Evaluation of RadVil, a Radar-Based Very Short-Term Rainfall Forecasting Model

BRICE BOUDEVILLAIN

Laboratoire d'étude des Transferts en Hydrologie et Environnement, Grenoble, and Laboratoire Central des Ponts-et-Chaussées, Bouguenais, France

HERVÉ ANDRIEU

Laboratoire Central des Ponts-et-Chaussées, Bouguenais, France

NADINE CHAUMERLIAC

Laboratoire de Météorologie Physique, CNRS, Aubière, France

(Manuscript received 4 January 2005, in final form 13 June 2005)

ABSTRACT

A very short-term rainfall forecast model is tested on actual radar data. This model, called RadVil, takes advantages of voluminal radar data through vertically integrated liquid (VIL) water content measurements. The model is tested on a dataset collected during the intensive observation period of the Mesoscale Alpine Program (MAP). Five rain events have been studied during this experiment. The results confirm the interest of VIL for quantitative precipitation forecasting at very short lead time. The evaluation is carried out in qualitative and quantitative ways according to Nash and correlation criteria on forecasting times ranging from 10 to 90 min and spatial scales from 4 to 169 km^2. It attempts to be consistent with the hydrological requirements concerning the rainfall forecasting, for instance, by taking account of the relation between the catchments' size, their response time, and the required forecasting time. Several versions of RadVil corresponding to several VIL measurement strategies have been tested. Improvements offered by RadVil depend on meteorological situations. They are related to the spatial and temporal evolution of the VIL field structure and the validity of the models assumptions. Finally, a relationship between the temporal structure of VIL fields and forecast quality is established.

1. Introduction

Improving the management of urban rain water has become an important issue for most cities. Reducing the pollution flux to the natural environment requires reducing sewer overflows and limiting urban runoff. The ability to improve flood warning requires the hydrological survey of urbanized catchments. In any case, an accurate management of urban rainwater requires the measurement of rainfall in real time with a good accuracy and simulations of the hydrological behavior of urban catchments at temporal and spatial resolutions consistent with the response time of urbanized catchments. The response time depends on the physical characteristics of the catchments such as slope and surface area. The small size of urban catchments, usually less than 50 to 100 km^2, explains the short response time of these catchments, usually less than 2 h. Such response times make rainfall forecasts quite valuable for operational services.

Rainfall forecasting for urban applications has been addressed by various approaches. The widely used methods are advection methods, which extrapolate the movement of rain zones derived from radar echoes (Li et al. 1995; Bellon and Zawadzki 1994). Some methods track the displacement of individual rain cells and extrapolate their velocity and others characteristics such as shape, intensity, and size (Einfalt et al. 1990; Brémaud and Pointin 1993; Ding et al. 1993; Denoeux and Rizand 1995; Johnson et al. 1998; Handwerker 2002). These advection methods do not explicitly deal with physical processes. They provide very limited information about the future dynamic development of the pre-

Corresponding author address: Brice Boudevillain, Laboratoire d'étude des Transferts en Hydrologie et Environnement, BP 53, 38 041 Grenoble CEDEX 09, France.
E-mail: brice.boudevillain@hmg.inpg.fr

cipitation fields. Their performance depends on the rainfall type with much better results for stratiform cases than for convective ones. In the particular case of convective cells, the forecast lead time may be very short (Faure et al. 2002) while the need for an accurate forecast is very important for urban applications.

Despite a heavy parameterization of precipitation, numerical weather prediction models (NWP) are very good from a physical point of view. Many weather services are moving toward limited area models with spatial grid spacings on the order of 2–3 km for operational forecasts in the very near future. Indeed with this grid spacing the spatial resolution becomes interesting for smaller-scale hydrological applications. The assimilation of radar information within numerical models (Ducrocq et al. 2000) is a promising evolution, but one which remains a subject of investigation for atmospheric research. For the smallest scales corresponding to the flash floods, these models remain unsuitable for hydrological needs in terms of spatial and temporal resolutions and in terms of computation time.

Intermediate solutions consist of combining various types of information as illustrated by Pierce et al. (2000) or Fox et al. (2001) who use the information provided by a NWP and combine a cell tracking method with a life cycle cell model. The method proposed in this paper, aims at improving radar based forecasting methods by means of voluminal scanning. The proposed way consists of representing dynamical and physical processes by a simple conceptual model (Georgakakos and Bras 1984) and using benefits from voluminal radar data to represent the evolution of vertically integrated liquid water content (VIL; Seo and Smith 1992). Several studies have addressed this approach without yet reaching clear conclusions, essentially because of the lack of adapted data. A numerical feasibility study (Thielen et al. 2000) confirmed a preliminary study done by simulation (Dolcine et al. 2000) and showed that this model might be able to perform better than a classical advection method at very short-term lead times (less than 1 h).

The objective of this paper is the evaluation of a very short-term rainfall forecasting model (hereafter called RadVil) based on the VIL evolution estimated by actual weather radar data. The data come from a MeteoSwiss operational radar located at 60 km to the north of Milan. The records correspond to five meteorological case studies of the intensive observation period of the Mesoscale Alpine Program (MAP; Bougeault et al. 2001). This paper is organized as follows. Section 2 addresses the formulation and the implementation of RadVil. The meteorological case studies selected for RadVil evaluation are presented in section 3. The methodology adopted to test the model is described in section 4. The obtained results are compiled and discussed in section 5. Section 6 provides conclusions and a perspective on future developments.

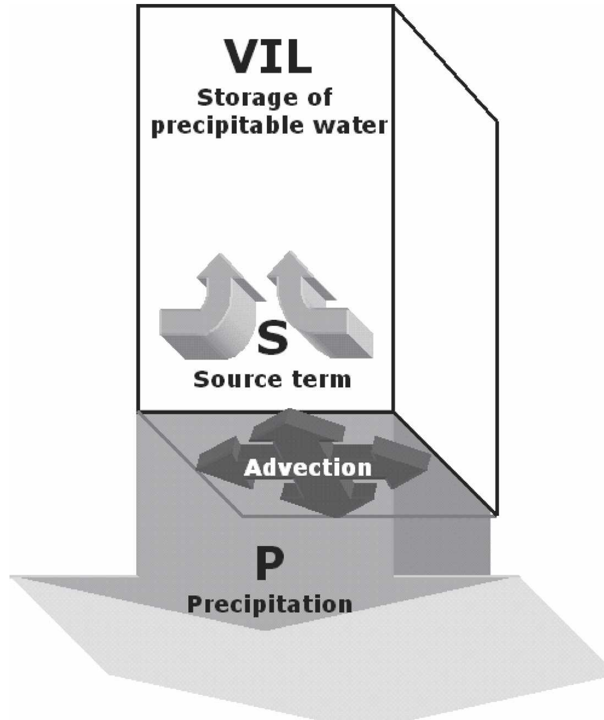

FIG. 1. Schematic representation of RadVil.

