13R.1 IMPROVEMENTS ON FLOW FORECASTING USING PRECIPITATION NOWCASTING BASED IN RADAR ADVECTION TECHNIQUES: ASSESSMENT OF PREDICTABILITY AND UNCERTAINTY PROPAGATION

Daniel Sempere-Torres*, Marc Berenguer, Carles Corral and Rafael Sánchez-Diezma
Grup de Recerca Aplicada en Hidrometeorologia. Universitat Politècnica de Catalunya, Barcelona (Spain)

1. INTRODUCTION

In hydrological warning systems, precipitation nowcast is a crucial issue in order to extend the time series of precipitation inputs feeding in real-time the runoff forecasting models. Indeed, even if a perfect rainfall-runoff model is used, the mere restriction due to the use of the measured rainfall up to a given moment will lead to a significant reduction of the hydrological model forecasting performances. Figure 1 shows how severe this reduction could be in a given case, and how important is for the flow forecasting in medium-sized basins (from hundreds to thousands km^2) to incorporate a quantitative forecast of the next rain rates: even in the case of rainfall forecasts affected by significant errors in the temporal distribution, their use lead to better results than non considering forecasts at all.

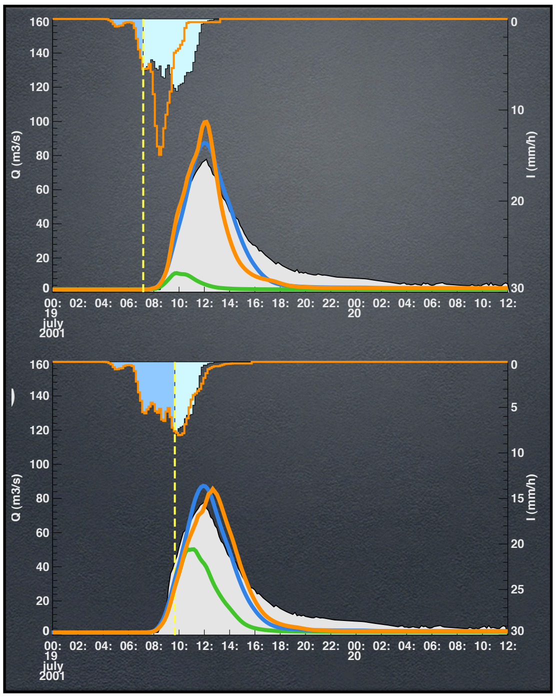

Figure 1: Example of the relevance of rainfall forecasts in hydrological warning systems: Even if the hydrological model used is able to reproduce the observed flows (solid curve) when all the rainfall input is known (blue line), it provides poor results when just the previous recorded rainfall are used, green line (note that this is the normal case in operational flood forecasting). The use of rainfall forecasts, even if they are affected by significant errors in the temporal evolution, lead to much better results (orange line) than non considering any rainfall forecasts. The plots shows these results at two different time step of the event.

In this framework, radar information is very useful since its high resolution, both in time and space, provides a good description of the rainfall field evolution. Thus, nowcasting techniques based on radar have shown some skill in extending the anticipation with which flow forecasts may be simulated through a distributed rainfall-runoff model. However, this improvement has been found to be very dependent on the nature of the event: the quality of flow forecasts decays rapidly for fast evolving precipitation patterns (for example, when short-lived convective cells affect the studied basin).

The main purpose of the present work consists of coupling the precipitation and hydrological forecasts , and explore the relation between the predictability of rainfall fields and the ability to anticipate the response of a given hydrological basin (that is, to obtain flow forecasts of good quality).

2. COUPLING PRECIPITATION NOWCASTING AND FLOW FORECASTS

An extensive review and classification of existing nowcasting techniques can be found in Wilson et al. (1998) and Wilson (2003). Among the nowcasting techniques based on the extrapolation of most recent radar observations the techniques developed by Germann and Zawadzki (2002) and Seed (2003) take into account that the small-size patterns of the precipitation field decorrelate faster than those that have larger scales. Therefore, they propose to filter out the small-scale patterns as the forecasting time increases. The main purpose of the present study is to assess the performance of one of these nowcasting techniques (S-PROG -Seed 2003-) in the area of Barcelona (NE Spain) from two different perspectives: (a) from the perspective of the forecasted precipitation fields and (b) from the perspective of the forecasted flows simulated with a distributed rainfall-runoff model fed with the forecasted rainfall.

This second point of view matches with the concept of *hydrological validation* (Sempere Torres et al., 1999). This concept consists of assessing the performance of any technique applied to improve precipitation estimates from the perspective of the discharges simulated by a rainfall-runoff model. Particularly, the hydrological validation can be used to measure the impact of the rainfall forecasting on the ability of the hydrological model to anticipate the flows, thus it turns out to be an interesting approach to verify the goodness of the different methodologies when the aim is not just to forecast the rain rates in a given point, but providing estimates of the rainfall affecting a surface (the hydrological basin). So the results are assessed in terms of a derived integral variable (the flows at the outlet of the basin), providing a more realistic picture of what can be achieved in hydrological applications than what the punctual comparisons in term of rain rates can offer.

A main point in hydrological validation is which *reference hydrograph* is used to compare it against the simulated flows. The main sources of *reference hydrographs* are flow observations (Obled et al. 1994; Sun et al. 2000; Carpenter et al. 2001; Borga 2002; Gourley and Vieux 2003; Kouwen et al. 2004; Vieux and Bedient 2004) and hydrographs computed with the hydrological model using series of precipitation fields, both obtained from raingauges (Borga 2002; Pellarin et al 2002) or in a simulation framework (Winchell et al. 1998; Sánchez-Diezma et al. 2001). But few papers focused in the effect of using short-term forecasted precipitation fields based on meteorological radar data jointly with a rainfall-runoff model.

In the present study, the hydrograph simulated by the distributed rainfall-runoff model *DiCHiTop* (see a description in Corral et al. 2001) using the full series of observed radar fields was chosen as the *reference hydrograph*. Working in such a way allows us to analyze the improvements achieved by using forecasted precipitation fields separately from the accuracy of the rainfall-runoff model (since both forecasted and reference are using the same one). However, in order to derive reliable results it was previously necessary to set a good set of parameters for *DiCHiTop* by calibrating the model to typical rainfall runoff events on the studied basin. This ensured a good performance of the model, producing realistic estimated hydrographs, comparable to measured flows (for the implemented model, this was analyzed in detail in the study of Corral 2004).

3. THE NOWCASTING TECHNIQUE

The implemented technique for the rainfall short-term forecasting is based on S-PROG (see a detailed description in Seed 2003) and although there are some slight differences in comparison with the original description, we will use this name hereafter. S-PROG is a simple extrapolation technique that assumes steady state conditions, in the sense that the most recently measured precipitation field is advected according to an estimation of the current motion field of the precipitation (see a general scheme in Fig. 2).

Additionally, S-PROG proposes to filter out the small scale patterns of the rainfall field as the forecasting time increases (see an example of the forecast in Fig. 3), because the temporal evolution of the patterns of the precipitation field having smallest scales have been demonstrated to be very unpredictable using an extrapolation technique (Germann and Zawadzki 2002).

