THE FLASH PROJECT

Improving the Tools for Flash Flood Monitoring and Prediction across the United States

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FLASH advances the state of the science in operational flash flood monitoring and prediction in the U.S. National Weather Service.

Flash flooding remains a significant threat to those who live in the United States and beyond. From 1 October 2007 to 1 October 2015, the National Weather Service (NWS) reported a total of 28,826 flash flood events in the Unites States, yielding an average of 3,603 per year according to the Storm Events Database (available at www.ncdc.noaa.gov/stormevents/ftp.jsp). Ten percent of these flash flood events resulted in combined crop and property damages exceeding $100,000 (U.S. dollars) per event. A total of 278 individuals lost their lives due to flash floods in the United States during this 8-yr period. Fatalities resulting from floods and flash floods show no clear trend in recent decades. A brief point regarding the subdivision of floods into faster-responding flash floods is required here, as this segregation impacts some of the statistics reported in the literature. While there is no real physical basis for separating floods and flash floods, it is oftentimes necessary to divide them based on scale due to differing operational responsibilities within agencies, including the NWS. According to the NWS Glossary (NWS 2012; italics added), flash floods are rapid rises of water in "a stream or creek above a predetermined flood level, *beginning within six hours of the causative event*." Flash floods fall within the responsibility of local NWS Weather Forecast Offices (WFOs) distributed throughout the United States, while the 13 regional River Forecast Centers (RFCs) handle larger-scale river flood events. The tools and product displays utilized within the WFOs differ from what is used for river flood warnings at the RFCs. The primary focus hereafter is on flash floods, while some of the statistics reported below apply to larger-scale river floods.

Špitalar et al. (2014) studied flash flood fatalities and injuries from 2006 to 2012 in the United States and revealed no apparent trend in either. An interesting result from this study was the finding that most human-impacting events occur in rural settings. However, when a flash flood occurs in an urban center, there are many more human impacts per event. Ashley and Ashley (2008) analyzed flood fatalities from 1959 to 2005; they found a median value of flood fatalities at 81 per year with no statistically significant trend. Several studies cite the role of vehicles as a significant factor in the cause of death during flash floods in the United States, accounting for more than half of the fatalities (French et al. 1983; Ashley and Ashley 2008; Kellar and Schmidlin 2012; Sharif et al. 2015; Terti et al. 2017). Despite the lack of increases in flash flood events or fatalities over this short period, they will likely increase in frequency and magnitude in coming decades. First, the U.S. population continues to urbanize (United

Nations 2010); urbanized basins respond quickly to rainfall due to reduced infiltration and faster conveyance of water in channelized canals. This urbanization process places an increasing number of individuals and their vehicles in exposed environments (Montz and Gruntfest 2002). Second, climate change studies have projected an intensifying hydrologic cycle under future emission scenarios, resulting in more intense rainfall events and flash floods (Trenberth et al. 2003; Milly et al. 2005, 2008). Advancements in flash flood forecasting and monitoring are needed in order to keep pace with or to reduce the trend of flash flood fatalities in the United States and beyond.

Meteorological hazards such as lightning and tornadoes have resulted in fewer and fewer fatalities in recent decades due to improvements in the public alerting and detection systems, such as weather radar and mobile warnings (López and Holle 1996; Brooks and Doswell 2002) and wireless emergency alerts sent through mobile carriers (NWS 2016). Flash flood forecasts, on the other hand, have not witnessed the same benefit from these technological advances in observing and warning. Unlike severe weather and tornadoes, they depend on a meteorological hazard (typically rainfall) compounded by a hydrologic and human behavioral setting. There can be instances in which an intense rainfall event yields no flash flooding in an unpopulated area with dry, sandy soils. Conversely, seemingly innocuous rainfall amounts occurring over urban areas with impervious surfaces can have devastating consequences, like rainfall upstream of a steep canyon with hikers in it or rainfall near a low-water crossing at night. The present tools used by NWS forecasters for forecasting flash floods do not explicitly consider these additional factors, or only do so in a rudimentary way. These forecasters rely primarily on basin-specific flash flood guidance (FFG) products displayed within the Flash Flood Monitoring and Prediction (FFMP) system to provide warnings of impending flash floods (RFC Development Management Team 2003). The research community needs to improve precipitation estimates and short-term NWP forecasts, to understand and represent the underlying hydrological fluxes and storages, and to incorporate human vulnerabilities into a multidisciplinary flash flood prediction system in order to accomplish the ultimate goal of reducing impacts to lives and property.