2. Presentation of RadVil

a. Formulation

The present section deals with the formulation and the implementation of the rainfall forecasting model RadVil (Fig. 1) suited for hydrological purposes. The only input variables are surface rainfall rate and VIL measurements, both of which are provided by radar. The formulation of RadVil intends to take advantage of voluminal radar information to improve simple advection forecasting methods.

The model relies on two relationships:

- A continuity Eq. (1), which describes the temporal VIL (kg m^{-2}) evolution in an atmosphere column:

$$\frac{d(\mathrm{VIL})}{dt} = S(t) - P(t) \tag{1}$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} + v_x \frac{\partial}{\partial x} + v_y \frac{\partial}{\partial y}, \tag{2}$$

v_x and v_y are the horizontal components of the advection velocity (m s^{-1}), P stands for the ground rainfall rate (kg m^{-2} s^{-1}), which represents the output term from the column, and S represents the input term (kg m^{-2} s^{-1}) of rainwater in the column. Equation (2) outlines that the total derivative includes local changes and advection.
- A relationship between the VIL and the rainfall rate P:

$$P(t) = \frac{\mathrm{VIL(t)}}{\tau(\mathrm{t})}, \tag{3}$$

where $\tau(t)$ is called the response time. This parameter, scaled as a time, indicates the potential ability of the atmosphere column to produce ground precipitation from VIL.

RadVil can be seen as an improved simple advection model that groups together two components: horizontal and vertical advection. The vertical component is driven by the VIL evolution in the atmospheric column. The RadVil formulation is inspired from the model proposed by Georgakakos and Bras (1984), which summarizes the rainfall formation processes in the conceptual way of a reservoir model. This model was designed to be coupled with a hydrological model in order to forecast floods on catchments subject to flash flooding. Several versions of this model have been proposed according to available observations in order to estimate the water content of the atmosphere column (Lee and Georgakakos 1990; Seo and Smith 1992; French and Krajewski 1994; Georgakakos and Krajewski 1996; Dolcine et al. 2000). For RadVil, only the rainwater content that can be measured by conventional radar is taken into account. In the present formulation, the source term is deduced from the temporal evolution of the VIL.

b. *Model operation*

RadVil consists of an initialization phase and a forecasting phase. The initialization phase includes the following steps performed from radar data: estimation of rainfall rate and VIL, computation of the rain field advection velocity, and determination of the response time and the source term. The forecasting phase corresponds to the integration of Eq. (1) in order to forecast the VIL, from which we deduce the forecasted rainfall rate. RadVil operates at the spatial scale of the atmosphere column, which can vary from the radar pixel to a much larger extent. For this case study, which concerns very short-term forecast lead times on small catchments, it has been assumed that each radar pixel can represent an atmosphere column.

1) Initialization phase

Voluminal radar data provides the VIL and the rainfall rate fields. The response time field is directly deduced from VIL and rainfall rate fields.

The advection velocity is assumed to be constant in the study domain and is computed from two successive rainfall fields by a cross-correlation procedure. The source term S, the unknown parameter in Eq. (1), includes vapor water condensation, cloud to precipitation water conversion, and melting. It is estimated from two successive fields of VIL and rainfall rates fields using Eq. (1) after inversion and integration over the time interval Δt:

$$S(t) = \frac{\mathrm{VIL}(t) - \mathrm{VIL}^*(t - \Delta t)}{\Delta t} + P(t). \tag{4}$$

The star symbol means that the field of VIL$(t - \Delta t)$ has been advected with the predetermined velocity between $t - \Delta t$ and t in order to be superimposed as closely as possible onto the field of VIL(t). This operation introduces an error in the source term estimation. This error depends on the grid mesh size, on the time interval between the two images, and on the accuracy of the advection velocity.

2) Forecasting phase

The forecasting phase relies on an important hypothesis concerning the advection velocity, the source term, and the response time. It is accepted that all three remain constant at their initialization value during the forecast lead time. This assumption means that the rain system characteristics stay in a steady state during the forecast lead time. It is clear that this assumption might appear more or less realistic depending on the rainfall event characteristics, which makes it debatable. The assumption concerning the response time implies that whatever the VIL evolution is, the ratio between ground precipitation and VIL remain constant until the forecasting time. Thus, a bad rain estimate could occur even if the VIL forecast is good because the vertical column dynamics will have changed between the initialization and the forecast lead time. The steady-state assumption accepted for source term evolution is also quite important because this source term controls the VIL evolution.

These assumptions are helpful in comparing RadVil to a classical advection rainfall forecasting method, which can be expressed as follows:

$$\frac{\partial P}{\partial t} + v_x \frac{\partial P}{\partial x} + v_y \frac{\partial P}{\partial y} = 0, \tag{5}$$

whereas RadVil is expressed as

$$\frac{\partial \mathrm{VIL}}{\partial t} + v_x \frac{\partial \mathrm{VIL}}{\partial x} + v_y \frac{\partial \mathrm{VIL}}{\partial y} = S - P. \quad (6)$$

The comparison of the two previous equations indicates that they represent both Lagrangian persistence methods (Germann and Zawadzki 2002), which differ in the variables addressed by the steady-state assumption. The classical advection model applies the steady-state hypothesis to the rainfall rate whereas RadVil applies the steady-state hypothesis to the two variables (source term, response time), which summarize the rainfall dynamics. Temporal autocorrelation studies have been performed in order to quantify the limits of these assumptions. They are summarized in section 5c.

The predetermined advection velocity is applied to all the variables of the model using the Smolarkiewicz positive definite advection scheme (Smolarkiewicz 1984) with open boundaries conditions. Compared to a simple advection scheme, the Smolarkiewicz scheme produces a weak numerical diffusion but is more expensive computationally. Only one advection velocity for the whole domain is used. This restriction is acceptable if the domain is small or if the rain only concerns one small part of the domain. However, a better description of advection velocity could be provided by a tracking method. This ability is not considered in this paper, which intends to evaluate the interest of voluminal radar information in complement of classical advection methods.

Introducing Eq. (1) to Eq. (3) leads to the following expression:

$$\frac{d(\mathrm{VIL})}{dt} + \frac{\mathrm{VIL(t)}}{\tau(\mathrm{t})} = S(t). \quad (7)$$

The integration of this equation leads to the next VIL:

$$\mathrm{VIL}(t + dt) = \mathrm{VIL}^*(t)e^{(dt/\tau)} - S(t)\tau(t)[1 - e^{(dt/\tau)}], \quad (8)$$

with $\tau(t) = \tau$ during the forecasting phase. The predicted rainfall rate is obtained from the forecasted VIL using Eq. (3).