3.1. Tracking algorithm

The algorithm implemented to estimate the motion field of precipitation is based on *TREC* (*Tracking Radar Echoes by Correlation* -Rinehart and Garvey 1978-) to which continuity is imposed (in the way

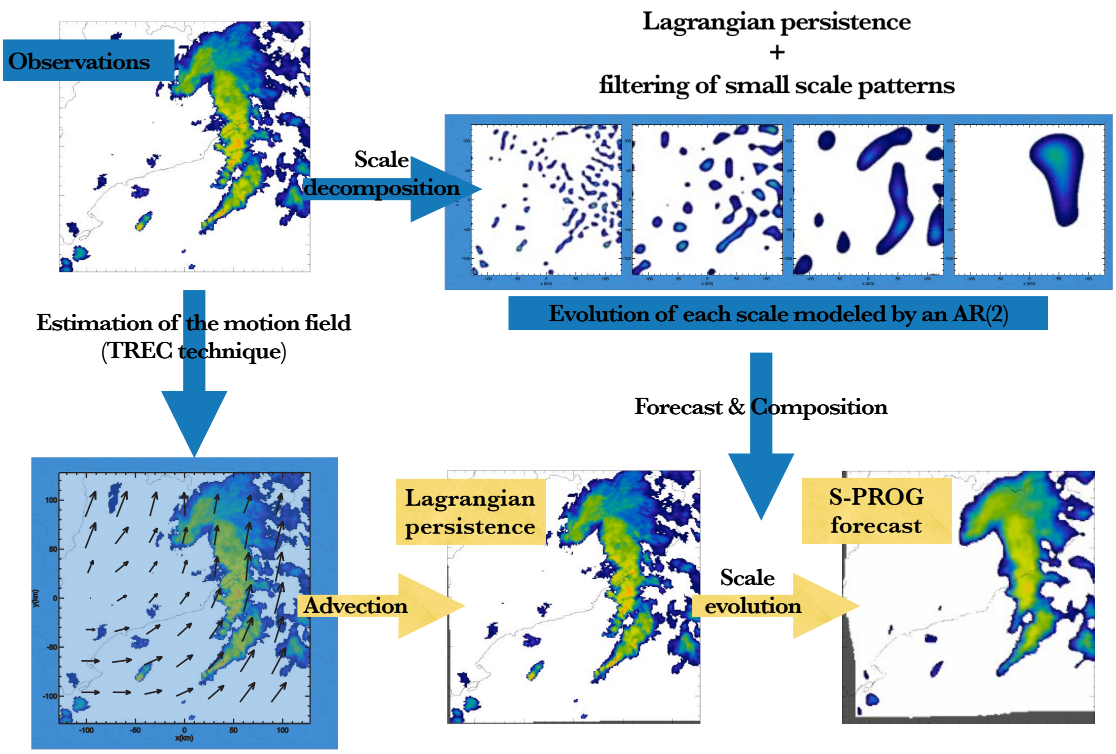

Figure 2: General scheme of the implemented rainfall field nowcasting technique. From most recent observations at time *t*, the motion field and coefficients of the AR(2) models that drive the evolution of each range of scales are derived. The forecast at *t+n* is obtained as the composition of the fields , which are advected according to the motion field derived at *t*.

proposed by Li et al. 1995). The motion field is obtained with a given resolution (in this case, 16 km) and it is finally densified to the pixel resolution using linear interpolation.

3.2. Spectral decomposition

Each obseved reflectivity field *Z(t)* (expressed in dB*Z*) is decomposed into a set of *m* field components $Y_k(t)$ representing the variability of the precipitation in a range of scales 2^k to 2^{k+1} (km), where $k \in [1,m]$, assuming a multifractal structure of precipitation fields that allows modeling them as a multiplicative cascade (an extensive review and discussion of this hypothesis may be found in Seed 2003). This decomposition is carried out using different band-pass filters in the Fourier spectrum (see Fig. 2).

After normalizing these field components, $Y_k(t)$, according to equation (1), an AR(2) model is fitted to the temporal series of each $X_k(t)$ using equation (2).

$$X_{k,i,j}(t) = \frac{Y_{k,i,j}(t) - \mu_k(t)}{\sigma_k(t)} \quad (1)$$

$$X_{k,i,j}(t) = \phi_{1,k}(t) \cdot X_{k,i,j}(t-1) + \phi_{2,k}(t) \cdot X_{k,i,j}(t-2) + \varepsilon_{k,i,j}(t) \quad (2)$$

where *i* and *j* stand for the pixel position, $\mu_k(t)$ and $\sigma_k(t)$ are the mean and standard deviation of the field component $Y_k(t)$, the coefficients $\phi_{1,k}(t)$ and $\phi_{2,k}(t)$ are obtained with the Yule-Walker equations as a function of the lag 1 and lag 2 autocorrelation coefficients, and $\epsilon_{k,i,j}(t)$ is a white-noise process.

3.3. Forecasting

Since the temporal evolution of each level is modeled according to an AR(2) model, the forecasted lead time *n* of the normalized field component, $\hat{X}_k(t+n)$, can be generated recursively following the model given in equation (3) (where the noise term, ϵ, is set to 0 to produce the expected "best" forecast):

$$\hat{X}_{k,i,j}(t+n) = \phi_{1,k}(t) \cdot \hat{X}_{k,i,j}(t+n-1) + \phi_{2,k}(t) \cdot \hat{X}_{k,i,j}(t+n-2) \quad (3)$$

The $\hat{Z}(t+n)$ fields are finally recomposed by means of equation (4).

$$\hat{Z}_{i,j}(t+n) = \sum_{k=1}^{m} \mu_k(t) + \sigma_k(t) \cdot \hat{X}_{k,i,j}(t+n) \quad (4)$$

Since smallest scales are less autocorrelated, forecasted fields representing small-scale variability will quickly tend to the *k*-component field mean, $\mu_k(t)$. Therefore, recomposed fields get smoother as the forecasting time increases, while the larger scale characteristics persist relatively longer (see Fig. 3).

The recomposition of the reflectivity field $\hat{Z}(t+n)$ is done in the Lagrangian domain, which means that this field is advected according to the estimated motion field derived at *t* with the mentioned *TREC* technique. The motion field is kept stationary during the forecasting time and it is implemented according to a *backward* scheme (see Fig. 8 of Germann and Zawadzki, 2002). The advected reflectivity is thus obtained from the velocity vector estimated at each point (i,j), $\mathbf{v}(t) = [u_{t,ij}, v_{t,ij}]$, according to:

$$\hat{Z}_{i,j}(t+n) = \hat{Z}_{i-\Delta i,\, j-\Delta j}(t+n-1) \quad (5)$$

where $\Delta_i = u_{t,ij} \times \Delta t$, $\Delta_j = v_{t,ij} \times \Delta t$ and Δt is the time step.

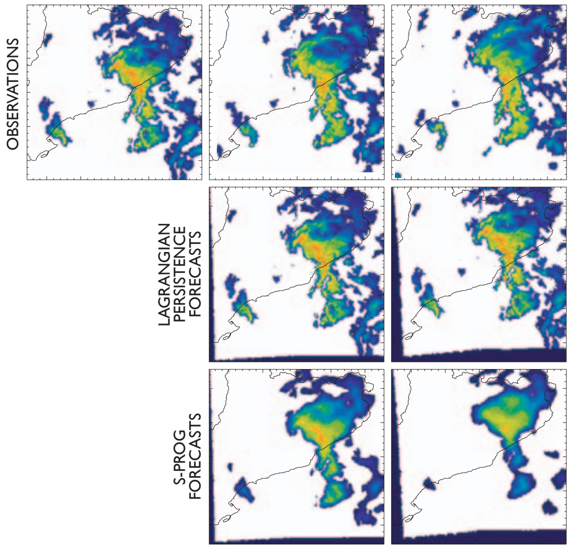

Figure 3: Top: Radar reflectivity fields, measured on 15 January 2001at 22:20, 22:50 and 23:20 UTC. Middle: 30- and 60-minutes forecasts generated on 15 January 2001 at 2:220 UTC by simple advection of radar fields (Lagrangian persistence). Bottom: 30- and 60-minutes forecasts generated on 15 January 2001 at 22:20 UTC by S-PROG (adding scale filtering to Lagrangian persistence).

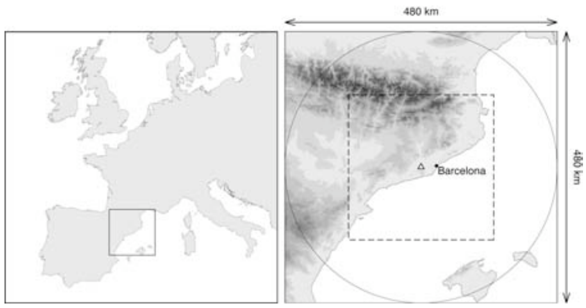

Figure 4: Location of the study area. Right: Triangle indicates the location of the Corbera C-band radar. The circumference shows the radar maximum range (240 km) and the dashed line square is the 256x256 km2 domain where the validation was carried out.