The Flooded Locations and Simulated Hydrographs (FLASH) project encompasses a suite of products to advance the state of the science in flash flood prediction. The FLASH project is an outgrowth from the Multi-Radar Multi-Sensor (MRMS) system that generates a suite of severe weather, aviation, and hydrometeorological products for the NWS across the conterminous United States (CONUS) and southern Canada (Zhang et al. 2016). MRMS provides precipitation estimates by mosaicking data from approximately 180 weather radars on a grid with a horizontal spacing of 1 km updated every 2 min. The unprecedented spatiotemporal resolution of the rainfall rates is essential for flash flood forecasting, especially in steep headwater basins and in urban environments that respond to the causative rainfall on the order of minutes. The FLASH system uses the MRMS rainfall rates to generate products that fall into the following categories: 1) comparison of MRMS rainfall estimates to static thresholds, 2) comparison of MRMS rainfall estimates to dynamic thresholds, and 3) as forcing to a distributed hydrologic modeling framework.

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PROJECT DESCRIPTION. Researchers and developers designed and optimized the FLASH system to improve NWS forecasters' ability to forecast flash flooding at WFOs. The FLASH product suite is designed to be all inclusive of the variable hydrometeorological processes that lead to flash flooding across the CONUS. Additionally, in recognition of historical NWS forecaster training and experience, components of the legacy FFG system are included. FLASH encompasses the comparison of MRMS rainfall estimates to static and dynamic thresholds, as well as forecasts from distributed hydrologic models that use MRMS rainfall as forcing. The FLASH system uses the same 1-km-resolution grid containing the MRMS rainfall estimates, yielding over 10.8 million grid points across the domain. The update frequency of the products varies but can be as high as 2 min. An underlying prerequisite of all FLASH products is the capability to resolve hydrometeorological processes at or finer than the flash flood scale, as defined by the NWS, so that they will be applicable to forecasting operations across the entire CONUS and beyond.[1] All products described below are summarized in Table 1.

Table 1. Description of the FLASH product suite. The products listed here are the ones that correspond to the initial implementation [version 11 (v11)] of FLASH into the NWS. All products are generated on the same 0.01° × 0.01° grid as the MRMS products across the CONUS.

Product	Status	Range of values	Update frequency (min)
QPE average recurrence interval (1, 3, 6, 12, 24 h, and max intervals)	v11	0–200 yr	2
Radar-only QPE-to-flash-flood guidance ratio (1, 3, 6 h, and max ratios)	v11	0%–500%	2
CREST unit discharge	v11	0–20 m^3 s^{-1} km^{-2}	10
CREST discharge	v11	0–100,000 m^3 s^{-1}	10
CREST soil saturation	v11	0%–100%	10

First, the FLASH system compares MRMS radar–only rainfall estimates to static precipitation frequency values that have been published in NOAA Atlas 14 (Perica et al. 2013). The computations of precipitation frequency values use annual maximum rainfall time series at rain gauge locations across the United States (with the exception of Texas, Washington, Oregon, Idaho, Montana, and Wyoming). Fitting a distribution to the data enables the computation of rainfall average recurrence intervals (ARIs), also referred to as return periods, for a given duration of precipitation ranging from 5 min up to 60 days. The FLASH product compares the real-time estimated MRMS radar–only accumulations (mm) to the static frequency values for durations from 30 min up to 24 h in order to compute the closest ARI (yr) at each grid point with updates every 2 min. Output products include estimated rainfall ARIs corresponding to 30 min, and 1, 3, 6, 12, and 24 h, and then the maximum ARI for any duration. These products provide an estimate of the rarity of the rainfall, which forecasters can use directly for flash flood forecasting or in conjunction with other FLASH products that consider the underlying hydrology.

Clark et al. (2014) describe the history, evolution, and current state of the NWS FFMP program across the United States. Moreover, they provide a systematic evaluation of FFG using observations of flash flooding. Several methods for producing FFG have been developed at regional RFCs. The FLASH products rely on the standard FFG grids produced by the RFCs issued every 6, 12, or 24 h, or as necessary during a flash flood event. The National Centers for Environmental Prediction (NCEP) Weather Prediction Center mosaics the most recently issued RFC grids together to create a national grid on an hourly basis. The ratio product simply compares the latest MRMS radar–only rainfall estimate to its collocated FFG value. The MRMS rainfall grids have an update frequency of 2 min, which also applies to the ratio product despite the relatively infrequent updates with the FFG issuance. Ratios greater than 1.0 (or 100%) suggest that rainfall amounts have exceeded the threshold amount to cause bank-full conditions on small streams.