RadVil might face the following sources of errors:

- estimation of the advection velocity: local velocities versus global velocities, accuracy of the velocity estimation method;
- measurement of VIL: this subject has been addressed in detail Boudevillain and Andrieu (2003);
- estimation of the new variables: response time and source term;
- formulation of the VIL evolution: the adopted reservoir model remains schematic;
- steadiness of tau and S during the forecast lead time.

The magnitude of these error sources depends on forecast lead time and meteorological context. We think that the errors concerning the response time and the source terms might play a crucial role.

3. Case studies and model application

The reflectivity radar data used in this study is taken from five events out of the intensive observation periods of the MAP. This program aims at improving our knowledge in meteorological and hydrological orographic phenomena (Binder et al. 1999; Bougeault et al. 1998). The program comprises eight scientific projects covering the following fields: orographic precipitation mechanisms, incident upper-tropospheric potential vorticity anomalies, hydrological measurements and flood forecasting, dynamics of gap flow, nonstationary aspects of foehn in a large valley, 3D–gravity wave breaking, potential vorticity banners, and structure of the planetary boundary layer over steep orography. This project was initiated in 1994 by MeteoSwiss and the Swiss Federal Institute of Technology. It gathered together partners from 14 countries: weather services, schools, universities, governments, and private research centers.

A special observation period took place from September to November 1999 (Bougeault et al. 2001). Several intensive observation periods (IOP) constitute a important database of particularly interesting weather situations from a scientific point of view. One of the strongly instrumented target areas was the Lago Maggiore area. During these IOP, several aircraft measurements took place, six weather radars were installed in the area while other many measurements were recorded by automatic surface stations, radio soundings, wind profiler, sodars, scintillometers, Doppler lidar, etc.

a. Area target and case studies

For the purpose of testing RadVil in actual conditions, we use voluminal data of the Monte-Lema MeteoSwiss operational radar. This C-band radar is located on the Monte-Lema mountain at an altitude of 1625 m. Polar reflectivity volumes of Lema radar have a time resolution of 5 min, a radial resolution of 1 km, an azimuthal resolution of 1°, and maximum range of 230 km. The whole volume consists of 20 elevations and is completed within 5 min. The used data were interpolated to a 1-km horizontal mesh size Cartesian grid.

Five case studies have been selected. They correspond to precipitation episodes that concern the flat 90 km × 90 km area represented on Fig. 2 by the dashed

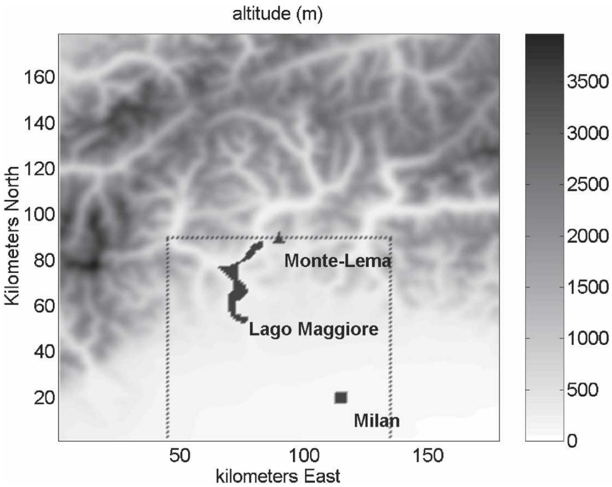

FIG. 2. Topography of area target. RadVil is performed and tested in the area delimited by the dashed box.

box. The fourth case study has been performed on a restricted 70 km × 70 km area centered on the south part of the 90 km × 90 km area because the rainfall field observed close to the radar seems incorrect during a part of this case study.

1) FIRST CASE STUDY (17 SEPTEMBER 1999)

This case study is particularly appreciated for its meteorological interest as well as the quality and the quantity of the observations that have been carried out. A squall line developed during the afternoon over the mountains northwest of Lago Maggiore and moved toward southeast during the night. The squall line was included in a large mesoscale convective system. The first large convective cells appeared around 1700 UTC over the windward slopes of the Alps to the northwest of the Lago Maggiore. At 1900 UTC, they merged into a squall line that propagated to the southeast. The amount of precipitation reached 70 mm in some locations. The system then continued to propagate over Milan later during the night. The time range between 2015 and 2350 UTC is treated in this study.

2) SECOND CASE STUDY (19 SEPTEMBER 1999)

This heavy rain event began with stratiform precipitation, which became convective during the evening and the night. The period between 2000 and 2350 UTC is studied hereafter. The convective cells are much less intense and the clouds have a much smaller vertical extension than those of 17 September.

3) THIRD CASE STUDY (30 SEPTEMBER 1999)

This study relates to a rapid frontal passage. Soundings at Milan show an atmosphere becoming unstable during the morning. Significant precipitation fell onto the Lago Maggiore area. The precipitation rapidly evolved as it moved across the mountain, into and across the Lago Maggiore region. We study a squall line that was formed between 1400 and 1655 UTC.

4) FOURTH CASE STUDY (24 OCTOBER 1999)

This rainfall event occurring between 1100 and 1330 UTC has been extracted from a long stratiform event. Precipitation occurred ahead of a front moving slowly toward the east with a strong southwesterly flow at high level.

5) FIFTH CASE STUDY (6 NOVEMBER 1999)

A cold front passage on the Alps caused strong winds and significant precipitation. The rise of warm and moist southerly flow by the cold front produced intense rainfalls on all the Lago Maggiore area between 1300 and 1755 UTC.

b. *RadVil implementation on MAP case studies*

The recorded polar radar data is projected onto a 1 km × 1 km horizontal and 0.5 km vertical Cartesian grid. Mask effects related to the Alps are significant, especially in the area located at the northwest of the radar. These effects reduce available radar information at the lowest altitudes. To test RadVil in the best conditions, the evaluation domain is restricted to a flat area of 90 km × 90 km located south of the radar. This ensures a good hydrological visibility for the radar. The mesh size is selected as small as possible, that is, the radar pixel, in order to totally exploit the high resolution of the images. Computations are carried out on each elementary mesh so that the forecasts are obtained at the measurement resolution.