4. IMPLEMENTATION FRAMEWORK

The implementation of S-PROG was carried out in the vicinity of Barcelona (see Fig. 4). This region has a typical Mediterranean climate: it is affected by intense rainfall events that frequently lead to important floods. In this area, at the end of summer, mountain ranges near the coast act as natural barriers causing the updraft of warm wet air from the sea, what encourages the generation of local intense convective storms. However, stratiform systems (with high spatial and temporal extensions) are also common, especially in winter and spring.

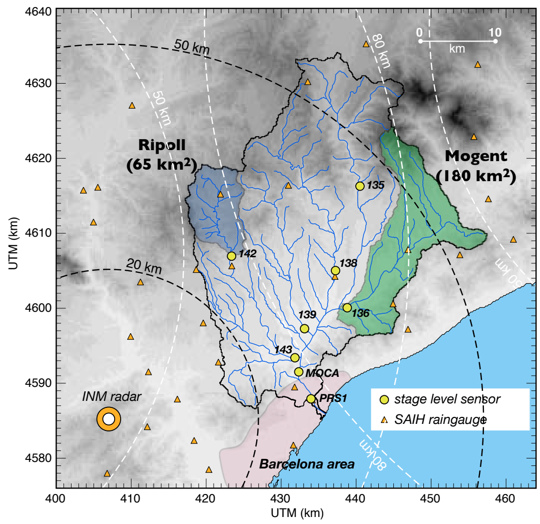

Figure 5: Basins where the proposed nowcasting technique is hydrologically validated: the quality of forecasted precipitation fields was assessed in three different-sized catchments: Besòs (1015 km^2), Mogent (180 km^2) and Ripoll (65 km^2).

The validation was carried out on six selected rainfall events corresponding both to convective and stratiform situations (the radar loops of the events can be watched at http://www.grahi.upc.edu/events.php). In order to seek possible scale effects, the analysis has been performed in four different-sized domains. The first one is the 256x256 km2 square centered at the radar site (see Fig. 4) and the other 3 correspond to the Besòs basin (1015 km2) and two of its sub-basins: Mogent -180 km2- and Ripoll -65 km2- (see Fig. 5).

The hydrological validation has been carried out in the framework of the Besòs basin and its sub-basins in four of the selected events (for which significant flows were measured in this basin). The Besòs river is a Mediterranean complex catchment: the upper part (with some mountains above 1000 m) is mainly rural and afforested, while the planes have suffered a continuous urbanization process during the last decades, being the area close to the outlet very densely populated. This basin is instrumented with 7 level sensors (but only the 3 of them defining the analyzed basins are used in this study) and well covered by the catalan radar network.

4.1 . Radar data

For this study we have just used the nearest radar to the basin, the C-band radar of the Spanish Institute of Meteorology (INM) located at Corbera de Llobregat, near Barcelona (between 15 and 60 km far from the basin, see Fig. 5).

Raw radar data were corrected for mountain screening effects (with the algorithm proposed by Delrieu and Creutin 1995), ground clutter contamination (the technique proposed by Sánchez-Diezma et al. 2001, was used both for ground echoes identification and for their substitution with rainfall estimation) and problems of signal stability (with the technique described by Sempere-Torres et al. 2003).

4.2 . The rainfall-runoff model

DiCHiTop (see a more complete description in Corral et al. 2001 and in Corral 2004) is a grid-based model designed to use distributed rainfall fields. The basin is split into square hydrological cells matching the radar information (in the case of this application, with a resolution of 2x2 km^2). At this cell scale, a twofold lumped model is applied to transform

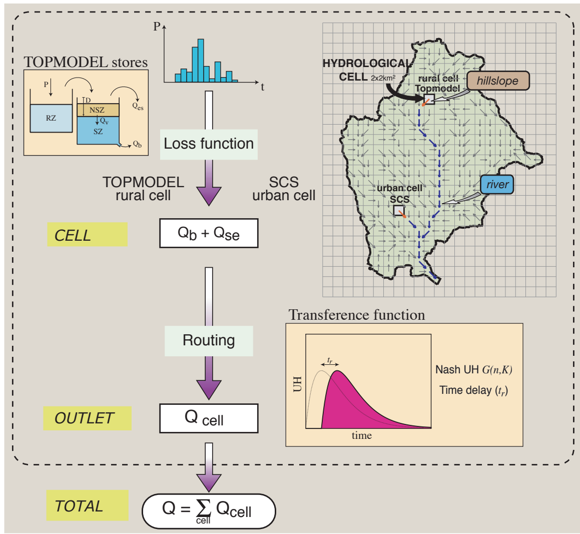

Figure 6: Scheme of the distributed rainfall-runoff model DiCHiTop: the basin is divided into a grid of square hydrological cells using a DEM. The generation of runoff at the cell scale depends on the degree of urbanization.These cell flows are routed to the outlet of the basin independently by means of a Nash Unit Hydrograph derived from the drainage system. Finally, the basin hydrograph is calculated as the linear combination of all the routed cell hydrographs.

precipitation inputs into flow depending on the degree of urbanization of each cell. In rural areas, the runoff is generated using the TOPMODEL equations (Beven and Kirkby 1979), while in urban cells the SCS loss function (Mockus 1957; Rawls et al. 1992) is applied.

The runoff generated at each cell is routed to the outlet of the basin according to a transfer function derived from the main drainage system, which classifies basin cells as hillslope or stream cells. In the hillslope path, the output from a cell is attenuated in its journey to the nearest stream, where a fully channeled flow is assumed. This response is thus modeled by applying the Nash Unit Hydrograph (Nash 1957) in the hillslope path and a time delay in the stream, which is dependant on the distance to the outlet.

The hydrograph at the basin outlet is finally calculated as the linear combination of all transferred cell hydrographs (see a general scheme of the model in Fig. 6).

The five parameters of the distributed rainfall-runoff model DiCHiTop were previously calibrated for

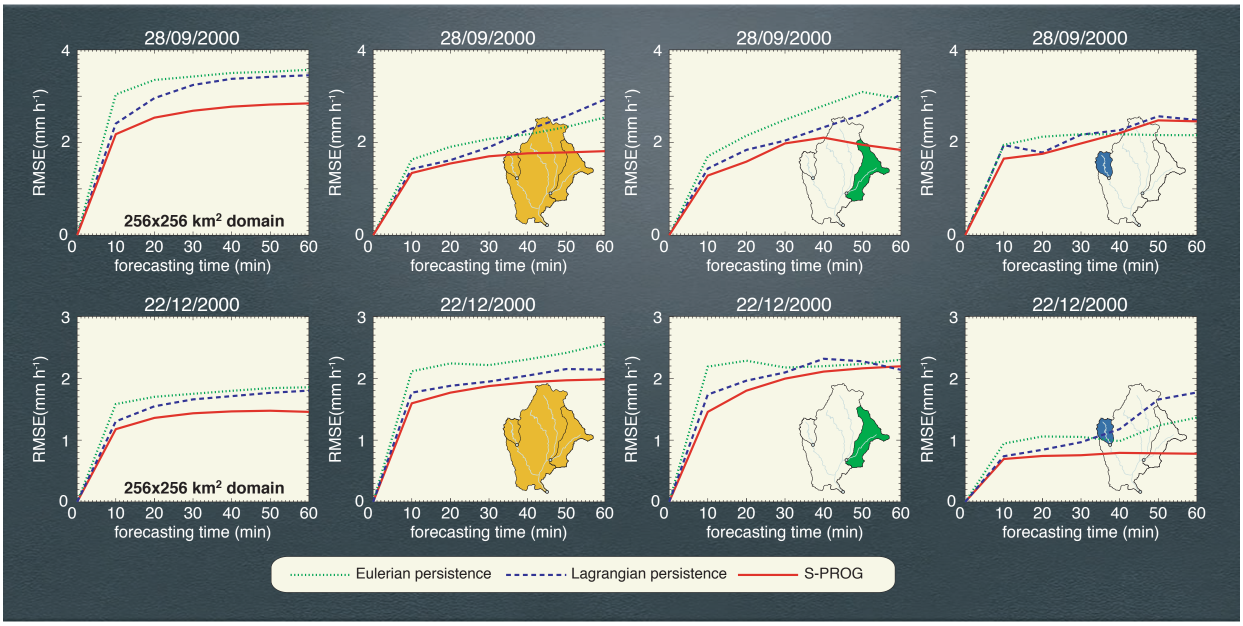

Figure 7: RMSE (in mm h-1) as a function of the forecasting time for selected events, evaluated in the 256x256 km2 domain of Fig. 4 and for the three different-sized basins shown in Fig. 5. The three lines distinguish between forecasting techniques: dotted line corresponds to Eulerian persistence (last radar scan is kept static as forecast), dashed line to Lagrangian persistence (advection of last radar scan according to the estimated motion field) and solid red line to S-PROG.