In recent years, advances in high-performance massively parallel computing and remote sensing of the Earth's atmosphere, surface, and subsurface have led to the advent of regional, continental, and even global models that forecast Earth's water and energy cycles (Wood et al. 2011). The resolution of the forcing datasets and digital elevation models motivates accompanying horizontal gridcell model resolutions on the order of 1 km, while physical process representation through parameterization at subgrid scale requires careful consideration (Beven and Cloke 2012). Nonetheless, the European Commission in partnership with the European Centre for Medium-Range Weather Forecasts (ECMWF) has implemented the Global Flood Awareness System, which provides flood information on a daily time-scale basis using quantitative precipitation forecasts (Alfieri et al. 2013). Remote sensing of precipitation by active and passive microwave instruments provides inputs to the Global Flood Monitoring System operated by

[1] Users can access real-time experimental and operational FLASH products online (at http://flash.ou.edu).

the National Aeronautics and Space Administration (NASA) and the University of Maryland (Wu et al. 2014). The Ensemble Framework for Flash Flood Forecasting (EF5) is a distributed hydrologic modeling system that also applies globally; the implementation discussed hereafter runs at continental scale and utilizes the MRMS rainfall forcing.

EF5 is an open-source framework that encompasses the relevant processes for flash flood modeling (Fig. 1); it is the hydrologic modeling engine central to the FLASH project. The precipitation forcing normally comes from the MRMS rainfall estimates; however, the Hydrometeorological Testbed—Hydrology (HMT-Hydro) experiment (Martinaitis et al. 2017) incorporated forcing from short-term radar-based extrapolations [referred to as advective-statistical system quantitative precipitation forecast (ADSTAT QPF) in Fig. 1] and quantitative precipitation forecasts supplied by the High Resolution Rapid Refresh model (referred to as "HRRR QPF" in Fig. 1). The water balance components of EF5 utilize climatological mean monthly potential evapotranspiration (PET) estimates (V. Koren et al. 1998, unpublished report). We prefer a simple handling of evapotranspiration rates in lieu of implementing a sophisticated energy balance in a land surface model because the modeling objective is rainfall-driven flash flood forecasting. The model simulations need to provide forecasts out to 6 h within 10 min of clock time and thus demand computational efficiency. Additional model physics and two-way coupling would need to be incorporated for modeling systems designed to handle the seasonal water balance for water resources management, snowpack dynamics and subsequent melting, coastal flooding exacerbated

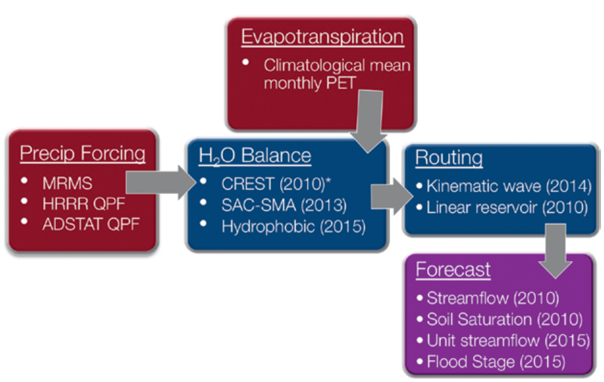

Fig. 1. Flowchart describing the EF5 system configured for the FLASH project. The red boxes indicate model forcings, blue boxes are model physics modules, and the purple box contains output products. The years in parentheses correspond to the date each component was incorporated into EF5.

by storm surges, and surface water and groundwater interactions in karstic aquifers. The Weather Research and Forecasting Model hydrological extension package (WRF-Hydro) modeling framework (Gochis et al. 2015) is the hydrologic modeling core of NOAA's new National Water Model, which is being designed to address these multiple hydrologic applications.

