J8.4 USE OF 4 KM, 1 HR, PRECIPITATION FORECASTS TO DRIVE A DISTRIBUTED HYDROLOGIC MODEL FOR FLASH FLOOD PREDICTION

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1. INTRODUCTION

A performance objective in the National Oceanic and Atmospheric Administration's (NOAA) Strategic Plan (NOAA, 2004) is to "Increase lead-time and accuracy for weather and water warnings and forecasts." In this paper, we investigate the use of a distributed hydrologic model and a precipitation nowcast algorithm to meet this objective for flash flood forecasts. A flash flood is a flood that begins within six hours of the causative event (NWS, 2005). More specifically, we focus on flash floods in small basins caused by heavy or excessive rainfall. These floods typically occur in basins smaller than about 260 km^2 (Davis, 1998).

Distributed hydrologic models provide a natural framework for flash flood modeling because they can produce relatively high resolution forecasts compared to lumped river models (that is, models with parameters and calculations applied uniformly over the entire basin area) currently used at National Weather Service River Forecast Centers (NWS RFCs). Results from the Distributed Model Intercomparison Project (DMIP) (Smith et al., 2004; Reed et al., 2004) show that distributed models can produce simulations comparable to or better than lumped models at RFC basin scales. For flash flood applications, the key question is whether these distributed models can produce useful simulations at ungauged interior locations.

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Although distributed models in DMIP showed reasonable simulations over a range of basin sizes, only one basin studied in DMIP is small enough to be a flash flood basin. We anticipate greater modeling uncertainties in small basins (Carpenter and Georgakakos, 2004). Will increased model errors and uncertainty at smaller scales outweigh the benefits of distributed modeling? At what scales can the distributed model provide useful forecasts? Our ongoing work with distributed modeling, including some components planned for DMIP 2 (http://www.nws.noaa.gov/oh/hrl/dmip/2/index.html), will use more small basin data to investigate these important questions.

The DMIP work has focused mostly on assessing the accuracy of flood simulations. Another important aspect of flood forecasting is lead-time. By definition, the response time of flash flood basins is small, so the use of forecast precipitation data can provide a substantial contribution to forecast lead-time. In very small basins, use of forecast precipitation may be the only way to achieve any actionable lead-time. Thus, effective use of a distributed hydrologic model for flash flood forecasting will require using gridded precipitation forecasts as input. The viability of this proposed concept is the subject of this study.

Gridded precipitation forecasts could also be used in conjunction with NWS Flash Flood Guidance (FFG) procedures to enhance lead-times (Sweeney, 1992). However, use of a distributed hydrologic model offers the potential to improve upon current FFG procedures, which are based on lumped river models (Reed et al., 2004; Reed et al., 2005).

For this research we use 1 hour, 4 km resolution QPF grids produced by the Multisensor Precipitation Nowcaster (MPN) (Guan et al., 2005). MPN produces extrapolation nowcasts of rainfall for arbitrary durations up to an hour at a 5-minute update frequency based on current and recent-past mosaicked WSR-88D radar reflectivity data and real-time rain gauge data to adjust known radar biases. It is an extension of the Flash Flood Potential (FFP) algorithm (Walton et al. 1985; Walton and Johnson, 1986; Walton et al., 1987). MPN is currently a non-operational prototype but has been integrated with an advanced version of the Multisensor Precipitation Estimator (MPE), an operational algorithm currently available to Weather Forecast Offices (WFOs) and RFCs (http://www.nws.noaa.gov/oh/hrl/papers/papers.htm#wsr88d). For this preliminary study, we did not use rain gauge data within MPN and only used radar data from single sites since the chosen basins that we examined were well covered by a single radar.

The MPN algorithm is more suitable for driving a distributed hydrologic model than current operational nowcast algorithms within the WFOs System for Convection and Nowcasting (SCAN) (Kitzmiller et al., 1999; Kitzmiller, et al, 2002). In addition, quantitative precipitation forecast (QPF) grids produced at the NWS Hydrometeorological Prediction Center (HPC) are too coarse in space and time to be useful for direct input into a flash flood model.