the Besòs basin by means of an optimization process minimizing the Root Mean Square Error (RMSE) between simulated and observed hydrographs for a number of events (different to those analyzed here). The model is currently running in real-time at the Water Agency of Catalunya hydrological warning center using raingauge-adjusted radar fields with a time step of 10 minutes (a full description and analysis of the performance of the model may be found in Corral 2004).

5. VALIDATION IN PRECIPITATION TERMS

The first evaluation consisted of assessing the differences between the forecasted and the observed precipitation fields. Results are presented in terms of the RMSE as a function of the forecasting time (also called lead time) in units of rain rate, assuming a climatological Z-R relationship for the studied area derived from disdrometer measurements (Sempere-Torres et al. 1997; Sempere-Torres et al. 1998).

The performance of S-PROG is thus compared against the results of Eulerian and of Lagrangian persistences. These three techniques represent progressive levels of sophistication: the difference between Eulerian and Lagrangian persistences is that advection of the rainfall field is introduced in the second (according to the motion field estimated with the TREC technique of section 3.1.); on the other hand, the difference between Lagrangian persistence and S-PROG is that S-PROG filters out small-scale patterns of the rainfall field.

Figure 7 shows the results of comparing precipitation forecasts against actually measured radar fields expressed in terms of the RMSE (in mm h -1). In the entire analyzed domain (256x256 km^2) and for all studied cases, Lagrangian persistence produces better results than Eulerian persistence. Moreover, the introduction of scale filtering (S-PROG) yields significantly better results, and in general terms this improvement is independent of the size of the analyzed domain.

A further discussion can be found at Berenguer et al., 2005.

6. HYDROLOGICAL VALIDATION

As the main objective of the present study was to validate different rainfall nowcasting techniques from a hydrological point of view it was, therefore, necessary to compare forecasted hydrographs against a reference hydrograph.

As mentioned in section 2, we defined the reference hydrographs as the output flows simulated with the rainfall-runoff model at the outlet of the basin using as input the complete series of observed radar fields. In this study, they were assumed to be the reference, since the reference hydrographs are expected to be the best estimates of the actual discharges at the outlet.

On the other hand, *forecasted hydrographs* were obtained according to the analysis of the multiple step ahead forecast (see for example WMO 1992): They are built with the flow estimates forecasted using the model with an anticipation τ at each time step of the event, t_i (i=1,...,p). At t_i, all available rainfall information (both the radar fields measured between t_1 and t_i and the forecasts for t_{i+1},...,$t_i+\theta$ -where θ is the duration of the rainfall forecast-) is input to the rainfall-runoff model to produce the simulated hydrograph that would be available at t_i in operational real-time conditions. Thus, hereafter, we will call them *real-time hydrographs* (*p real-time hydrographs* are generated during the event). Finally, the *forecasted hydrograph* obtained with an *anticipation* τ is built from the set of the *p real-time hydrographs*, as the sequence of the *p*

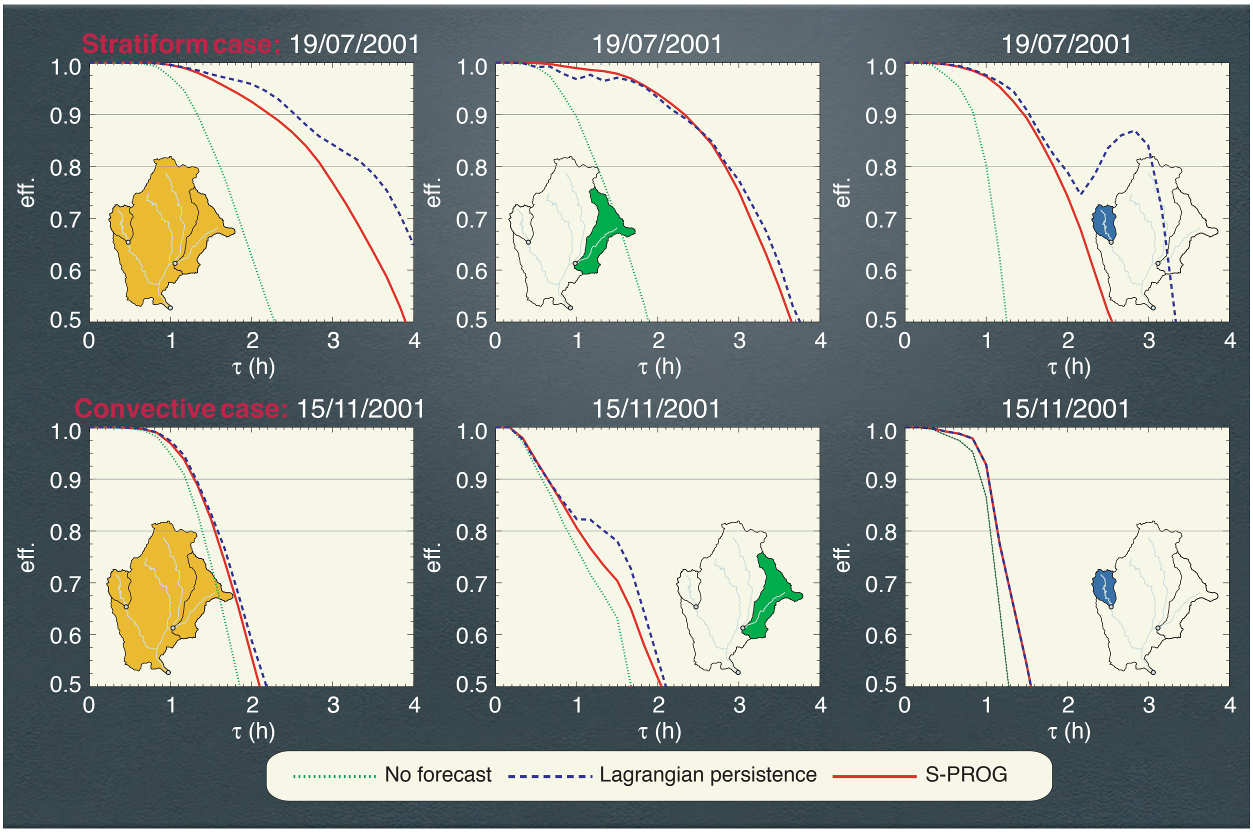

Figure 8: Evolution of the Nash efficiency of the forecasted hydrographs as a function of the anticipation with which hydrographs are simulated, . Different lines represent hydrographs simulated with precipitation fields forecasted with different techniques: with no forecast (dotted line), Lagrangian persistence (dashed line) and S-PROG (solid line).

flow values $Q_{t_i}(t_i+\tau)$ forecasted at each time step t_i for $t_i+\tau$ (i=1,...,p).

This way of generating *forecasted hydrographs* allows us to assess the reliability of runoff estimates simulated for τ hours ahead. This methodology was chosen as an option close to operational conditions of real-time flow-forecasting systems. However, *forecasted hydrographs* may not be considered as "real hydrographs", because they are not generated with an only run of the rainfall-runoff model, but with the flow estimates simulated at different time steps, from the set of *real-time hydrographs* of the event.

