catchment may then decrease and eventually disappear. This means that the surface of the catchment where subsurface flow actually takes place may change in time and space. It is no longer considered to be equal to the overall catchment area, as it is in TOPMODEL. This leads us to consider dynamic drainage areas $a_{i,t}$ in (20) for each pixel, which now may vary between zero (if no subsurface downslope flow takes place on the hillslope) and the total topographic upslope area (if subsurface flow takes place over the entire hillslope). The water content of the dry part of the catchment where there is no lateral subsurface downslope flow is set to a maximal value *do* [expressed as a deficit as in TOPMODEL formalism (see Beven et al. 1995)], as in Habets and Saulnier (2001). Here, the rest of the TOPODYN model is kept the same as the TOP-MODEL version used in Saulnier et al. (1998). TO-PODYN is used as an event-based model, assuming homogenous soils over the catchment, because no spatial information was available. Four parameters need to be calibrated:

- *K*₀ (m h⁻¹) the saturated conductivity (an isotropic soil is assumed with identical downslope and vertical conductivity);
- *m* (m), the shape of the exponential decrease of the transmissivity with water content deficit respectively;
- SRMax (m), the maximum level of interception and root zone storage (initially empty for each event); and
- INTER (m h⁻¹), the maximum rate of water layer loss by interception and evapotranspiration, determined at each time step from the content available in the interception/root zone storage.

At each time step, the subsurface/return flow drainage from the subsurface store is transferred to the outlet by a routing algorithm based on isochrones. The direct runoff from the contributing areas is converted to an effective rainfall and is transferred to the outlet by a unit hydrograph function, identified by the first differenced transfer function (FDTF)–Eruhdit method (Duband et al., 1993).

b. Implementation and results of the hydrologic simulation

Ideally, we would have liked to carry out the rainfallrunoff modeling over the entire Ardèche basin (2240 km² at Sauze Saint Martin). However, the presence of karstic areas in the lower part of the catchment (region of the well-known Ardèche Gorges) prevents satisfactory modeling within the TOPMODEL/TOPODYN framework. The Vogüé catchment was therefore selected for the hydrologic simulation, for the following reasons:

1) A hydrologic study has recently been carried out on this basin (Datin 1998) with a calibration of TOP-MODEL based on 35 rain events (26 for calibration and 9 for validation). One of the advantages of TO-PODYN is that it uses the same set of four parameters as TOPMODEL for which the following values were determined by Datin (1998): $K_0 = 21 \text{ mm h}^{-1}$, M = 0.032 m, INTER = 0 mm h⁻¹, and SRMax = 0.014 m. These values were used hereafter for the TOPODYN simulations.



FIG. 5. Results of the hydrologic visibility procedure for the Bollène radar over the azimuthal sector corresponding to the Ardèche catchment. The operational scanning procedure is considered with measurements performed at three elevation angles: 0.8°, 1.2°, and 1.8°. The GCR technique is not applied in the simulations displayed. The left-hand column refers to results obtained with the "pseudo-CAPPI" procedure, based on range consideration only, used for compositing the radar measurements. The right-hand column refers to the "hydrologic composite" based on the selection of the elevation angle that minimizes the rain-rate error at any point. The top graphs present the elevation angles selected for the two compositing methods (lowest, medium, and highest elevation angles in blue, yellow, and orange, respectively). The next

2) The available areal hourly rainfall time series of the Cévennes 1986–88 experiment (see Figs. 2a and 2b) were calculated over the Gardon d'Anduze catchment (Fig. 1), the size of which (550 km²) is close to that of the Vogüé catchment (635 km²).