Both quantitative precipitation estimates (QPE) produced at the NWS Arkansas-Red Basin River Forecast Center (ABRFC) and QPF grids produced by MPN are used in this study. The QPEs were generated by ABRFC using merged radar and rain gauge data. To produce forecast hydrographs for selected events, QPE and QPF grids are fed to the Hydrology Laboratory Research Modeling System (HL-RMS) (Koren, 2004). In this implementation of HL-RMS we use a gridded version of the Sacramento model and a kinematic wave algorithm for overland flow and channel routing. The same algorithms performed well in DMIP. Enhancements to HL-RMS were made to facilitate the hindcast experiments described below.

Previous researchers have also used short-term dynamical or nowcast rainfall forecasts to drive hydrologic models (Yates et al., 2000; Pereira Fo et al., 1999; Bell and Moore, 2000); however, these tests have been limited to few events. A goal of this project is to analyze many case studies to better characterize the potential use of these approaches for operational forecasting.

It is expected that QPF grids will have greater errors and uncertainty than QPE. Thus, hindcast studies that incorporate the use of forecast data are necessary to help define the spatial and temporal scales at which useful results can be achieved with the proposed approach. Procedures for ingesting MPN grids into HL-RMS have been developed and a few hindcast case studies have been run. Initial results for four hydrograph events are described in this paper.

2. METHODOLOGY

The basins studied are located in eastern Oklahoma and northwestern Arkansas (Figure 1). Hourly data from three stream gauges in this region are used in this paper. The data were obtained from the United States Geological Survey (USGS). Data from several other stations in this region have also been obtained and will be used in future work to strengthen our conclusions.

Although the QPE and QPF rainfall grids being used are at a nominal 4 km spatial resolution, HL-RMS was run using 2 km cells to get a reasonable representation of basin morphology in small basins. Cell-to-cell connectivity for the 2 km network was derived using 30-m Digital Elevation Model data and the algorithms of Reed (2003) (Figure 1). Rainfall input values for each 2 km cell were sampled from the overlapping 4 km cell.

Parameters for the gridded Sacramento model were derived using the National Resource Conservation Service (NRCS) Soil Survey Geographic Databases (SSURGO) and the 1992 National Land Cover Dataset (NLCD) available from the USGS (Koren et al., 2002; Anderson et al, 2005; Soil Survey Staff, 2005; USGS, 2005). Only flow measurement data (cross sectional area and flow) at two downstream gauges Tahlequah (2484 km^2) and Eldon (795 km^2) were used to derive channel routing parameters. Channel routing parameter values at upstream cells were derived using geomorphological relationships (Koren, 2004). In summary, to produce the results presented here, Sacramento model, overland flow, and channel routing parameters were all uncalibrated.

Guan et al. (2005) compared the performance of several modeling configurations within MPN. Based on their results, the QPF grids used here were produced using (1) no growth and decay accounting, (2) the FFP progressive spatial smoothing algorithm, and (3) local storm motion vectors.

Two convective rain events from an initial list of twelve possible cases were selected for our preliminary study based on the actual occurrence of hydrograph flood peaks with rapid rises recorded at USGS stream gauges and the availability of archived radar reflectivity data for either of two WSR-88D radars covering the basins: KINX Tulsa, OK and KSRX Ft. Smith, AR. The first event includes rainfall from 4/22/2004 22 to 4/24/2004 17 UTC. During this period there were three pulses of rainfall that produced three hydrograph flood events in the basins modeled. The second rainfall event is from 7/2/2004 4 UTC to 7/3/2004 10 UTC. One hydrograph flood event was produced during this period. For the April period, the MPN results were produced using data from the KINX radar while the July event used KSRX data. For both the April and July periods, there were warned and verified flash floods by NWS forecasters in the counties containing the basins modeled.