4. Evaluation methodology

The primary objective of this paper is to assess the interest of RadVil for rainfall forecasting at lead times not exceeding one hour. To this end, RadVil is compared to: (i) a classical advection method (Adv.); (ii) the persistence of rainfall during the forecast lead time (Pers.). Three criteria are used to evaluate the model performances: the correlation coefficient (CC), Nash criterion (Nash), and the limit of predictability (LP); CC and Nash are binned respectively as follows:

$$\mathrm{CC} = \frac{\sum_{i=1}^{n} [(y_i - \bar{y})(\hat{y}_i - \bar{\hat{y}})]}{\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2 \sum_{i=1}^{n} (\hat{y}_i - \bar{\hat{y}})^2}}, \quad (9)$$

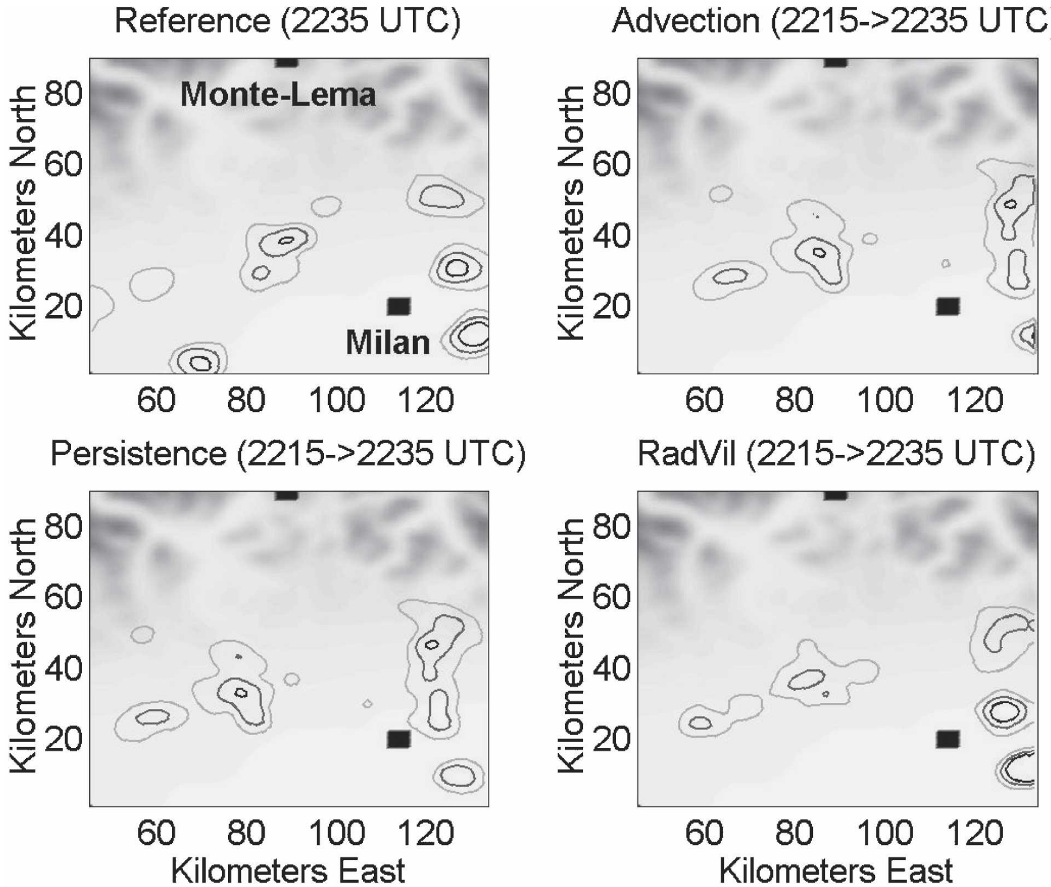

FIG. 3. Qualitative evaluation of RadVil on the first case study (17 Sep 1999): x–y plot of the (top left) reference rainfall at 2235 UTC, and (bottom left) the forecast of the persistence model (equal to the reference field at 2215 UTC), (top right) the advection model, and (bottom right) RadVil for 2215 UTC + 20 min. The x and y axes are given in km. The rainfall isohyets are contoured with spacings of 10, 20, 30, and 40 mm h^{-1}.

where y is the reference value and $\hat{y}$ is the forecasted value (mm h^{-1});

$$\text{Nash} = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \overline{y})^2}. \qquad (10)$$

The limit of predictability (LP) is defined as the forecast lead time for which the coefficient of correlation between reference and forecasted instantaneous rainfall rates becomes less than a certain fixed value. A value of 0.5 is chosen in this study.

The reference rainfall is provided by the radar data at the lowest available elevation. A classical Z–R relationship is used to derive the rainfall rate from the radar reflectivity factor. As far as VIL is concerned, several relationships proposed in Boudevillain and Andrieu (2003) have been applied in order to assess VIL from voluminal radar data. Details are given in section 5b.

5. Results

a. RadVil evaluation

Figure 3 illustrates the comparison of the three quantitative precipitation forecasts methods. It shows, in a qualitative way, the interest of RadVil instead of a classical advection routine. On the left-hand side, the reference rainfall field is represented at 2235 UTC. At the bottom of the same side, the rainfall fields predicted at 2215 UTC by the persistence model is plotted. On the right-hand side, the rainfall fields predicted at 2215 UTC by the advection routine (at the top) and the RadVil model (at the bottom) are shown. Figure 3 shows that, for the first case study, RadVil can catch the development of rain cells. This information, which is not predicted by the simple advection model, might be proved useful for hydrologic applications such as the management of sewer networks in urban areas.

Figure 4 illustrates a quantitative comparison of RadVil to advection and persistence in terms of the limit of