The "ensemble" part of EF5 refers to the multiple water balance concepts presently supported in the framework, including the Sacramento Soil Moisture Accounting (SAC-SMA) model (Burnash et al. 1973), the Coupled Routing and Excess Storage (CREST) model (Wang et al. 2011), and a "hydrophobic" model that prohibits water from infiltrating the underlying soils. CREST differs from SAC-SMA in that it uses a "percent imperviousness" parameter to describe the low infiltration rates over urban areas. Water flows laterally in the unsaturated zone using linear reservoirs and on the surface using either linear reservoirs (in the original CREST implementation) or through the kinematic wave approximation to the 1D Saint-Venant equation. The linear reservoir approach is conceptually simpler but requires parameterization of the reservoir responses, whereas the kinematic wave approximation is based on physical principles. The kinematic wave routing scheme also requires parameters. Vergara et al. (2016) describe a regionalization technique for estimating the routing parameters in the model channels that comprises approximately 25% of the total 10.8 million grid cells. First, they directly estimate the parameters at U.S. Geological Survey (USGS) stream gauge locations and then regionalize them using multidimensional statistical modeling guided by spatially distributed maps of variables describing the geomorphology, hydroclimatology, and land use. Surface roughness and slope dictate the routing parameters in the overland grid cells. This results in a priori routing parameters at all grid cells across the CONUS.

The EF5 products include soil saturation (%), discharge ($m^3\ s^{-1}$), and discharge normalized by the cell's upstream drainage area (referred to as unit discharge; $m^3\ s^{-1}\ km^{-2}$). The soil saturation state is the water content of the top-layer soils in relation to their maximum water capacity. Soil saturation provides antecedent conditions that can qualitatively inform forecasters on the potential hydrologic response to an impending rain system. The unit discharge product is most directly applicable to flash flood forecasting. The normalization of discharge by basin area helps to focus the products on those specific locations that are most likely experiencing anomalous flows, rather than merely identifying large discharges that occur regularly in major river systems like the Mississippi River. Moreover, there is a basis for computing the observed unit peak discharges for catastrophic flash floods throughout the world and for establishing "envelope curves"; these curves vary regionally, but they provide the maximum expected unit peak discharge for a given drainage area (Gaume et al. 2009). A hydrologic model designed to forecast flash floods must therefore be able to accurately simulate unit peak discharges.

UNIT PEAK DISCHARGE EVALUATION.

The EF5 products differ from the traditional rainfall-based flash flood guidance in that they directly forecast the surface hydrologic conditions. Here we evaluate them in a robust, statistically sound manner. A reanalysis project at the National Severe Storms Laboratory (NSSL) produced a decadal archive of MRMS radar–only precipitation rates at 1-km spatial resolution with 5-min update frequency from the raw level-II Next Generation Weather Radar (NEXRAD) data archive. These precipitation rates resemble the real-time estimates, but they do not get the benefits of dual-polarization radar variables for improved quality control. Next, we identified 1,643 USGS-gauged basins that met the following criteria: 1) there must be no known upstream regulation or diversion of river discharge, 2) at least 80% of the basin must fall within an area where the MRMS radar beam height is 1 km AGL or less, 3) snowfall must contribute less than 30% of the annual precipitation, and 4) the contributing drainage area must be less than 1,000 km^2. The goal of the objective evaluation was to assess the EF5's ability to simulate flash floods independent of errors from factors such as regulation, snowmelt, and biased MRMS inputs. This objective evaluation concentrates on EF5's implementation of the CREST water balance and the kinematic wave routing scheme.

After running EF5 forced by the MRMS radar–only rainfall dataset over the 1,643 filtered basins between 1 March 2004 and 31 December 2011, we developed an automated procedure to compare the simulated time series to the observed time series. This is accomplished by examining the observed discharge time series record, identifying individual events, extracting the peak discharges, computing the unit peak discharges, and then comparing these results to the equivalent simulated values from EF5. These event-based characteristics compose the publicly available unified flash flood database described in Gourley et al. (2013). There were a total of 33,726 events in the analysis. The basin areas range from 1.1 to 999.7 km^2 with a median of 115.8 km^2, a first quartile of 37.8 km^2, and a third quartile of 305.6 km^2. Figure 2a shows a density-colored scatterplot of the simulated versus observed unit peak discharges for the entire dataset. Peak flows simulated by the CREST water balance module with kinematic wave routing correlate well with observed discharges as indicated by a Pearson (linear) correlation of 0.64 and Spearman (rank) correlation of 0.79.