The hindcast experiments presented here involved driving the distributed model with hourly, 4 km multisensor QPE grids for several years prior to the chosen rain events to get initial model states. Given these initial states, the model was then run continuously, once an hour at the top of the hour, for the duration of each selected storm with a forecast model run for each of four possible types of one-hour QPF input rainfall: 1) zero-valued QPF, 2) "persistent" QPF (i.e., the previous hour's multisensor QPE was used as the QPF), 3) one-hour QPF from MPN, and 4) "simulation" (multisensor QPEs for all future hours used as QPF). For all input configurations, multisensor QPE was used prior to the forecast update time, and (except for #4) zero-valued QPF was assumed beyond the 1-hour forecast period. A 4-day hydrograph forecast was produced each hour when there was a significant amount of forecast average rainfall (> 0.5 mm in an hour) within any of the basins modeled. Output hydrographs were saved for selected gauge locations. During the storm, states to initialize each 4-day forecast were also maintained using the multisensor QPE grids.

Although MPN is capable of producing sub-hourly rainfall forecasts at sub-hourly time intervals, we only use 1-hour forecasts generated at the top of the hour in these experiments.

In future tests we plan to incorporate an additional data source, radar-only QPE data, for the most recent hour or hours. This will more closely emulate a forecast situation at a WFO where multisensor QPE grids will not be available quickly enough for flash flood applications.

3. RESULTS AND DISCUSSION

Hydrographs for the Baron Fork at Dutch Mills, AR, (105 km^2) are shown in Figures 2a and b. The time between heavy rain occurrence and hydrographs peaks is about 2 – 3 hours for Dutch Mills, indicating these are flash flood events. Figures 2a and b show results for three separate forecast times corresponding to three distinct hydrograph peaks. (A1: 4/23/2004 0 UTC, A2: 4/23/2004 7 UTC, and A3: 4/24/2004 4 UTC in Figure 2a and B1: 4/23/2004 2 UTC, B2: 4/23/2004 8 UTC, and B3: 4/24/2004 7 UTC in Figure 2b). These times were selected because they are right before or after hours with heavy rainfall. A1, A2, and A3 are the earliest forecasts that predict floods for their respective events. For each time, there is a QPF (solid), zero QPF (dashed), and persistence forecast (shaded). The solid magenta line is the simulation as defined above.

Since Dutch Mills is not an RFC forecast point, we don't have an official flood stage/flow estimate. For reference, bankfull flow and 2x bankfull flow estimates are included on the Figures 2a and b. Examination of bankfull flow and flood flow estimates from nearby RFC forecast points suggest that the ratio of flood flow to bankfull flow at a site ranges from approximately 1 to 3.

As one would expect, the QPF results are higher than the zero QPF results for all peaks. Additionally, the results in A1, A2, and A3 demonstrate that floods could be predicted sooner using either the QPF or the persistence results when compared to the 0 QPF results. Consistent with the results of Guan et al. (2005), the QPF results either outperform persistence or perform similarly to persistence for all forecasts except A1.

In A1 the persistence forecast produces the best hydrograph, but this is partly due to under simulation by the model for these events with the uncalibrated model. In A1, the mean areal QPF for Dutch Mills for 4/22/2004 23 – 4/23/2004 0 UTC was 9.5 mm while the observed mean QPE for this hour was 30.0 mm. The 9.5 mm QPF available for a 4/22/2004 23 UTC run was not enough to produce a notable hydrograph rise out of the model. That is why the 4/23/2004 0 UTC forecast (the earliest forecast to indicate a flood) is shown in Figure 2a. The QPF for 4/23/2004 0-1 UTC was 20.1 mm while the observed QPE was only 5.7 mm for the same hour, causing the forecast at 4/23/2004 0 UTC to be much higher than the simulation.

The forecasts for events B1, B2, and B3 show the improvement that can be gained for the same events with additional 2, 1, and 3 hours of data respectively. Normally we would not expect the forecasts to produce results closer to the observed data than the raw model simulation as seen in B1 and B2. This occurs in these events due to the general under simulation by the model and mean areal QPF values that are greater than the corresponding mean areal QPE values for the hour immediately following the forecast time. For 4/23/2004 2-3 UTC the QPF was 15.2 mm and QPE was 3.8 mm. For 4/23/2004 8-9 UTC the QPF was 15.7 mm and the QPE was 6.1 mm.