The reference discharge curves were calculated with the areal hourly rainfall time series for the two events of 13-15 November 1986 and 4-6 October 1987 for which rain totals of 120 and 150 mm, respectively, were observed at the catchment scale. In terms of peak discharge (250 and 400 m³ s⁻¹), these two events are representative of the 25% and 37% quantiles, respectively, of the 35 actual events available for the Vogüé catchment (the first three events of the series reach peak discharges of 2350, 1400, and 1000 m³ s⁻¹). The only difference between the reference and the radar-derived discharge simulations lies in the rain input. For the two available radar locations (Nîmes and Bollène) and the scanning strategies used by Météo-France, the radar rain-rate error maps were calculated for each hourly time step using the corresponding VPRs (Figs. 2a and 2b). These error maps were then used to "spatialize" the uniform reference rainfall over the catchment. As in section 4, the sensitivity to (i) compositing procedures and (ii) implementation of a GCR technique was assessed. Some of the discharge curves are presented in Fig. 6, while Tables 3a and 3b list quantitative criteria regarding these simulations. The criteria used are (i) for the rain, the $|\overline{RE}|$, and the \overline{RE} criteria calculated over the Vogüé catchment, and (ii) for the discharge, the ratio of radar-derived to reference peak discharges, and the ratio of radar-derived to reference total runoff volumes, together with the efficiency (Nash and Sutcliffe 1970) and the correlation coefficient of the radar-derived and reference discharge time series.

The case of the MELODI radar operated at Nîmes (Fig. 6a and Table 3a) is typical of the radar performance at long range, with important underestimations on both the rainfall and the discharge resulting from screening and VPR effects. Since almost no ground clutter is present over the Vogüé catchment, the results are rather similar for the "GCR on" and "GCR off" simulations. The vertical structure of the rain has a marked influence with significantly better performance for 4-6 October 1987. This result could, however, be partly due to the brightband artifact. Note an amplification of the errors on both the peak discharge and the runoff volume (Table 3a) with respect to the areal rainfall error. The hydrologic compositing procedure provides a significant improvement over the pseudo-CAPPI method for the 4-6 October 1987 event. However, this is not the case for the 13-15 November 1986 simulation. Remember that the elevation angle was chosen on the basis of the average Cévennes VPR presented in Fig. 2c. This choice may not be optimal for all the VPRs of the time series.

Figure 6b presents the results obtained with the MTO2000 radar operated at Bollène with "GCR off." The dramatic impact of ground clutter in the upper subcatchments of the Ardèche basin is clear in this simulation. The situation is extreme for the pseudo-CAPPI composite with major rain and discharge overestimation. These errors are reduced to about 35%-40% for the areal rainfall with the hydrologic compositing procedure. This level of accuracy in terms of rainfall is, however, insufficient to allow hydrologic use of the radar data; here again, the runoff volume and peak discharge errors are amplified to about 100%-110% and 85%-95%, respectively. When the GCR model is applied (Fig. 6c), both compositing techniques provide similar results, reflecting a moderate underestimation (about 15% on the rainfall and about 25%-30% on the peak discharge) due to the screening and VPR effects. Finally, the two dotted curves in Figs. 6a and 6c and the "VPR CORR" lines in Tables 3a and 3b refer to the results of a simulation aimed at correcting the beam blockage and VPR effects in addition to the application of the GCR technique. For this purpose, VPR identification was performed using the procedure proposed by Andrieu and Creutin (1995) and further developed for volume scanning radar by Vignal et al. (1999, 2000). Note that, for the simulations presented, two elevation angles (3° and 4°) were added to the operational scanning protocols of the Nîmes and Bollène radar systems in order to perform VPR identification over the Ardèche catchment with unblocked elevation angles. For the Bollène radar, an almost perfect restitution of the reference discharge is thus obtained. However, note that a significant underestimation remains for the Nîmes radar, a fact that tends to confirm the difficulty of radar data correction for long ranges (80-100 km). Extensive simulations performed by Pellarin (2001) are not presented here for the sake of conciseness. However, Fig. 7 summarizes the results obtained for the two radar systems in terms of error on peak discharge and runoff volume as a function of the error on areal rainfall. The amplifying trend of the error on the runoff parameters compared to the error on the rainfall is clearly illustrated in this figure, a result of the nonlinearity of the rainfallrunoff processes.

6. Conclusions

The aim of the present study was to develop a simulation procedure that could be used to predetermine

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graphs present the relative error maps derived from the hydrologic visibility procedure with the average value $\overline{|\text{RE}|}$ (%) the 10% and the 90% quantiles (%), respectively, of the statistical distribution of the rain-rate errors RE calculated with the available 71 hourly VPRs.