Peak timing errors decrease with smaller basin areas due to shorter concentration times. We estimated the mean concentration time for each basin using an empirical relationship for basin lag time developed by Mockus (1961, unpublished report), which is based on the basin slope, stream length, and the Natural

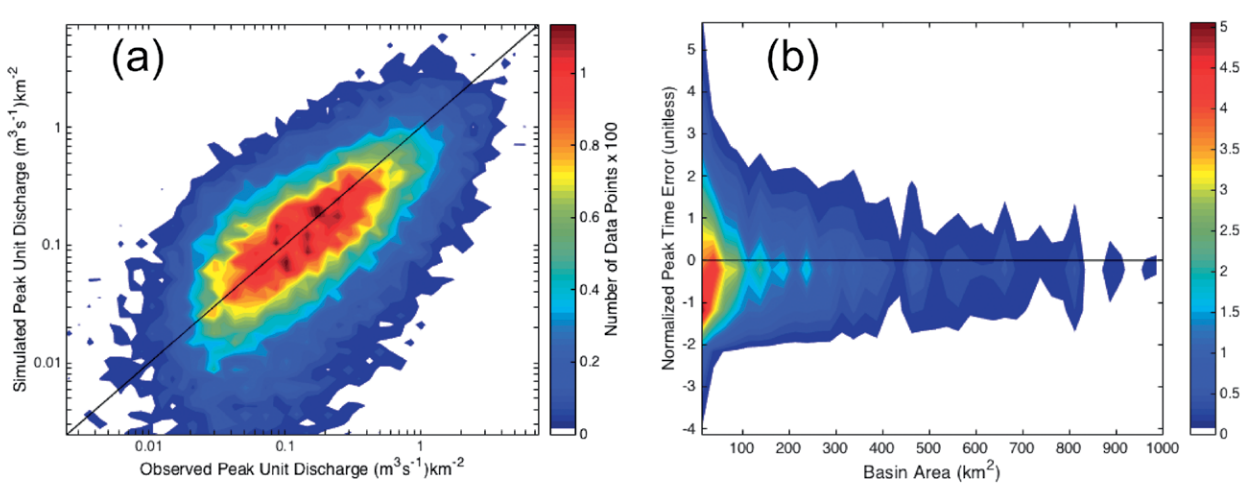

FIG. 2. Density-colored scatterplot comparing (a) simulated peak unit discharge from the CREST distributed hydrologic model with kinematic wave routing to USGS observations at 1,643 gauged basins for 33,726 events between 1 Mar 2004 and 31 Dec 2011. (b) The normalized peak timing error is computed as the peak timing error divided by the estimated basin concentration time and is plotted as a function of drainage area.

Resources Conservation Service curve number. The normalized peak timing error was computed as the peak timing error (h) divided by the estimated mean concentration time (h) and is plotted as a function of basin area in Fig. 2b. There is a very slight tendency to simulate peak discharges too early. The magnitude of the peak discharge is controlled more by the CREST water balance module, whereas the timing is dictated by the kinematic wave routing function. The a priori estimates of the kinematic wave parameters are data driven and regionalized as previously described, whereas the CREST water balance parameters are related to observable features of the land surface (e.g., soil types, land use/cover, topographic derivatives).

The spatial variation of the errors in peak discharge simulation using the CREST water balance model with kinematic wave routing is shown in Fig. 3. Underestimation in the magnitude of peak discharge simulation is evident in Colorado with additional variations in skill in the Intermountain West, whereas there are no regional biases in the eastern two-thirds of the CONUS. The peak timing errors in Fig. 3b reveal no regional dependencies. A vast majority of the event peaks are simulated with errors less than 2 h. Next, we computed contingency table statistics for flood peaks that exceeded action stage (typically related to the bank-full stage) for a subset of the USGS basins that had defined flood stages and met the aforementioned criteria for anthropogenic effects, radar coverage, snowmelt contribution, and basin scale; these computations were computed for all three water balance modules. Table 2 reveals the CREST water balance module has the best overall skill in detecting flood peaks that exceed the action stage. The critical success index (CSI) with CREST is 0.38, which can be compared to the benchmark skill established for the flash flood guidance tool used operationally in the NWS (Clark et al. 2014). Although Clark et al. (2014) used a different sample in terms of period and basins, the CSI with FFG was 0.20. The differences in CSI and Heidke skill score (HSS) among the different water balance components are not considerable, highlighting the importance of accurate rainfall forcing and possibly routing. The MRMS precipitation product has been comprehensively evaluated across the CONUS in Chen et al. (2013). A relevant finding from that study was the dependence of the bias with the radar-only precipitation product on the radar quality index product; underestimation was more prevalent in regions with poor low-level radar coverage.

The performance of EF5 unit peak discharge and the timing of peak discharge shown in Figs. 2 and 3 and Table 2 is what can be expected in basins that are well covered by radars, have no significant contribution from snowmelt, and are unregulated by dams and other anthropogenic hydraulic structures. The following examples demonstrate the forecast capability of the FLASH products for two well-observed urban flash flood events.