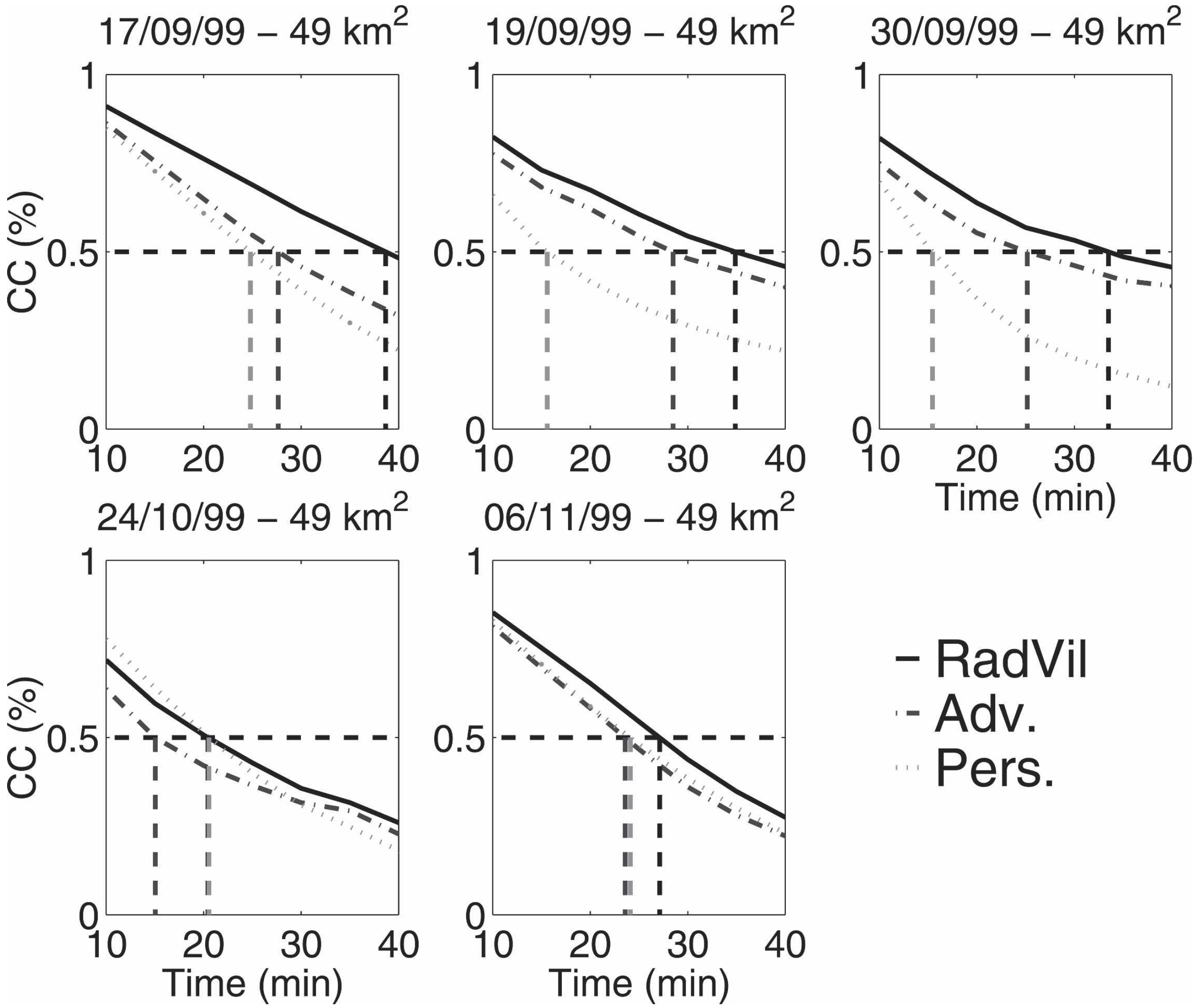

FIG. 4. Quantitative evaluation of RadVil on the five case studies: correlation coefficient as function of forecast time for cumulated rainfall on 49 km^2 catchments by the three rainfall forecasting methods. The limits of predictability of the three methods are represented by the vertical dashed lines.

predictability for the five rain events, and considering catchments of 49 km^2. It also demonstrates the ability of the model to forecast instantaneous rainfall. The forecast lead time is shown on the x axis in minutes and the performance criteria is plotted on the y axis. A comparison of the limits of predictability provided by the different methods is useful from a practical point of view. Considering the predictability threshold value defined in section 3, Fig. 4 shows that, on 49 km^2 catchments, this limit increases thanks to RadVil by about 10 min on the first case study (17 September 1999). On the second, third, and fifth case studies (19 and 30 September and 6 November 1999), for the same catchment size, the improvement reaches about 5 min. On the fourth case study (24 October 1999), the gain provided by RadVil is weak.

The results obtained for various catchment surfaces ranging from 4 to 169 km^2 are grouped in Table 1. They show that RadVil allows a gain of 5 to 7 min compared to advection method, and a gain exceeding 11 min compared to the persistence method.

From a hydrological point of view, the accumulated rainfall during the response time of the catchment is an important quantity, insofar as it is helpful to anticipate the flow rate evolution. The response time of the catchment depends on its characteristics of slope, surface, and drainage network, and can display significant variations for a given surface area (Thielen et al. 2000). Nevertheless, the following values have been accepted as indicative: a response time of 15 min for a catchment of 4 km^2, 30 min for 16 km^2, 45 min for 49 km^2, 60 min for 81 km^2, and 90 min for 169 km^2. The performance of

TABLE 1. Limit of predictability (LP, min) of RadVil and advection model vs persistence model for the five rain events and various catchment surfaces.

Date	Surface area	4 km^2	16 km^2	49 km^2	81 km^2	169 km^2
17 Sep 1999	LP(Adv.)−LP(Pers.)	3.3	3.0	2.5	2.4	3.0
	LP(RadVil)−LP(Pers.)	9.1	10.3	11.7	13.3	15.0
19 Sep 1999	LP(Adv.)−LP(Pers.)	10	10.6	13.7	13.0	16.5
	LP(RadVil)−LP(Pers.)	13.0	14.7	18.7	19.7	23.3
30 Sep 1999	LP(Adv.)−LP(Pers.)	6.4	6.8	8.4	9.5	11.0
	LP(RadVil)−LP(Pers.)	13.0	14.1	15.8	17.8	16.5
24 Oct 1999	LP(Adv.)−LP(Pers.)	−3.3	−3.8	−3.5	−5.5	−5.6
	LP(RadVil)−LP(Pers.)	0.0	−0.2	0.8	0.0	0.6
6 Nov 1999	LP(Adv.)−LP(Pers.)	−0.3	−0.5	−0.6	−1.5	−4.5
	LP(RadVil)−LP(Pers.)	4.3	4.0	3.9	4.2	0.5
Mean	LP(Adv.)−LP(Pers.)	3.2	3.2	4.1	3.6	4.1
	LP(RadVil)−LP(Pers.)	7.9	8.6	10.2	11.0	11.2

RadVil has been compared to Adv. and Pers. by considering the accumulated rainfall during the catchment response time.