FIG. 6. Hydrologic visibility rainfall–runoff simulations performed over the Ardèche catchment at Vogüé (635 km²) with the TOPODYN model for the Cévennes rain events of 13–15 Nov 1986 and 4–6 Oct 1987. In these figures, the hyetographs and the thick discharge line correspond to the reference areal rainfall (uniform in space) and discharge, respectively. Various radar error patterns derived from the hydrologic visibility results are added to the uniform reference rainfall. The thin black line corresponds to the pseudo-CAPPI simulation and the gray line to the "hydrologic composite" resulting rainfall–runoff simulation. The dotted lines on (a) and (c) correspond to the simulation performed with rain-rate space–time series corrected for ground clutter, mask, and VPR effects (involving radar "measurements" at two additional elevation angles for the VPR estimation).

					Discharge			
		Rainfall		Error on	Error on peak discharge (%)	Efficiency	Correlation coefficient	
Ardèche cathment at Vogüé (635 km²)		RE	RE	volume (%)				
(a) MELODI radar at Nîi	mes							
NOV 1986 GCR off	Pseudo-CAPPI composite	-64.5	64.5	-79.4	-83.7	-1.717	0.815	
	Hydrologic composite	-68.3	68.3	-82.1	-85.8	-1.882	0.817	
NOV 1986 GCR on	Pseudo-CAPPI composite	-64.5	64.5	-79.4	-83.7	-1.717	0.815	
	Hydrologic composite	-68.3	68.3	-82.1	-85.8	-1.882	0.817	
	VPR CORR	-31.3	32.8	-41.5	-47.4	0.187	0.921	
OCT 1987 GCR off	Pseudo-CAPPI composite	-52.5	52.5	-74.9	-79.8	-0.701	0.910	
	Hydrologic composite	-46.8	46.8	-67.6	-71.7	-0.443	0.821	
OCT 1987 GCR on	Pseudo-CAPPI composite	-52.4	52.4	-74.8	-79.7	-0.700	0.910	
	Hydrologic composite	-46.8	46.8	-67.6	-71.7	-0.443	0.821	
	VPR CORR	-12.2	24.8	-19.4	-27.7	0.834	0.975	
(b) MTO2000 radar at B	ollene							
Nov 1986 GCR off	Pseudo-CAPPI composite			Extremely bad results				
	Hydrologic composite	35.6	35.6	111.7	96.5	-4.828	0.761	
Nov 1986 GCR on	Pseudo-CAPPI composite	-15.7	17.3	-20.1	-25.5	0.789	0.977	
	Hydrologic composite	-14.2	15.2	-19.0	-24.0	0.815	0.983	
	VPR CORR	-1.7	5.2	0.8	-0.5	0.999	0.999	
Oct 1987 GCR off	Pseudo-CAPPI composite	Pseudo-CAPPI composite Extremely bad results						
	Hydrologic composite	38.7	38.7	97.8	+84.7	-2.270	0.864	
OCT 1987 GCR on	Pseudo-CAPPI composite	-17.6	17.6	-27.8	-32.5	0.731	0.989	
	Hydrologic composite	-16.2	16.2	-25.9	-30.6	0.762	0.990	
	VPR CORR	1.7	8.0	5.0	2.8	0.990	0.996	

TABLE 3. Performance of (a) the Nîmes MELODI S-band radar and (b) the Bollène MTO2000 S-band radar over the Ardèche catchment (635 km² at Vogüé) in terms of rainfall and discharge estimation.

the quality of rain-rate estimates that a given weather radar operating in a mountainous region may obtain over a given hydrologic catchment. The "hydrologic visibility" procedure, thus developed, consists of three steps. The first step is the quantification of the mountain returns and beam blockage effects using a digitized terrain model according to the procedure proposed by Delrieu et al. (1995). The second step is the quantification of the error on the rain rate for a given elevation angle. Under the assumptions of 1) independent scattering of the rain and mountain targets, 2) decomposition of the 3D reflectivity field into a horizontal field multiplied by the vertical profile of reflectivity (VPR), 3) negligible attenuation effects, and 4) a perfectly known Z-R relationship, the rain-rate error was derived from an integration over the radar resolution volume depending on the VPR, the eventual beam blockage between the radar and the target, and the mountain-backscattered power. The third step involves compositing, that is, combining radar measurements performed at various elevation angles to obtain the best possible rain-rate field. Finally, the impact of the space-time structure of the rain-rate errors in terms of discharge was also assessed using the TOPODYN distributed hydrologic model.