CASE STUDIES. During the afternoon of 31 May 2013, a supercell thunderstorm produced a tornado approximately 40 km (25 mi) west of downtown Oklahoma City, Oklahoma (OKC), in El Reno, Oklahoma. This was only 10 days following the devastating tornado rated as a category 5 event on the enhanced Fujita scale (EF5) that struck Moore, Oklahoma, 20 km (12 mi) to the south of OKC, killing 24 people and causing $2 billion in property damage. While public concern and media interest remained on yet another tornado threatening the OKC area, the supercell thunderstorm took on more of an east–west

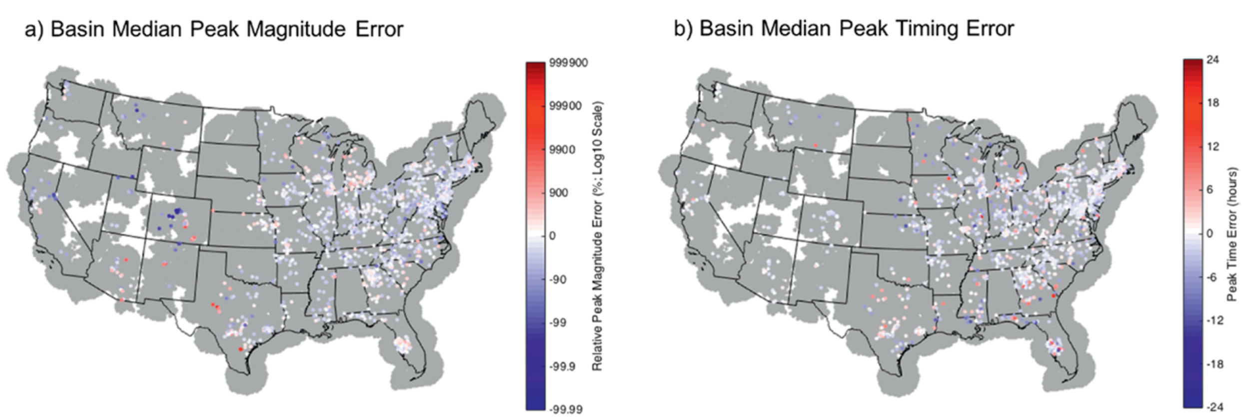

Fig. 3. (a) Spatial depiction of the peak magnitude error (%) for the USGS gauged basins used in the study. (b) Spatial depiction of the peak timing error (h). The gray-shaded regions correspond to areas that have radar coverage by the NEXRAD network within 2 km of the ground.

TABLE 2. Statistics for the three water balance components supported in EF5. The Pearson (linear) correlation and Spearman (rank) correlation correspond to the observed and simulated peak flow values. Contingency table statistics are reported based on the number of hits, misses, false alarms, and correct negatives to compute the probability of detection (POD), false alarm ratio (FAR), CSI, and HSS. Scores in boldface correspond to the best performing water balance component according to each statistical measure.

Water balance module	No. of events	Pearson correlation	Spearman correlation	POD	FAR	CSI	HSS
CREST	12,771	**0.64**	**0.79**	0.54	**0.43**	**0.38**	**0.41**
SAC-SMA	18,934	0.57	0.70	0.49	0.48	0.34	0.37
Hydrophobic	14,573	0.55	0.71	**0.93**	0.67	0.32	0.37

orientation and became quasi stationary. This placed the core of the thunderstorm directly over OKC for several hours. Storm total rainfall accumulations from MRMS approached 250 mm (10 in.) with the greatest accumulations directly over the OKC metropolitan area and a second maximum closer to the tornado to the northwest (see Fig. 4a). The City of Oklahoma City Office of Emergency Management provided very detailed flash flood reports from their first responders that included times and locations of high-water rescues, water in homes, street closures, 13 fatalities, and damages estimated at $16 million.[2] This flash flood event was the deadliest in OKC's history and the second deadliest statewide behind the 1984 Tulsa event, which also incidentally occurred on Memorial Day weekend.