Figures 3a, b, and c and Figure 4 show hydrographs for Osage Creek near Cave Springs, AR, (90 km^2) and Sager Creek near West Siloam Springs, OK, (49 km^2) respectively during a July 2004 storm. For Cave Springs, the rainfall event is double peaked. The lag from the first rainfall peak to the hydrograph peak is about 5.5 hours and from the second rainfall peak to the hydrograph peak is about 2.5 hours. For West Siloam Springs, the lag between the maximum observed rainfall and the hydrograph peak is about 2.5 hours. Hence, these are both flash flood events.

Figures 3a, b, and c show a sequence of forecasts at 4, 5, and 6 UTC on 7/3/2004. Use of QPF data at all three forecast times shows improvement over the 0 QPF and persistence cases. The QPF based forecast at 4 UTC is particularly valuable since it provides the most lead-time. The biggest difference between the QPF and 0 QPF cases is seen in Figure 4 for West Siloam Springs. This occurs because the main driver for the flood in this basin is a single hour of heavy rainfall. In this case, the areal averaged QPF predicted for this basin at 6 UTC closely matches the QPE from 6-7 UTC (QPF = 49 mm, QPE = 52 mm). Similarly, an accurate areal averaged QPF value at 5 UTC resulted in a very good simulation for Cave Springs in Figure 3b (QPF = 34.7; QPE for 5-6 UTC = 29.8).

QPF and QPE rainfall patterns for two hours during the July event are shown in Figure 5. The storm was moving from north to south. This pattern explains why the hydrograph rise at Cave Springs was predicted at 4 UTC (Figure 3a) but not until 6 UTC (Figure 4) at West Siloam Springs.

To begin to understand whether or not model forecasts could add lead-time to current forecasting capabilities, we compare the earliest time that the model forecasts a flood in the selected basins to the times that NWS flood warnings were actually issued in the county containing the respective basin. Dutch Mills is in Washington County, AR. NWS flash flood warnings were issued for Washington County at 4/23/2004 0:35 UTC, 4/23/2004 08:55 UTC, and 4/24/2004 05:19 UTC. Using the proposed methodology, the QPF based forecasts would have predicted floods in Dutch Mills at earlier times: 4/23/2004 0 UTC, 4/23/2004 7 UTC, and 4/24/2004 4 UTC (A1, A2, and A3 in Figure 2).

Cave Springs is fully within Benton County, AR, and West Siloam Springs is mostly within Benton County. A NWS flash flood warning was issued for Benton County on 7/3/2004 at 0452 UTC. Figure 3a shows that a flow forecast at Cave Springs available from a 7/3/2004 4 UTC run would indicate a flood threat, another case where the model results could have been used to increase lead-time. The model would not have predicted a flood at West Siloam Springs until 6 UTC (Figure 4) because it is located farther south.

Although few cases have been run so far and the comparisons are not an exact match for operational conditions, the model results are consistent with forecasts issued and indicate the potential for improving lead-times. In future work with a larger sample of events, a few improvements to the comparisons can be made to make them more robust: (1) The model can be run more often than at the top of each hour, (2) gridded model results for the entire county can be evaluated rather than results only at specific basins, and as mentioned above, (3) we can more closely emulate operational conditions by using radar-only QPE for recent hours.

4. SUMMARY

This paper describes initial results from a study to evaluate the potential benefits of using a short-term precipitation nowcast algorithm in conjunction with a distributed hydrologic model for flash flood forecasting. Procedures for ingesting MPN grids into HL-RMS were developed and a few hindcast case studies were run. These studies were for three events during April 2004, and an event in July 2004 near the border between northeast Oklahoma and Arkansas.

Model simulations and forecasts from an uncalibrated distributed hydrologic model compared well with observed streamflow data for the selected events in three small basins. Hydrographs generated using 1-hour, gridded QPF from MPN consistently improved upon 0 QPF and persistence based hydrographs.

Model results were consistent with verified NWS flash flood warnings and showed the potential for improving lead-times for convective storm events and thus for advancing the NOAA performance objective to increase lead-time and accuracy for weather and water warnings and forecasts.