For the operational scanning strategies of the two weather radar systems operated by Météo-France in Nîmes and Bollène, and considering VPR and areal rainfall time series representative of the Cévennes rain climatology, we confirm that ground clutter has a tremendous impact on both rainfall and runoff estimates. Furthermore, the "hydrologic compositing" procedure, based on the selection of the elevation angle minimizing the rain-rate error at a given point, is preferable in mountainous regions to the "pseudo-CAPPI" procedure based on radar-range considerations only. The hydrologic compositing method acts as a ground-clutter reduction (GCR) technique; however, it is insufficient when applied to the Bollène radar for the elevation angles considered. An almost perfect GCR technique was simulated in order to assess the effects of beam blockage and VPR alone. These effects lead in the present case to severe and slight underestimations for the Nîmes and Bollène radar systems, respectively. The identification of the VPR time series using two additional elevation angles and the correction of beam blockage and VPR effects proved to be effective for the Bollène radar system but insufficient for the Nîmes radar system. Corrections for ground clutter, beam blockage, and VPR effects are, therefore, compulsory for the hydrological use of radar in mountainous regions in addition to the optimization of the radar location and scanning strategy. However, at ranges greater than roughly 80 km, this refined data processing may not be sufficient, and the use of radar networks becomes necessary. The rainfallrunoff simulations indicate an amplification of the errors on the peak discharge and runoff volume compared to the areal rainfall error. These results emphasize the need to increase the quality of radar estimates if hydrologic applications are foreseen.

Despite the strong hypothesis performed, the hydro-



FIG. 7. Evolution of the error on (a) the peak discharge and (b) the runoff volume as a function of the error on the areal rainfall over the catchment. The figure displays the results of an extensive set of simulations corresponding to both the Nîmes and Bollène radars, with various levels of refinement in the radar data processing. Note the amplification of the discharge errors compared to the areal rainfall errors as a result of the nonlinearity of rainfall–runoff processes.

logic visibility procedure seems to provide sound results from a practical perspective. In order to increase the acceptance of this approach, radar-rain gauge comparisons are being performed to assess the quality of the hydrologic visibility theoretical errors. For this purpose, the Météo-France operational radar data collected during the years 2000 and 2001 are compared to the in situ data of a 160-rain gauge network at an hourly time step, using a geostatistical framework. Since full volumetric radar data are not available during this period, focus is given in the mentioned study to the validation of relief-induced errors and the assessment of the operational GCR technique. A complementary study based on the dataset collected during the HYDROMET inte-

grated radar experiment (HIRE98) (Uijlenhoet et al. 1999) is also being performed to assess the VPR-induced errors by means of direct VPR measurements realized with a vertically pointing radar located 80 km from the Nîmes radar. The preliminary results show the relevance of the VPR-induced theoretical error at very short time steps (e.g., 5 min), a confirmation of the results already obtained by Andrieu and Creutin (1991) at daily time steps. Finally, the Bollène 2002 experiment to be realized in cooperation with Météo-France will be devoted to the operational test of a nine-elevation scanning strategy. This experiment will allow a complete validation of the proposed simulation approach and further improvement to the description of the Cévennes VPR climatology. We also plan to develop the hydrologic visibility concept using, as the reference rainfall, the 3D rain fields obtained by high-resolution radar measurements and also the rain outputs of high-resolution, nonhydrostatic meteorological models. The use of such 3D rain fields may allow us to eliminate many of the assumptions that were necessary in the present work.

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