Finally, the statistic used to evaluate the quality of forecasted flows is the multiple step ahead forecast efficiency index, $eff(\tau)$: the forecasted hydrographs, $Q_{t_i-\tau}(t_i)$, were compared against the reference hydrograph, $Q_{\text{ref}}(t_i)$, in terms of the Nash efficiency (Nash and Sutcliffe 1970) expressed as a function of the anticipation with which the flow estimates were forecasted, t (see equation 6, where $\overline{Q_{\text{ref}}}$ is the mean flow value of the reference hydrograph).

$$eff(\tau) = 1 - \frac{\sum_{t_i=\tau}^{t_p}\left[Q_{\text{ref}}(t_i) - Q_{t_i-\tau}(t_i)\right]^2}{\sum_{t_i=\tau}^{t_p}\left[Q_{\text{ref}}(t_i) - \overline{Q_{\text{ref}}}\right]^2} \qquad (6)$$

Figure 9 shows the evolution of the efficiency of forecasted hydrographs (compared to the reference hydrograph) with the anticipation of flow forecasting, τ, for two selected events. The results obtained using rainfall forecasts obtained with Lagrangian persistence (dashed line) and S-PROG (solid line) are compared against the results of considering no precipitation forecast as input of the rainfall-runoff model (dotted line).

In all cases, the inclusion of a nowcasting technique based on radar scans (Lagrangian persistence or S-PROG) significantly improved the quality of the forecasted hydrographs. However, the hydrographs simulated with precipitation fields forecasted using S-PROG were not better than those obtained using rainfall fields derived by simple advection of the last radar scan. This result may be explained by two factors: (a) because hydrological basins tend to integrate and filter out precipitation patterns, making the filtering capacity of S-PROG useless compared to Lagrangian persistence (an additional filter of small-scale patterns is not worthwhile), and (b) because this filtering is modifying the intensity values distribution with the forecasting time as the advected field gets smoothed, affecting also the mean areal rainfall over the basins.

7. ANTICIPATION ABILITY AND PRECIPITATION LIFETIME

Taking into account that in general terms a simulated hydrograph obtaining a Nash efficiency of 0.90 may be considered as a good match to the

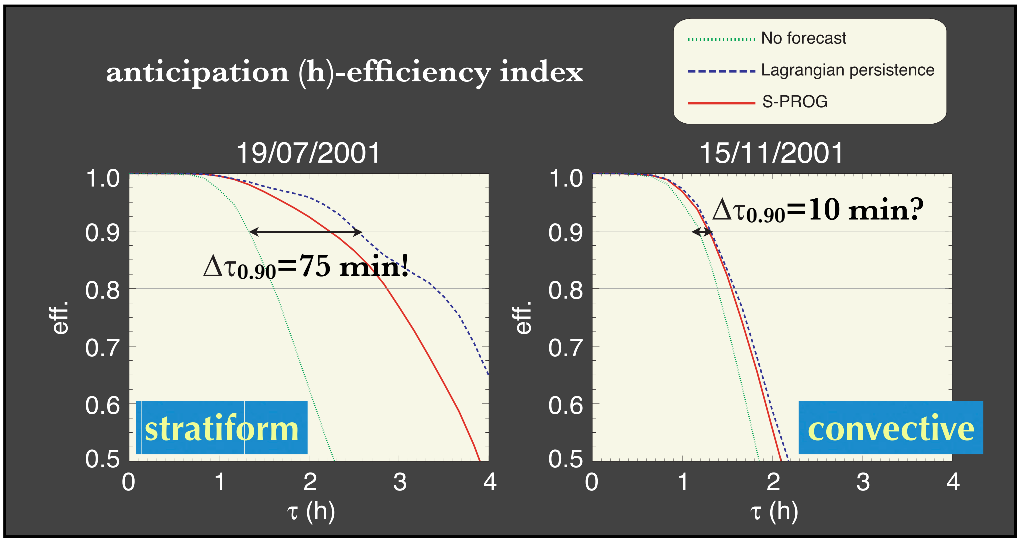

Figure 9: Evolution of the Nash efficiency of the forecasted hydrographs as a function of the anticipation and measurement of the anticipation gain $\tau_{0.90}$ for two different events. Different lines represent hydrographs simulated with precipitation fields forecasted with different techniques: with no forecast (green dotted line), Lagrangian persistence (dashed line) and S-PROG (red solid line).

reference hydrograph, the anticipation for which this efficiency is obtained, $\tau_{0.90}$, can provide an idea of the anticipation with which simulated flows could be accurately forecasted. For instance, without any rainfall forecast, for the cases of 22 December 2000 and 19 July 2001 in the Besòs basin, $\tau_{0.90}$ was around 90 minutes). This may be considered as a first approximation of the lag time of this basin (approximately, the time elapsed between the rainfall input and the main response of the basin), which may be estimated between 90 and 120 minutes, depending on the event.

In the Besòs basin, the results show that $\tau_{0.90}$ could be extended further between 10 and 80 minutes when a nowcasting algorithm based on radar scans is implemented (seeFig. 9). It is also shown that $\tau_{0.90}$ clearly depends on the nature of the rainfall event (traditionally in their stratiform or convective character) and on the precipitation distribution over the basin. For example, it is worth noting that the worst results for all basins were obtained for the event of 15 November 2001. In this case, the use of a short-term forecasting technique hardly allowed us to extend the anticipation in which flows could be forecasted accurately ($\tau_{0.90}$ is not increased by more than 10 minutes using a forecasting technique, see Fig. 9). During this event, both stratiform and convective periods affected the studied area; very influential cells were rapidly enhanced by mountain chains close to the coast and quickly moved over the studied basins, producing high rainfall intensities (see the radar loops at http://www.grahi.upc.edu/events.php). The poor results can be explained by the limitations of the analyzed nowcasting techniques, which can take into account neither the role of the orography nor the generation and evolution of short-duration convective cells. On the other hand, for the event of 19 July 2001, the obtained results were very good (see Fig. 9). Although the first part of this event could be considered as mainly convective, it had a long stratiform second period that significantly affected the studied domain. Moreover, the convective systems were quite large, well organized and had long lifetimes (see the radar loops at http://www.grahi.upc.edu/events.php). Their evolution were, therefore, more predictable than the evolution of the small storm cells of the 15 November 2001 case (as justified in Wilson et al. 1998). Furthermore, the field advection remained reasonably stationary during the different parts of the event. All these factors allowed $\tau_{0.90}$ to be extended for 80 minutes (up to 150 minutes) in the Besòs basin when using Lagrangian persistence and S-PROG.

In the small basins, $\tau_{0.90}$ was shorter than in the Besòs basin, but it could also be usefully extended: in the Mogent basin the improvement was significant, between 10 and 70 minutes (similar to the results obtained in the Besòs), and in the Ripoll basin the extension was between 10 and 40 minutes.

These results, and the fruitful comments of Seed, 2004 have lead us to explore how to define in a more objective way the nature of the precipitation fields from the point of view of predictability and to study the potential relation between this predictability and the anticipation that rainfall forecasting can induce in hydrological flow forecasting.

Once we have tested that the lifetime L of the radar fields ($L = \int_0^\infty c(\tau)\,d\tau$) could be a good indicator of their nature regarding predictability, we have started analyzing its relation with the hydrological induced anticipation $\tau_{0.90}$ on the four events studied here. The provisional results are presented in Figure 10, in which 3 events show a very clear linear relation between L and $\tau_{0.90}$ a which leads to think that it really exists a real relation between predictability and anticipation. The fourth event (15 January 2001) is clearly out of the relation, indicating that further work is required to fully understand the problem.

This fourth event is a long and complex event in which several temporal phases showing different behaviors are concatenated. As a provisional conclusion we suggest that the lifetime calculated for the whole event is useless and work is in progress to improve its definition on the case of complex events to take care of the multiplicity of phases and natures. If this initial hypothesis is confirmed and a better definition of the predictability of the phases leads to a confirmation of the linear trend, the relation between lifetime and anticipation could be of relevant interest to provide in advance estimates of the uncertainties associated to the hydrological application of the precipitation nowcasts and their reliability in extending the anticipation of the flow forecasts and warnings.