The obtained results are displayed in Fig. 5 in term of Nash Coefficient. These results allow us to draw the following comments. RadVil performs slightly better results than Adv. and much better than Pers. in four out of the five case studies. The improvement allowed by RadVil is more significant for the most convective rain event (17 September 1999). In the fourth case study (24 October 1999) while applying the Nash criterion to small catchments, RadVil brings no improvement. Nevertheless, it is important to notice that, for all the case studies, the results are not really satisfying when the accumulation time exceeds 45 min. In fact, the three methods obtain scores close to 0.0 or negative scores (negative values mean that the rainfall forecasting method performs worse than a rainfall forecast equal to the mean rainfall).

b. *Extended evaluation: Influence of VIL measurement strategy*

The VIL is usually estimated by assuming that all precipitation is in the form of liquid water, which is not realistic most of the time. Yet, the upper layer of the atmospheric column contains ice water. The melting layer, below the 0°C isotherm contains ice and liquid water. The lowest layer is composed of liquid water. Boudevillain and Andrieu (2003) have proposed an alternative method to better estimate the VIL in taking into account the properties of ice water. RadVil forecasting model has been then tested according to three different VIL estimate techniques: (i) the whole water column is assumed to be in the liquid form (regular version); (ii) the water column is considered under mixed phase (both liquid and solid precipitation) but only the liquid part is treated (liquid version); (iii) the water column is considered under mixed phase and is taken into account in a more realistic way (alternative version). The two latter versions assess the 0° isotherm. The third version applies a different relationship between radar reflectivity factor and water content on both sides of the isotherm. Radar bins corresponding to the 0°C isotherm have been removed in order to avoid brightband problems.

The three VIL estimation methods can lead to three different physical interpretation of the model. The RadVil formulation remains unchanged in these three versions but the physical meaning is quite different. Indeed, according to whether the ice is taken into account or not, the response time values may vary significantly. On the histograms of the Fig. 6, it clearly appears that the VIL measurement method plays a key role in the value of the response time. When the regular version is used, the response time has a modal value of 15 min. When the precipitation water content is measured by the alternative version, the precipitation water total content is larger. Indeed, ice water is underestimated by the regular version. The underestimation being corrected by the alternative version, the value of the VIL is raised and the response time then becomes more significant: approximately 1 h. When liquid water alone is taken into account in the precipitation water content (liquid version), the response time becomes extremely short with values approaching 10 min.

If the response time is interpreted as the capacity of the atmospheric column to transform its integrated water content into a precipitation rate at ground, this capacity is more significant for liquid water than for ice water. The ice seems to be stored at higher altitudes. A physical interpretation is difficult because this approach does not describe the microphysical processes related to ice phase. The study of the distributions of the response time values thus shows that the vertical dynam-

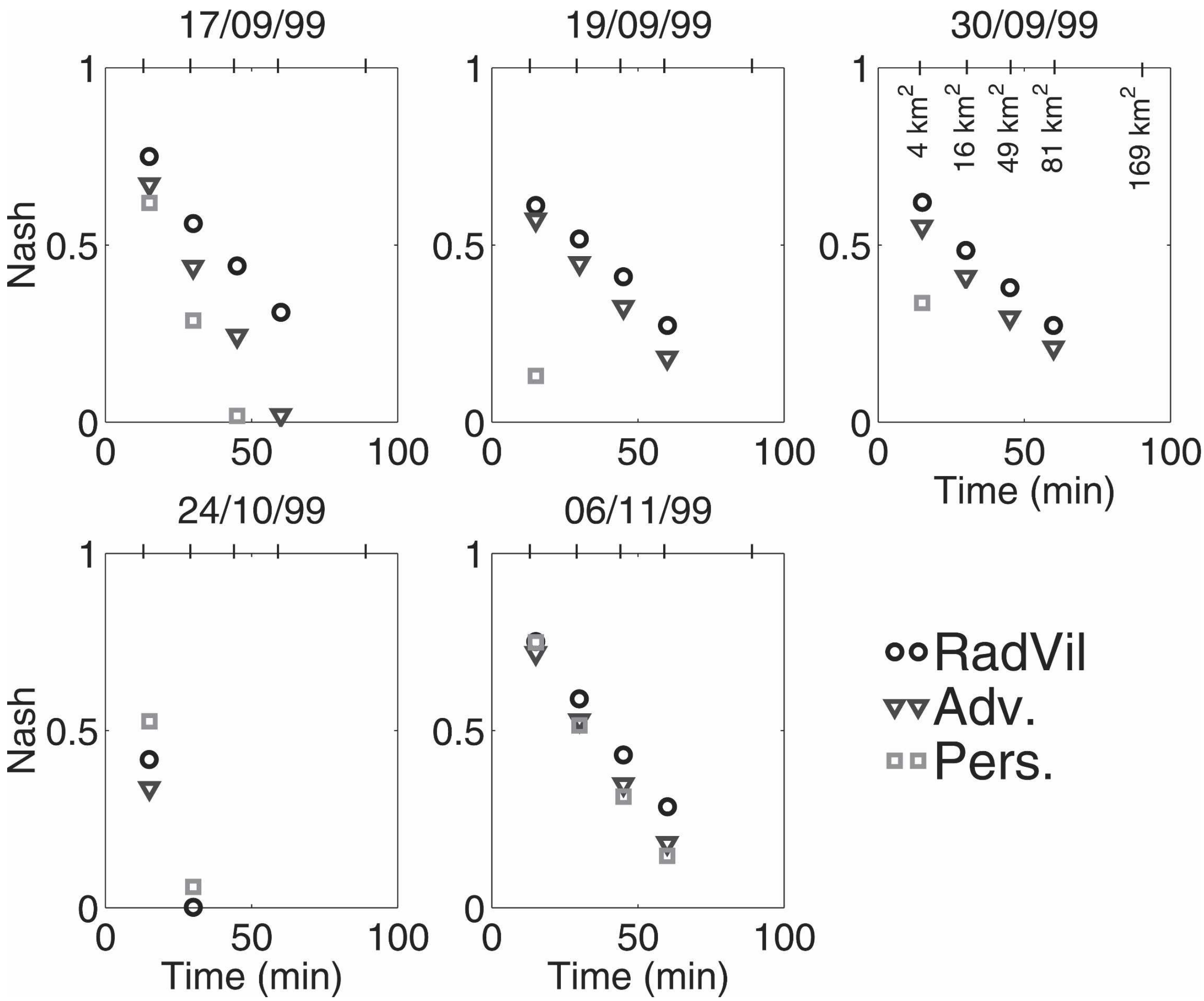

FIG. 5. Quantitative evaluation of RadVil on the five case studies: Nash criterion as function of catchment response time (corresponding to a surface area, indicated on the rhs) for cumulated rainfall by the three rainfall forecasting methods.

ics of precipitation in RadVil is strongly influenced by the method of water content estimation.