More case studies must be examined to answer key questions such as: At what spatial scales is the model applicable? How applicable is the model in different parts of the country and at different times of the year with different levels of data quality? At what temporal frequency should the model be run? By building an archive of case studies to answer these questions, we can also more easily evaluate improvements to either the nowcaster or distributed modeling algorithms.

ACKNOWLEDGEMENTS

This work was partially supported by the NWS Advanced Hydrologic Prediction Service (AHPS) program.

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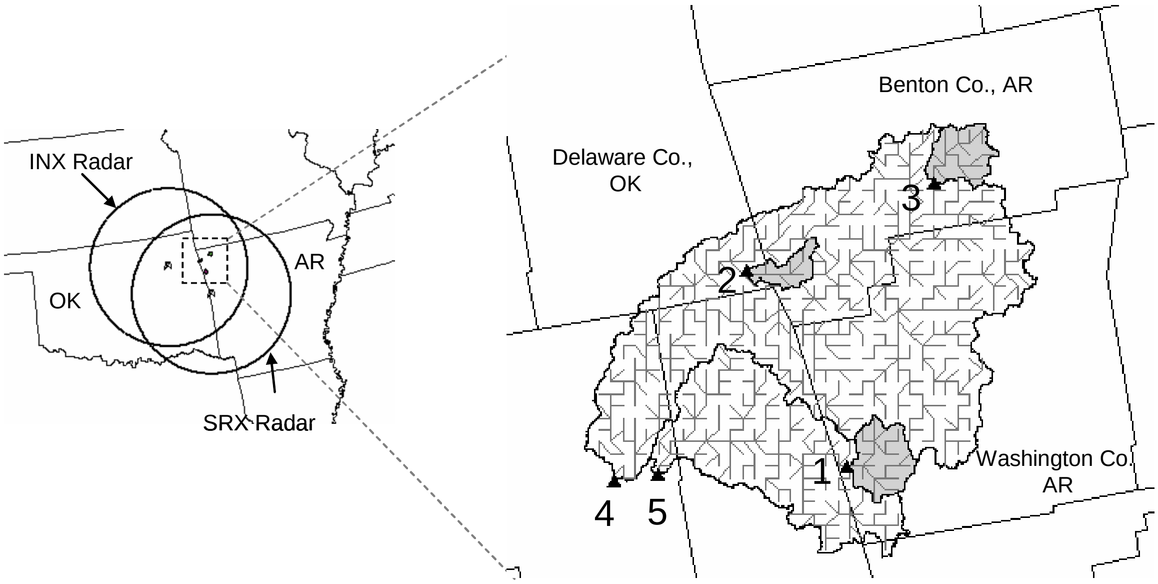

No	USGS No	Name	Area(km2)
1	7196900	Baron Fork at Dutch Mills AR	105
2	7195865	Sager Creek near West Siloam Springs OK	49
3	7194880	Osage Creek near Cave Springs AR	90
4	7196500	Illinois River near Tahlequah OK	2484
5	7197000	Baron Fork at Eldon OK	795

Figure 1. A location map that includes cell-to-cell connectivity for the gridded routing model. Each line segment in the connectivity network is from the center of one 2 km cell to the next.