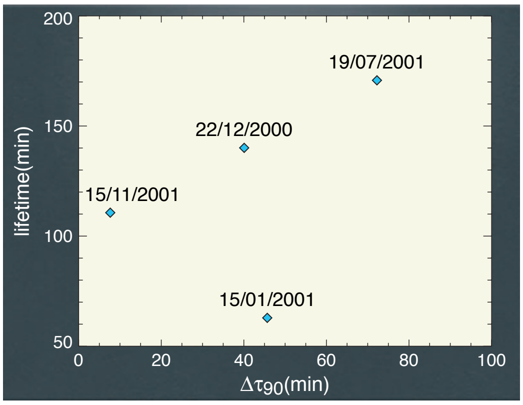

Figure 10: Relation between the lifetime of the precipitation events used for the hydrological validation and their effect in increasing the anticipation of the flow forecasting when precipitation nowcasts are used as input of the hydrological model.

8. FACTORS AFFECTING THE QUALITY OF FORECASTED HYDROGRAPHS

Several factors in the nowcasting methodologies can seriously affect the accuracy of forecasted hydrographs. Particularly, three main factors are here analyzed to assess the sensitivity of the results to them: (a) the influence of using a stationary motion field to generate rainfall forecasts (limitation assumed both by Lagrangian persistence and S-PROG), (b) the importance of a good forecast of the mean areal rainfall and (c) the relevance of a good description of the spatial distribution.

8.1. Influence of a stationary motion field in the forecasts

To analyze the sensitivity of the forecasts to an improvement in the motion field estimates, a sequence of S-PROG improved forecasts have been generated with the particularity of using an "updated" motion field: i.e. instead of using the same motion field identified at the starting time of the forecast, *v(t)*, the improved version uses the actually observed motion field at any time step *v(t+n),* derived from the observed radar fields at time *t+n*, $Z(t+n-1)$ and *t.*, $Z(t+n)$

Therefore, in this simulation, the advection is performed using the best possible motion field at that time, which means that the difference with the perfect forecast is no longer due to the stationarity of the motion field.

The quality of the forecasted hydrographs obtained using S-PROG with this "updated motion" is presented in Fig. 11 (blue dashed line). They should be compared against forecasted hydrographs simulated with the habitual configuration of S-PROG (with a stationary motion field estimated at t from the last observed radar fields, *Z(t-1)* and *Z(t)* -red solid line-). From the results, no significant improvements in the quality of the forecasted hydrographs could be appreciated when the "updated motion" field is used to advect the most recent radar field. What confirms that the motion field is generally well identified and that it is not a crucial issue to improve the present methodologies (with lead times up to 120 minutes).

8.2. Impact of the forecasted mean areal precipitation

The effect of a good estimation of the mean areal rainfall over the basin is now explored. To do it, at each time step forecasted rainfall fields are now replaced by series of θ=2 hours of uniform rainfall fields with intensity equal to the actual observed mean areal rainfall over the studied basin.

The objective is to build the forecasted hydrograph that would be obtained if the right mean areal rainfall were known in advance, without taking into account the role of the distribution of the rainfall over the basin (the evolution of the resulting efficiency of the flow forecasts with τ is plotted with orange dotted line in Fig. 11).

Using these rainfall fields as forecast allows us to significantly improve previous results. In general, the efficiency of these forecasted hydrographs keeps over 0.90 up to τ of around the basin hydrological lag time (the memory of the hydrological system) plus the length of the rainfall forecasts, θ=2 hours (around 3.5 h). Beyond this point, there is a break in the efficiency line and the quality of the forecasted hydrographs decays rapidly.

This analysis can also lead us to quantify the importance of a good description of the spatial distribution of the precipitation field over the basins. If Nash efficiency-τ curves that come from using uniform fields are compared against the results obtained by using θ=2 hours of actually observed radar scans as rainfall forecast (violet dash-dotted curve in Fig. 11 –notice that it is parallel with a delay of 2 hours to the curve obtained without rainfall forecast-). The distance between orange dotted and violet dash-dotted curves is only explained by the spatial description of the precipitation field. It can be seen that these differences are less important for the Ripoll basin (65 km^2) than for the Mogent and Besòs basins (180 and 1015 km^2), where a good spatial description of the rainfall inputs allows the model to generate better forecasted hydrographs.

These results partially agree with the conclusions of Obled et al. (1994), who found that the accuracy of the volume of precipitation over the basin leads to significant improvements in the resulting hydrographs (simulated with a rainfall-runoff model also based on Topmodel). However, they did not find improvements in simulated hydrographs when they used distributed

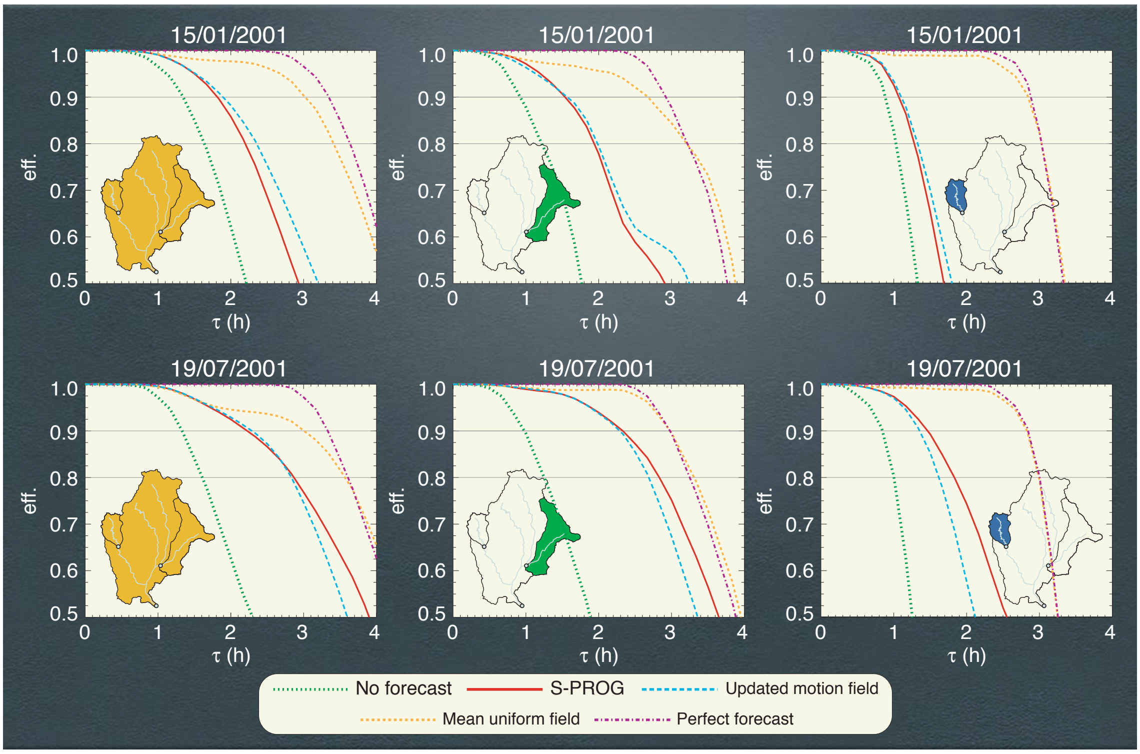

Figure 11: Evolution of the Nash efficiency of the forecasted hydrographs as a function of the anticipation with which hydrographs are simulated, τ. Different lines represent hydrographs simulated with precipitation fields forecasted with different techniques: with no forecast (green dotted line), by S-PROG (red solid line), by S-PROG using "updated motion fields" (blue dashed line), with =2 hours of an uniform field with the observed mean areal rainfall (orange dotted line) and also with =2 hours of actual radar scans (violet dashed-dotted line).

precipitation fields with a better spatial description and concluded that the only purpose of using them is to improve the accuracy of the incoming rainfall volume over the basin rather than taking into account any interaction between the incoming rainfall field and the simulated mechanisms of flow generation. In our case, the bigger the basin the more important these interactions become, being of little importance for the case of the Ripoll basin (which has an area similar to the 71 km2 of the basin studied by Obled et al. 1994).