The three versions of RadVil have been compared. It appeared, on the whole, that the model performance is rather better when the regular version of RadVil is used. In this version, ice precipitation is treated as liquid precipitation, which corresponds to an underestimation of the solid water content. This result shows the limits of this modeling approach, which is based on the concept of representing the atmosphere as an ensemble of single columns. Whereas liquid precipitation water evolution seems to be relatively simple and therefore representable using only one dynamic parameter (response time), ice precipitation water content evolution is more complex. Indeed, the dynamics of ice is very different: it derives from several microphysical processes that cannot be characterized by only one dynamic parameter. Therefore, the concept of a simple reservoir no longer appears valid in describing these processes. A solution might consist of splitting the single reservoir into two reservoirs in series or in parallel representing the liquid phase and the ice phase, respectively. These reservoirs would then be able to be superimposed and/or juxtaposed. Above all, three questions must be addressed: (i) the estimation of the water content of each reservoir, (ii) the exchanges between the reservoirs, (iii) the advection velocities for the reservoirs.

c. Discussion and analysis

As explained in section 2b(2), RadVil is based on the assumption of a steady-state source term and response time during the forecast time. The main assumptions of the two other models only apply for the rainfall field:

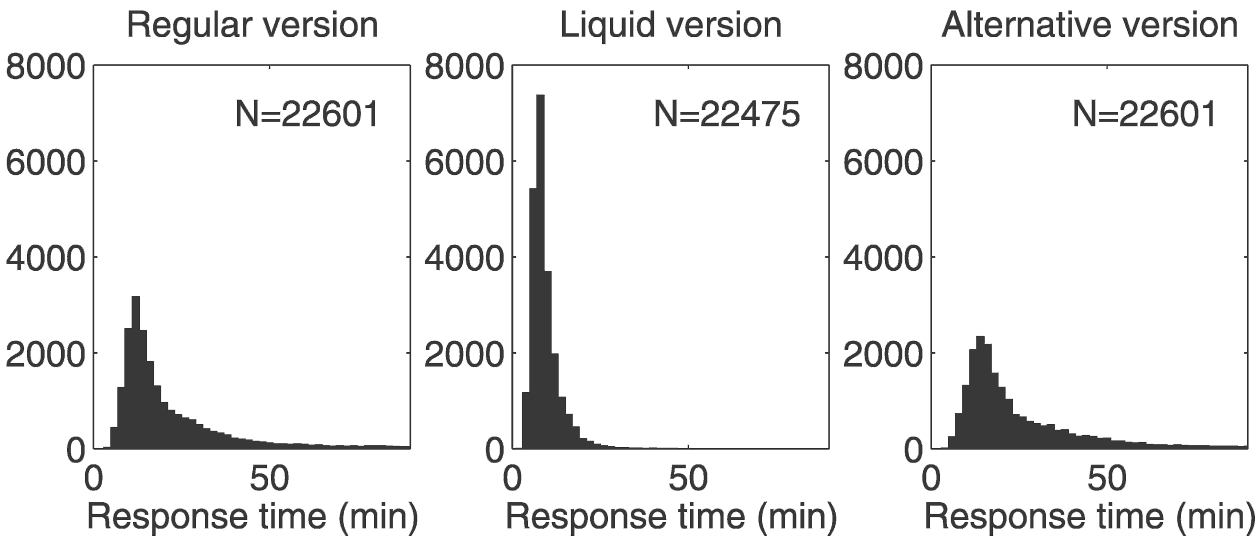

FIG. 6. Response time as function of the VIL estimate technique for the first case study (17 Sep 1999).

the advection model is based on the assumption of a steady-state rainfall rate and the persistence model does not consider any change. The model performances depend on the validity of these assumptions. Therefore, a statistical study has been performed in order to check the evolution assumptions of RadVil and of two other models on the five case studies. The goal is to provide an indicator allowing for the design of the best model adapted to the current meteorological situation, that is, the model for which the main assumption is the least violated.

For this purpose, the time autocorrelation of VIL, source term, response time, and rainfall fields have been computed to give information about the validity of the steady-state or persistence assumptions. It indicates how the spatial coherence of the variable decreases with time.

The time autocorrelation coefficient is obtained in the following way: for several forecasting lead times and for each initial time, the field displacement is calculated by maximizing the correlation coefficient between two successive images (at t and at $t + \Delta t$). This maximum correlation is considered as an indicator of the internal evolution of the field: higher this indicator is, the more realistic is the steady-state assumption of the field. The process is applied on all the available images for time lags of up to 30 min.

The best performance of RadVil should be correlated to high values of the time autocorrelation (TAC) of the response time and the source term fields. Alternatively, the best performance of the advection model should be related to high values of the TAC of rainfall fields. The obtained results (not shown) showed that this a priori relationship was not so easy to highlight. On the one hand, in the TAC computation, which takes into account advection effects, the time autocorrelation is always underestimated because the advection procedure is never entirely perfect. On the other hand, comparisons between the TACs of the response time, the source term, and the rainfall are difficult to obtain because of nonlinear relationships between the source term, or response time, and the rainfall rate and the VIL are not linear.

Despite these difficulties, a simple qualitative relationship between the VIL TAC and the performances of RadVil has been able to be established. Figure 7 shows the evolution of TAC of VIL with time for the five case studies. It appears that the case studies for

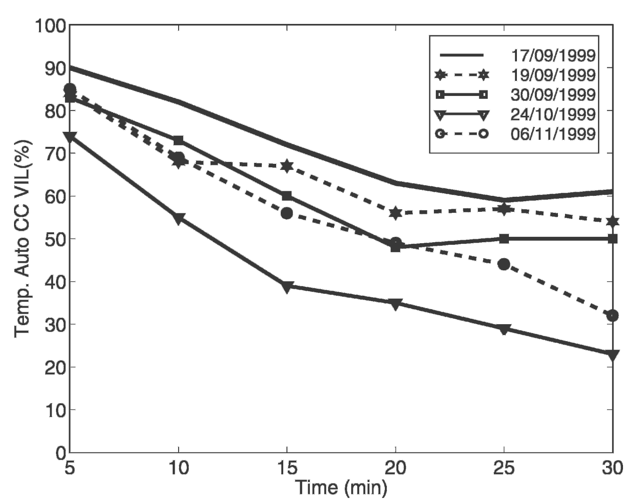

FIG. 7. RTAC Coefficient of VIL fields on the five case studies.

which the best results of RadVil are encountered correspond to the cases where the VIL TAC is high and exhibits a weak decrease (the three first case studies of 17, 19, and 30 September 1999). On the contrary, the least favorable results are found for cases where the VIL TAC is weak and displays a strong decrease (the fourth and fifth case studies of 24 October and 6 November 1999). The VIL and rainfall TAC associated with latest radar images can provide an indicator of the quality of forecast that one can expect with RadVil.