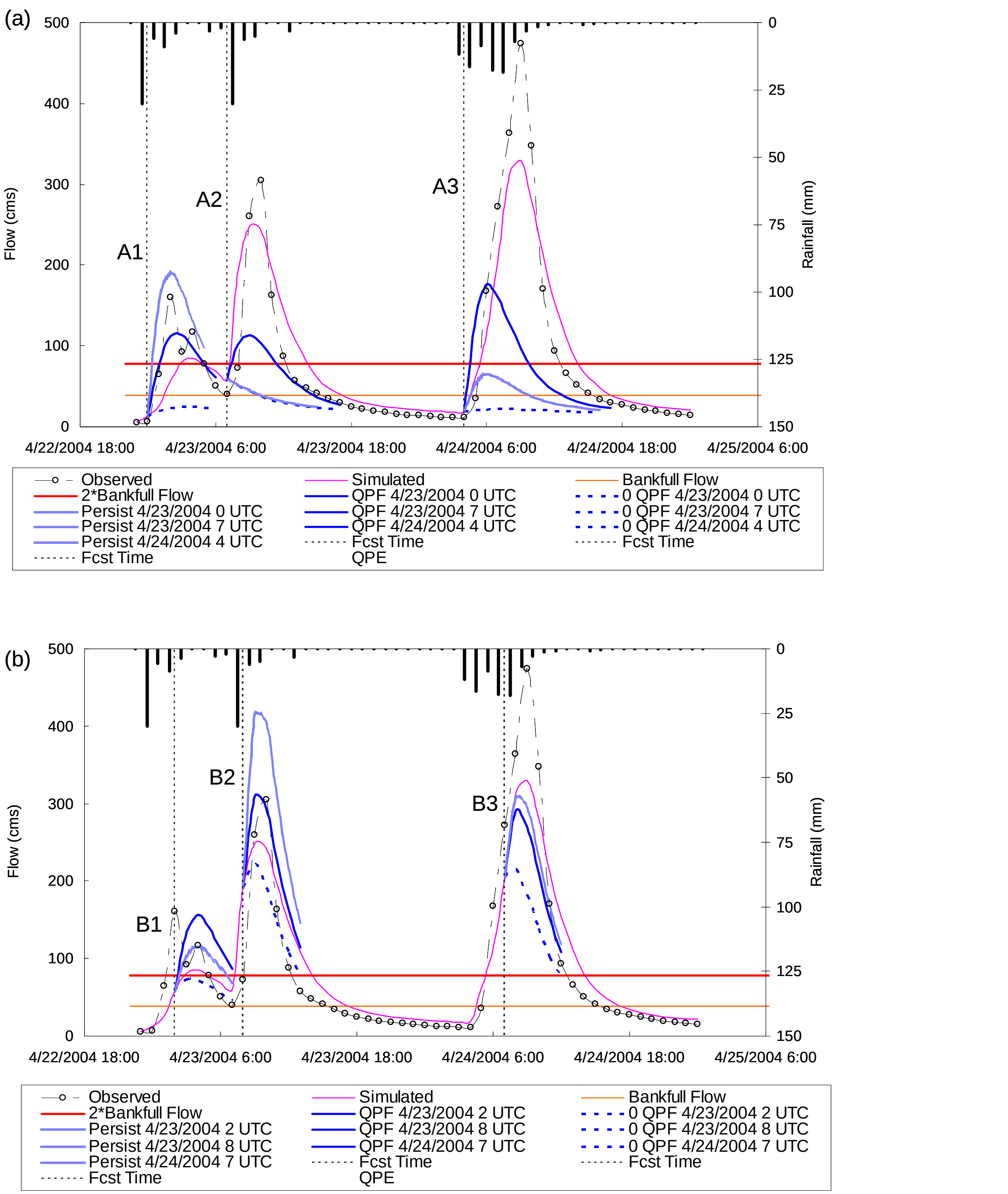

Figure 2. (a) Three event hydrographs at Baron Fork at Dutch Mills, AR. (b) The same three events at later forecast times. Dashed vertical lines indicate the start of the forecasts.