There are two main factors that could explain the importance of the rainfall distribution over the basin: (a) differences due to the localization of small rainfall patterns over the basin respect to the uniform field are more important in bigger basins, which may result in significant differences in the response time of the basin, as suggested by Obled et al. (1994), and (b) differences between the mean areal rainfall calculated over the basin and the rates of each individual rainfall pattern (for example, of a small convective cell) also tend to be higher in bigger basins, which in combination with the non-linear processes of runoff generation results in quite different hydrographs.

Finally, the main conclusion from the analyzed results is that one of the most important points to improve the quality of forecasted hydrographs is a good estimate of the mean areal rainfall of the forecasted fields over the basin. This conclusion is also in agreement with the fact that the influence of a good spatial distribution is more acute for larger basins, what is in fact the best way to improve the mean areal rainfall estimation of its sub-basins, which become hydrologically relevant as the size of the domain increases.

9. CONCLUSIONS

In the present study the radar-based nowcasting technique S-PROG was implemented in a Mediterranean area using data from different events representative of the climatic characteristics of the studied region.

In terms of precipitation comparison, S-PROG produced better forecasted fields than Lagrangian and Eulerian persistence in all cases.

On the other hand, the hydrological validation showed that the use of a nowcasting technique based on radar data allows to significantly improve the quality of forecasted hydrographs. The anticipation with which flows could be estimated with enough quality was extended by between 10 and 80 minutes in the Besòs basin (1050 km^2). This could be considered a notable improvement in the fast response basins of the Mediterranean areas (that in many cases have hydrological lag times between 1 and 2 hours). However, the results obtained using S-PROG were not significantly better than the results obtained with a much simpler nowcasting technique (Lagrangian persistence, which does not include small-scale filtering).

In all cases, it has been noticed that the nature of the event (especially the type of precipitation and the degree of spatial organization of the rainfall field) has an important effect on the quality of the forecasted flow estimates. A relation between lifetime (as a measure of the predictability of the precipitation patterns) and the hydrological anticipation improvement, $\tau_{0.90}$, (as a measure of the ability to anticipate the flows thanks to the use of precipitation nowcasts) seems to exist, although more conclusive work are required. If this hypothesis could be confirmed, this property could provide substantial help to objectively associate the lead time and the hydrological usefulness of the rainfall nowcasts for a given storm, as well as to be the base for a measure of the expected uncertainties to associate to the forecast.

The influence of some of the main factors affecting the quality of the forecasted hydrographs have been also analyzed. Results show that no significant improvement in forecasted discharges is obtained when the best possible motion field is used to advect forecasted rainfall fields (instead of using just the one estimated at the start of the forecast).

Furthermore, we can conclude that the crucial factor to improve the quality of forecasted flows is the quality of the forecasted mean areal rainfall over the basin, as shown by feeding the hydrological model with series of uniform rainfall fields with the observed mean areal rainfall over the basin into the model. This analysis also allowed us to quantify the effect of the spatial distribution of the rainfall field over the basin, which was found to be more relevant in larger basins.

Finally, as the quality of the forecasted precipitation fields significantly decreases for lead times over 1 hour, it could be interesting to look for different alternatives that may lead to improve forecasted hydrographs. Germann and Zawadzki (2002) proposed the use of composite images from a radar network instead of single-radar data to increase the size of the rainfall domain. This will provide information about entire mesoscale and synoptic scale phenomena, leading to avoid the lack of information caused by the advection of areas out of the radar domain in case of high speeds. On the other hand, it also will result in better estimations of velocity fields (less affected by border effects in the area of interest). An alternative approach for the nowcasting technique would be the generation of probabilistic rainfall forecasts (using, for example, the techniques proposed by Germann and Zawadzki 2004 or Seed and Bowler 2003) as input of the rainfall-runoff model, in order to produce stochastic forecasted hydrographs.

These heuristic stochastic approaches are for the present a promising way to afford the generation of different precipitation scenarios compatible with the nowcasted fields and thus to study the uncertainty propagation in flow forecasts due to the uncertainty related to the precipitation forecasts.

Figure 12 shows an example in which one of these techniques has been applied to the rainfall nowcasts provided by S-PROG generating 40 compatible rainfall scenarios that have been introduced on the hydrological model of the Besòs river. The 40 outcoming hydrographs (white lines) are in fact a first estimate of the quality of the forecasted one (red line) due exclusively to the uncertainties associated to the precipitation nowcasting.

From a different perspective, interesting new ideas that focus on coupling NWP and distributed rainfall-runoff models in medium-sized basins of few thousands of km2 (see, for example, Jasper et al. 2002) seem to be a promising alternative to further

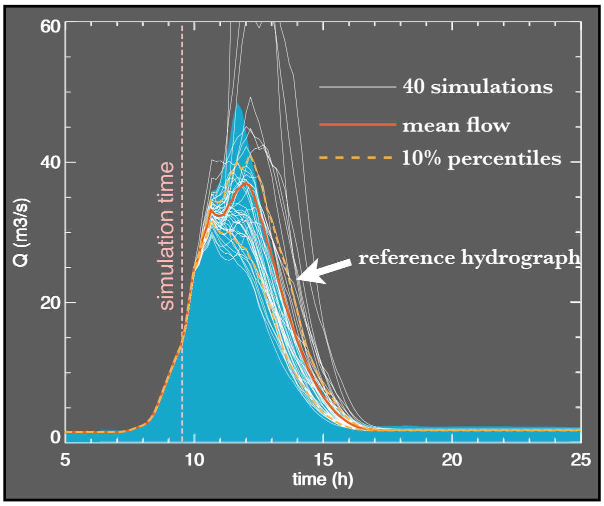

Figure 12: Sensitivity of the hydrological forecasts to the generation of multiple precipitation scenarios compatible with the precipitation nowcast at a given time step

extend the anticipation with which hydrographs may be forecasted.

All these ideas could be a way to overcome the present limitations of the current deterministic nowcasting techniques, and a first step towards coupled hydrometeorological methodologies for producing useful forecasting, and their associated uncertainties, at lead times over 2 hours.

ACKNOWLEDGEMENTS

We would like to express our thanks to Dr. Alan Seed for fruitful discussions on the implementation of S-PROG and its usefulness in flood forecasting as well as to Prof. Geoff Pegram for his supprot and encouraging discussions. Thanks are due to the Spanish Institute of Meteorology for providing radar data (thanks are specially due to Ramon Pascual and Miguel Lara) and to the Water Agency of Catalunya for providing hydrological data and funding support. This work has been done in the framework of the EC projects VOLTAIRE EC (EVK2-CT-2002-00155) and FLOODSITE (GOCE-CT-2004-505420).

REFERENCES

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

Beven, K., and M. J. Kirkby, 1979: A physically-based variable-contributing area model of basin hydrology. Hydrol. Sci. Bull., 24, 27-53.

Berenguer M., Corral, C., Sempere-Torres, D., Sánchez-Diezma, R. 2005: Hydrological Validation of a Radar-Based Nowcasting Technique, Journal of Hydrometeorology, 6, 532–549.

Borga, M., 2002: Accuracy of radar rainfall estimates for streamflow simulation. J. Hydrol., 267, 26-39.

Borga, M., E. N. Anagnostou, and E. Frank, 2000: On the use of real-time radar rainfall estimates for flood prediction in mountainous basins. J. Geophys. Res., 105, 2269-2280.

Carpenter, T. M., K. P. Georgakakos, and J. A. Sperfslagea, 2001: On the parametric and NEXRAD-radar sensitivities of a distributed hydrologic model suitable for operational use. J. Hydrol., 253, 169-193.