6. Conclusions

A very short-term rainfall forecast model based on voluminal radar data has been tested on actual radar data. This study proves that VIL, derived from voluminal radar data, could improve advection rainfall forecasting methods. It then confirms that voluminal radar scan protocol is useful for rainfall forecasting devoted to short-term hydrological applications. The improvement is significant for one case study and slight for the four other case studies. For all the studies, the performances seem still insufficient for practical applications of RadVil beyond 30 min or 1 h of forecasting time according to the cases.

Results show that the model performances are connected with the temporal structure of the VIL. Statistical studies on VIL showed that the RadVil quality of forecast depends on the space and time structure of the VIL. A qualitative index of confidence could indicate whether such a method is better adapted to the meteorological situation, or whether it would be more worthwhile to use alternative ones such as simple advection or persistence method.

RadVil seems to perform better in its simplest version, which does not take into account the actual liquid and ice phase of precipitation. However, RadVil does not represent liquid and ice dynamics by a satisfactory way. In fact, ice constitutes an important part of the precipitation water content in convective clouds, and is responsible for high rainfall rates. Ice precipitation could be discriminated from liquid precipitation by means of polarimetric techniques. A more developed formulation of RadVil including this new information needs to be done.

The advection velocity has been considered uniform in the study domain. The estimation of local velocities would improve RadVil and the advection method. Moreover the current evolution assumption is very strict. Coupling RadVil with a tracking cell method would allow the application of the steady-state assumption to each identified rain cell thus improving the forecasting. This method would allow for a better representation of the lifetime cycle of the rain cells.

With the same idea of exploiting available radar data for rainfall very short-term forecasting, Doppler products could be used to improve horizontal dynamics of the model. Indeed, comparisons between persistence, advection and RadVil methods have demonstrated that RadVil quality is strongly dependent on the advection quality.

Acknowledgments. The authors wish to acknowledge L. Dolcine and J. Thielen for the first studies performed on this model. We would also like to thank P. Tabary and G. Scialom for their assistance in the radar data usage. We finally thank the three anonymous reviewers and Sidney Burks who have contributed to improve the clarity of this paper. This work received the financial support of the French multiscale atmospheric and oceanic programme (PATOM).

REFERENCES

Bellon, A., and I. Zawadzki, 1994: Forecasting of hourly accumulations of precipitation by optimal extrapolation of radar maps. *J. Hydrol.,* **157,** 211–233.

Binder, P., A. Rossa, P. Bougeault, J. Moore, D. Jorgensen, and M. Bollinger, 1999: MAP implementation plan. [Available online at http://www.map.meteoswiss.ch/map-doc/mip/mip.pdf.]

Boudevillain, B., and H. Andrieu, 2003: Assessment of vertically integrated liquid water content radar measurement. *J. Atmos. Oceanic Technol.,* **20,** 807–819.

Bougeault, P., P. Binder, and J. Kuettner, 1998: MAP science plan. [Available from MAP Project Office, MeteoSwiss, CH-8044, Zurich, Switzerland.]

——, and Coauthors, 2001: The map special observing period. *Bull. Amer. Meteor. Soc.,* **82,** 433–462.

Brémaud, P. J., and Y. Pointin, 1993: Forecasting heavy rain from cell motion using radar data. *J. Hydrol.,* **142,** 373–389.

Denoeux, T., and P. Rizand, 1995: Analysis of rainfall forecasting using neural networks. *Neural Comput. Appl.,* **3,** 50–61.

Ding, X., T. Denoeux, and F. Helleco, 1993: Tracking rain cells in radar images using multilayer neural networks. *Proc. ICANN,* **93,** 962–967.

Dolcine, L., H. Andrieu, M. French, and J. D. J.-D. Creutin, 2000: Implementation considerations of a conceptual precipitation model. *J. Geophys. Res.,* **105,** 2291–2298.

Ducrocq, V., J. Lafore, J. Redelsperger, and F. Orain, 2000: Initialisation of a fine scale model for convective-system prediction: A case study. *Quart. J. Roy. Meteor. Soc.,* **126,** 3041–3065.

Einfalt, T., T. Denoeux, and G. Jacquet, 1990: A radar rainfall forecasting method for hydrological purposes. *J. Hydrol.,* **114,** 229–244.

Faure, D., P. Auchet, and O. Payrastre, 2002: Management of a detention settling basin using radar data and risk notion. *Water Sci. Technol.,* **45** (2), 19–26.

Fox, N., M. Sleigh, and C. Pierce, 2001: Forecast demonstration Project Sydney 2000—Part I: An overview of the project and the participating systems. *Weather,* **56,** 397–404.

French, M., and W. Krajewski, 1994: A model for real-time quantitative rainfall forecasting using remote sensing, part 1: Formulation. *Water Resour. Res.,* **30,** 1075–1083.

Georgakakos, K., and R. Bras, 1984: A hydrologically useful station precipitation model, 1. Formulation. *Water Resour. Res.,* **20,** 1585–1596.

——, and W. Krajewski, 1996: Statistical-microphysical causes of rainfall variability in the Tropics. *J. Geophys. Res.,* **101,** 26 165–26 181.

Germann, U., and I. Zawadzki, 2002: Scale-dependence of the predictability of precipitation from continental radar images. Part I: Description of the methodology. *Mon. Wea. Rev.,* **130,** 2859–2873.

Handwerker, J., 2002: Cell tracking with trace3d—A new algorithm. *Atmos. Res.,* **61,** 15–34.

Johnson, J., P. MacKeen, A. Witt, E. D. Mitchell, G. Stumpf, M. Eilts, and K. Thomas, 1998: The storm cell identification and tracking algorithm: An enhanced WSR-88D algorithm. *Wea. Forecasting,* **13,** 263–276.

Lee, T., and K. Georgakakos, 1990: A two-dimensional stochastic-dynamical quantitative precipitation forecasting model. *J. Geophys. Res.,* **95,** 2113–2126.

Li, L., W. Schmid, and J. Joss, 1995: Nowcasting of motion and growth of precipitation with radar over a complex orography. *J. Appl. Meteor.,* **34,** 1287–1301.

Pierce, C., P. Hardaker, C. Collier, and C. Haggett, 2000: Gandolf: a system for generating automated nowcasts of convective precipitation. *Meteor. Appl.,* **7,** 341–360.

Seo, D., and J. Smith, 1992: Radar-based short-term rainfall prediction. *J. Hydrol.,* **131,** 341–367.

Smolarkiewicz, P., 1984: A fully multidimensional positive definite advection transport algorithm with small implicit diffusion. *J. Comput. Phys.,* **54,** 325–362.

Thielen, J., B. Boudevillain, and H. Andrieu, 2000: A radar data based short-term rainfall prediction model for urban areas—A simulation using meso-scale meteorological modelling. *J. Hydrol.,* **239,** 97–114.