The 3-h MRMS-to-FFG ratio product revealed rainfall estimates exceeding critical rainfall thresholds to cause bank-full conditions for an expansive region, including the OKC metropolitan area (Fig. 4b). The greatest ratios were collocated with the highest ARI values closer to the tornado but displaced to the northwest from where most of the impacts occurred. The 3-h rainfall ARI product valid from 2200 UTC 31 May 2013 to 1200 UTC 1 June 2013 shows the heaviest precipitation was occurring northwest of the reported impacts in the OKC metropolitan area (see blue filled circles in Fig. 4c). The ARI product indicated a 0.5% annual exceedance probability (200 yr) event for grid cells closer to the tornado to the northwest, but the ARIs near the reported flash flood impacts were closer to 20% (5 yr). The same MRMS rainfall forced the EF5 unit peak discharge product shown in Fig. 4d. Unit peak discharges exceeded 10 m^3 s^{-1} km^{-2} directly over OKC with the highest concentration of impacts. The EF5 distributed hydrologic model product offers improvements over the other rainfall-based FLASH products in this event because it considers low infiltration rates over the OKC metropolitan area and routes the excess water downstream. Moreover, it provides a 6-h forecast of the discharges resulting from the MRMS-estimated rainfall inputs.

Following weeks of heavy rainfall, a slow-moving storm system with a history of producing flash flooding approached Houston, Texas, during the evening hours of 25 May 2015, again on Memorial Day.[3] The NWS WFO in Houston/Galveston issued its first-ever flash flood emergency for Harris County at 0452 UTC 26 May 2015. The maximum gauge-measured rainfall accumulation occurred at Brays Bayou and Beltway 8 with 280 mm (11 in.) in 12 h and 254 mm (10 in.) in 6 h (J. Lindner and S. Fitzgerald 2015, personal communication). City and county emergency response units responded to hundreds of calls for rescues, mainly from motorists trapped on flooded roadways. After the floodwaters receded, more than 1,000 stranded vehicles littered the highways and were towed. Floodwaters impacted more than 1,000 structures. The urban flash flood resulted in eight vehicle-related fatalities. Of these, rescuers were able to reach three elderly victims by boat, but the rescue boat capsized in the floodwaters, causing them to lose their lives.[4]

The 24-h MRMS radar–only rainfall product for the event shows a small region with 200–250 mm (8–10 in.) of rainfall over the Houston metropolitan region (Fig. 5a). The precipitation frequency estimates from the NOAA Atlas 14 series do not yet exist for the state of Texas, so there are no FLASH ARI products available for this event. However, the

[2] Twelve of the people who lost their lives were nonnative English speakers and took shelter in storm drain structures (culverts) underground in fear of the tornado.

[3] The Blanco River in nearby San Marcos, Texas, flooded from 330 mm (13 in.) of rain in its headwaters on 23 and 24 May, resulting in 11 fatalities and damage to hundreds of homes.

[4] The rescuers were unable to restart the gas-powered boat motor using the hand rope pull. A similar difficulty in restarting a gas motor on the rescue boat occurred with the July 1997 flash flood event in Fort Collins, Colorado.