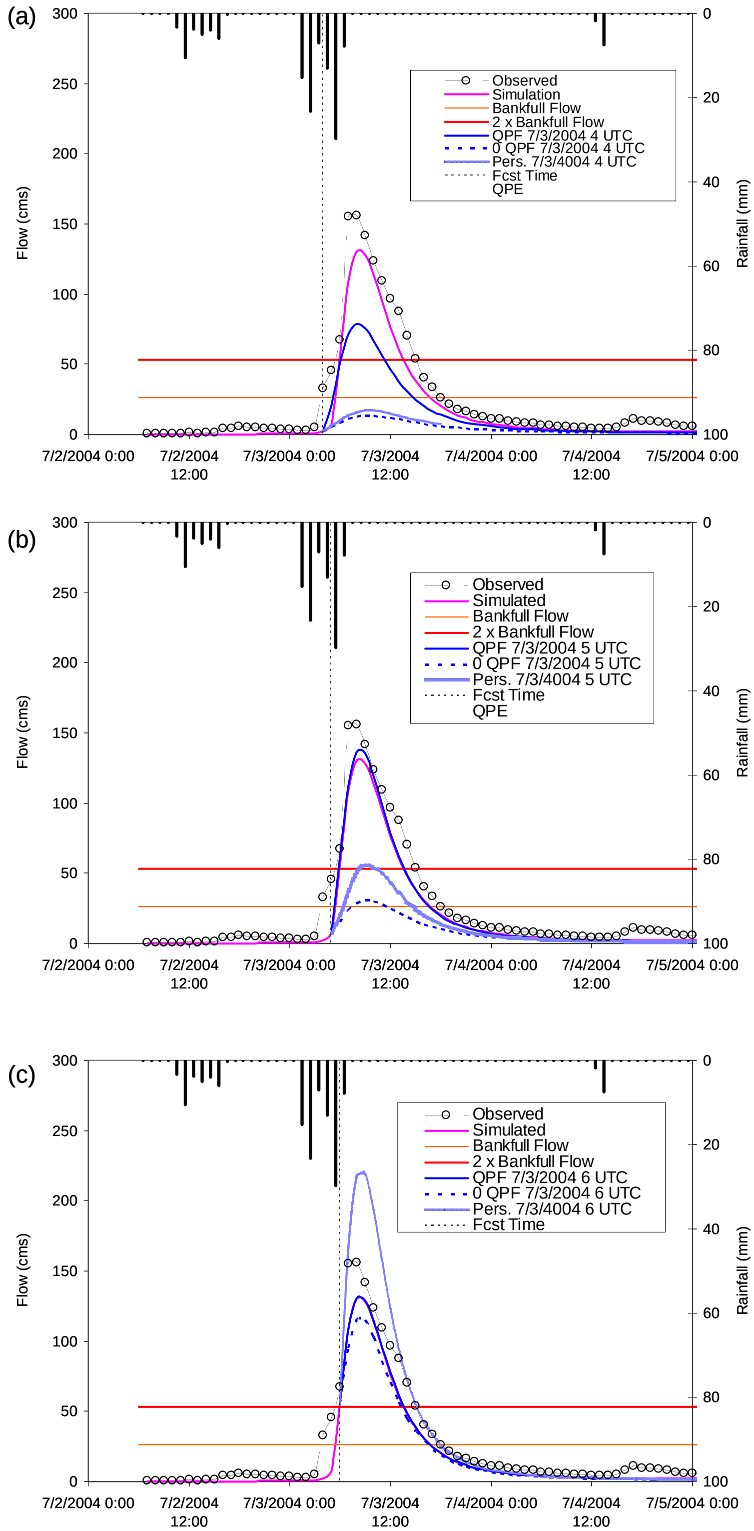

Figure 3. Forecasts for Osage Creek near Cave Springs, AR, at (a) 7/3/2004 4 UTC, (b) 7/3/2004 5 UTC, and (c) 7/3/2004 6 UTC.

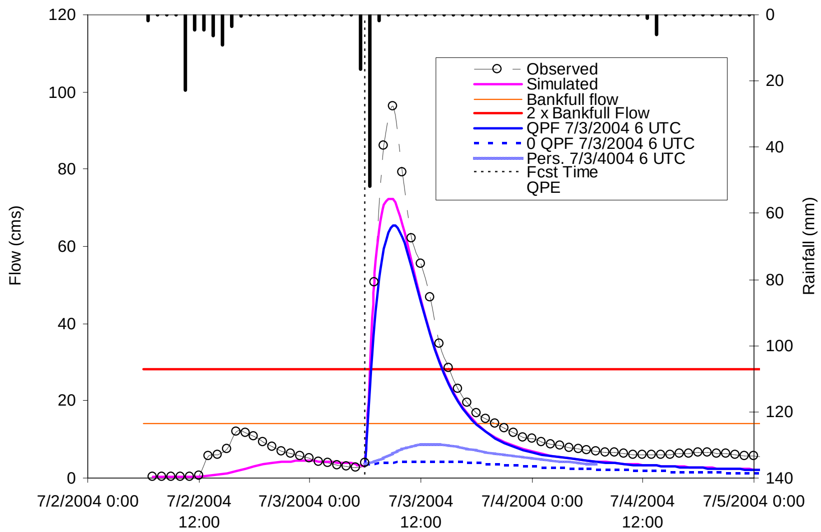

Figure 4. Forecasts at 7/3/2004 6 UTC for Sager Creek near West Siloam Springs, OK