Corral, C., 2004: Desenvolupament d'un model hidrològic per incorporar informació del radar meteorològic. Aplicació operacional a la conca del riu Besòs. Ph. D. Dissertation, Universitat Politècnica de Catalunya, 175 pp.

——, D. Sempere-Torres, M. Berenguer, and I. Escaler, 2001: A distributed rainfall runoff model integrated in an operational hydrometeorological forecasting system in Catalunya based in weather radar. Preprints, 5th Int. Symp. on Hydrol. App. of Weather Radar, Kyoto, Japan, Disaster Prevention Research Institute, 407-412.

——, M. Berenguer, D. Sempere-Torres, and I. Escaler, 2002: Evaluation of a conceptual distributed rainfall-runoff model in the Besòs catchment in Catalunya using radar information. Preprints, 2nd European Conf. on Radar Meteor., Delft, The Netherlands, 409-415.

Delrieu, G., and J. D. Creutin, 1995: Simulation of radar mountain returns using a digitized terrain model. J. Atmos. Oceanic Technol., 12, 1038-1049.

Dolcine, L., H. Andrieu, D. Sempere-Torres, and J.-D. Creutin, 2001: Flash flood forecasting with a coupled precipitation model in a mountainous Mediterranean basin. J. Hydrol. Eng., 6, 1-10.

Faurès, J. M., D. C. Goodrich, D. A. Woodlhiser, and S. Sorooshian, 1995: Impact of small-scale spatial rainfall variability on runoff modelling. J. Hydrol, 173, 309-326.

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.

——, and ——, 2004: Scale-dependence of the predictability of precipitation from continental radar images. Part II: Probability forecasts. J. Appl. Meteor., 43, 74-89.

Giannoni, F., J. A. Smith, Y. Zhang, and G. Roth, 2003: Hydrologic modeling of extreme floods using radar rainfall estimates. Adv. in Water Resour., 26, 195-203.

Gourley, J. J. and B. E. Vieux, 2003: A hydrologic approach to evaluating quantitative precipitation estimates. Preprints, 31st Conf. on Radar Meteorology, Seattle, WA, Amer. Meteor. Soc., 714-717.

Jasper, K., J. Gurtz, and H. Lang, 2002: Advanced flood forecasting in Alpine watersheds by coupling meteorological observations and forecasts with a distributed hydrological model. J. Hydrol., 267, 40-52.

Kouwen, N., A. Bingeman, A. Bellon, and I. Zawadzki, 2004: Operational issues: Real-time correction and hydrological validation of radar data. Preprints, 6th Int. Symp. on Hydrol. App. of Weather Radar, Melbourne, Australia.

Krajewski, W., K. P. Venkataraman, K. Georgakakos, and S. C. Jain, 1991: A Monte Carlo study of rainfall sampling effect on a distributed catchment model. Water Resour. Res., 27, 119-128.

Li, L., W. Schmid, and J. Joss, 1995: Nowcasting of motion and growth of precipitation with radar over a complex orography. J. App. Meteor., 34, 1286-1300.

Mockus, V., 1957: Use of storm and watersheds characteristics in synthetic hydrograph analysis and application, U. S. Dept. of Agriculture. Soil Conservation Service.

Nash, J. E., 1957: The form of instantaneous unit hydrograph. Hydrol. Sci. Bull., 3, 114-121.

——, and J. V. Sutcliffe, 1970: River flow forecasting through conceptual models, 1. A discussion of principles. J. Hydrol., 10, 282-290.

Obled, C., J. Wendling, and K. Beven, 1994: The sensitivity of hydrological models to spatial rainfall patterns: an evaluation using observed data. J. Hydrol., 159, 305 -333.

Pellarin, T., G. Delrieu, G.-M. Saulnier, H. Andrieu, B. Vignal, and J.-D. Creutin, 2002: Hydrologic Visibility of Weather Radar Systems Operating in Mountainous Regions: Case Study for the Ardeche Catchment (France). J. Hydrometeor., 3, 539-555.

Rawls, W. J., L. R. Ahuja, D. L. Brakensiek, and A. Shirmohammadi, 1992: Infiltration and soil water movement. Handbook of Hydrology, D. R. Maidment, Ed., McGraw-Hill Inc., 5.1-5.51.

Rinehart, R. E., and E. T. Garvey, 1978: Three-dimensional storm motion detection by conventional weather radar. Nature, 273, 287-289.

Sánchez-Diezma, R., D. Sempere-Torres, G. Delrieu, and I. Zawadzki, 2001: An Improved Methodology for ground clutter substitution based on a pre-classification of precipitation types. Preprints, 30th Int. Conf. on Radar Meteorology, Munich, Germany, Amer. Meteor. Soc., 271 -273.

——, ——, J. D. Creutin, I. Zawadzki, and G. Delrieu, 2001: Factors affecting the precision of radar measurement of rain. An assessment from a hydrological perspective. Preprints, 30th Int. Conf. on Radar Meteor., Munich, Germany, Amer. Meteor. Soc., 573-575.

Seed, A. W., 2003: A dynamic and spatial scaling approach to advection forecasting. J. Appl . Meteor., 42, 381-388.

Seed, A. W., 2004: Is the potential anticipation induced in flow forecasting by rainfall nowcasting related to the lifetime of the precipitation events? Personal communication.

——, and N. Bowler, 2003: A model to generate stochastic nowcasts of rainfall. Preprints, 31st Conf. on Radar Meteorology, Seattle, WA, Amer. Meteor. Soc., 704-708.

Sempere-Torres, D., J. M. Porrà, and J. D. Creutin, 1997: Characterization of rainfall properties using the Drop Size Distribution. Application to autumn storms in Barcelona. Preprints, WMO-INM Int. Conf. on Cyclones and Hazardous Weather in the Mediterranean Area, Mallorca, Spain, Intstituto Nacional de Meteorología, 621 -628.

——, ——, and ——, 1998: Experimental evidence of a general description for raindrop size distribution properties. J. Geophys. Res., 103, 1785-1797.

——, C. Corral, P. Malgrat, and J. Raso, 1999: Use of weather radar for combined sewer overflows monitoring and control. J. Environ. Eng., 125, 372-380.

——, D., R. Sánchez-Diezma, M. Berenguer, R. Pascual, and I. Zawadzki, 2003: Improving radar rainfall measurement stability using mountain returns in real time. Preprints, 31st Conf. on Radar Meteorology., Seattle, WA, Amer. Meteor. Soc., 220-221.

Shah, S. M. S., P. E. O'Connell, and R. M. Hosking, 1996: Modeling the effects of spatial variability in rainfall on catchment response, 2. Experiments with distributed and lumped models. J. Hydrol., 175, 89-111.

Sun, X., R. G. Mein, T. D. Keenan, and J. F. Elliot, 2000: Flood estimation using radar and raingauge data. J. Hydrol., 239, 4-18.

Vieux, B. E. and P. B. Bedient, 2004: Assessing urban hydrologic prediction accuracy through event. J. Hydrol., 299, 217-236.

Wilson, C. B., J. B. Valdes, and I. Rodriguez-Iturbe, 1979: On the influence of the spatial distribution of rainfall on storm runoff. Water Resour. Res., 15, 321-328.

Wilson, J., 2003: Thunderstorm nowcasting: past, present and future. Preprints, 31st Conf. on Radar Meteorology, Seattle, WA, Amer. Meteor. Soc., J13-J19.

——, N. A. Crook, C. K. Mueller, J. Sun, and M. Dixon, 1998: Nowcasting Thunderstorms: A Status Report. Bull. Amer. Meteor. Soc., 79, 2079-2099.

Winchell, W., H. V. Gupta, and S. Sorooshian, 1998: On the simulation of infiltration- and saturation-excess runoff using radar-based rainfall estimates: effects of algorithm uncertainty and pixel aggregation. Water Resour. Res., 34, 2655-2670.

WMO, 1992: Simulated real-time intercomparison of hydrological models. OHR No. 38, 241 pp.

Wyss, J., E. R. Williams, and R. L. Bras, 1990: Hydrologic modeling of New England river basins using radar rainfall data. J. Geophys. Res., 95, 2143-2152.