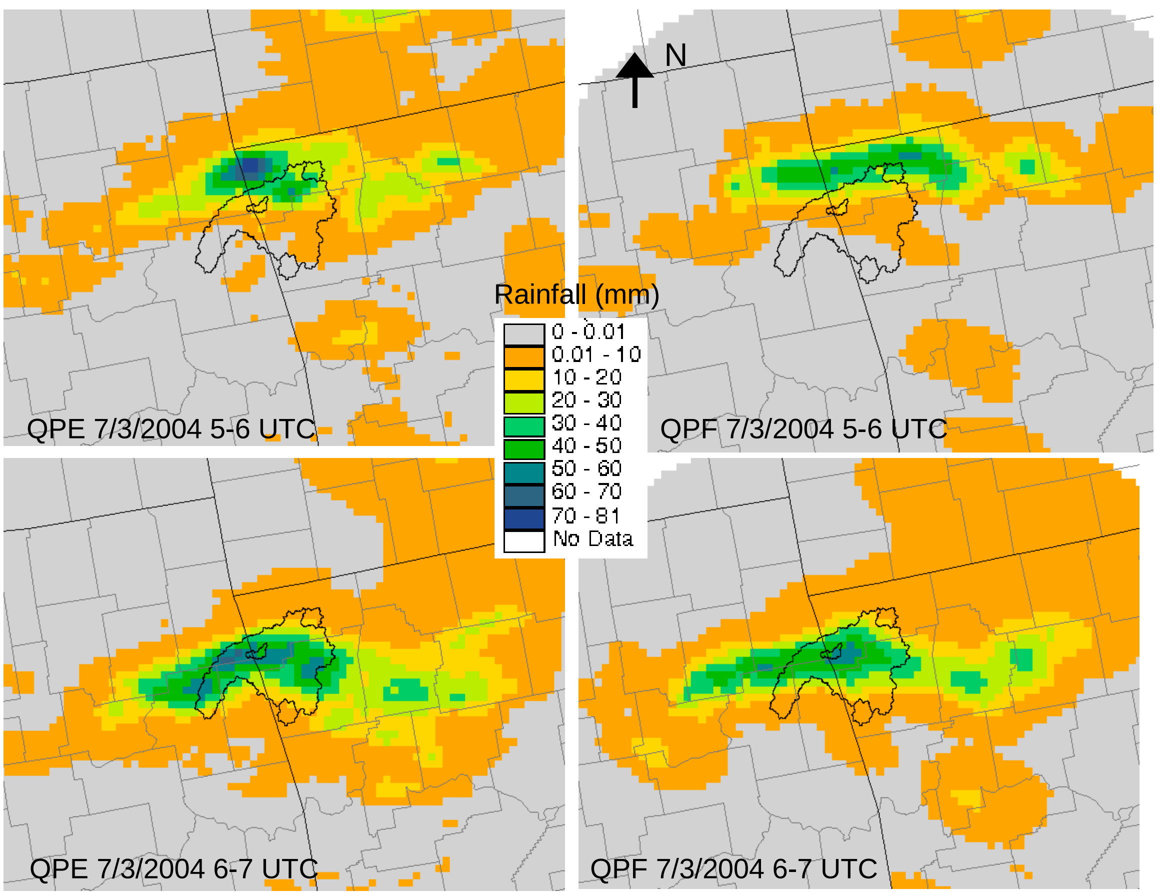

Figure 5. Left panels: observed precipitation for two hours during the 7/2004 storm. Right panels: forecasts issued for the same two hours at 5 UTC (top) and 6 UTC (bottom).