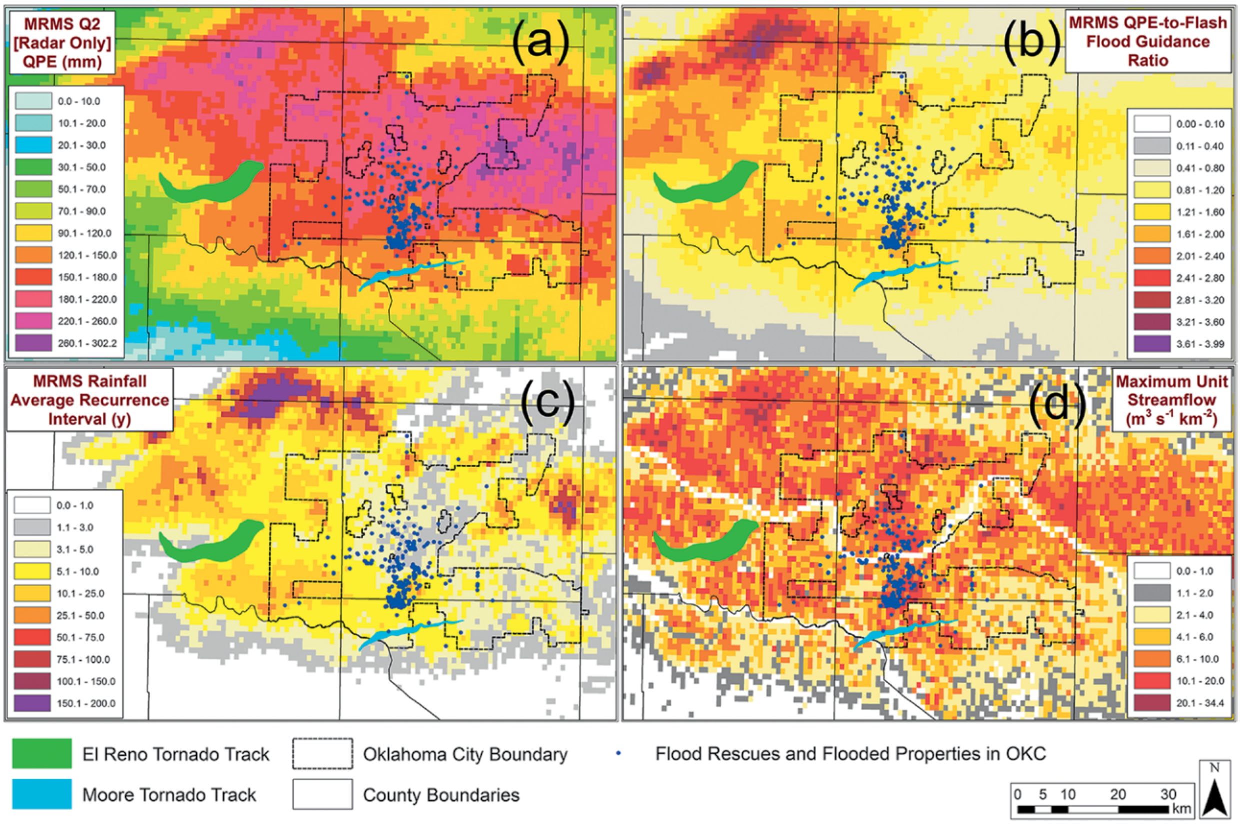

Fig. 4. (a) Accumulated 24-h rainfall estimates from the MRMS system ending at 1200 UTC 1 Jun 2013; (b) maximum 3-h ratio of rainfall to FFG from 2200 UTC 31 May 2013 to 1200 UTC 1 Jun 2013; (c) maximum 3-h average recurrence interval of rainfall for the same times as in (b); and (d) maximum unit discharge forecasts from the distributed hydrologic model for the same times as in (b) and (c). The blue dots correspond to known flooding reports collected from OKC, media, and social media. The reports include rescues, water in homes, street closures, and 13 fatalities. Recent tornado tracks are shown in colors as indicated in the legend.

Harris County Flood Control District computed the annual exceedance probability of rainfall in the 2–6-h accumulation period to be between 1% (100 yr) and 0.2% (500 yr) over Brays and Buffalo Bayous (J. Lindner and S. Fitzgerald 2015, personal communication 2015). The ratio product of the MRMS rainfall to FFG maximum valid at 0400 UTC 26 May 2015, 52 min prior to the NWS issuance of the flash flood emergency, indicates about 25% of Harris County exceeded flash flood thresholds (Fig. 5b).[5] Not surprisingly, most of the largest ratios are collocated with the heaviest rainfall in the western part of Harris County. There are indications that the eastern parts of the county flooded as well according to the USGS discharge observations, despite these areas having ratios of MRMS rainfall to FFG of less than 1.0.

The EF5 unit peak discharge product valid at 0400 UTC 26 May 2015 corresponds much more closely with the USGS flood observations (Fig. 5c). In particular, values in the 2–6 $m^3\ s^{-1}\ km^{-2}$ range extend in a southwest–northeast-oriented band displaced to the northwest of the primary maximum, which aligns well with gauges reaching flood conditions. Furthermore, these high unit discharge values extend into the eastern sections of the county, which did not receive as much heavy rainfall but still flooded according to the USGS observations. Values in the primary maximum exceeded 10 $m^3\ s^{-1}\ km^{-2}$, which are similar in magnitude to those that occurred with the OKC urban flash flood. The EF5 maximum discharge product highlights the major tributaries draining into the Gulf of Mexico; these values are not necessarily rare or unusual (Fig. 5d). However, it reveals a broad, contiguous swath of values in the 1–50 $m^3\ s^{-1}$ range centered over Houston. This indicates the CREST water balance model produced ponded conditions, where the rainfall rates exceeded the infiltration capabilities of the underlying urban surfaces.

[5] The plots presented in Fig. 4 were extracted from the online products archives (http://mrms.ou.edu; http://flash.ou.edu). The same websites also host the real-time product displays.

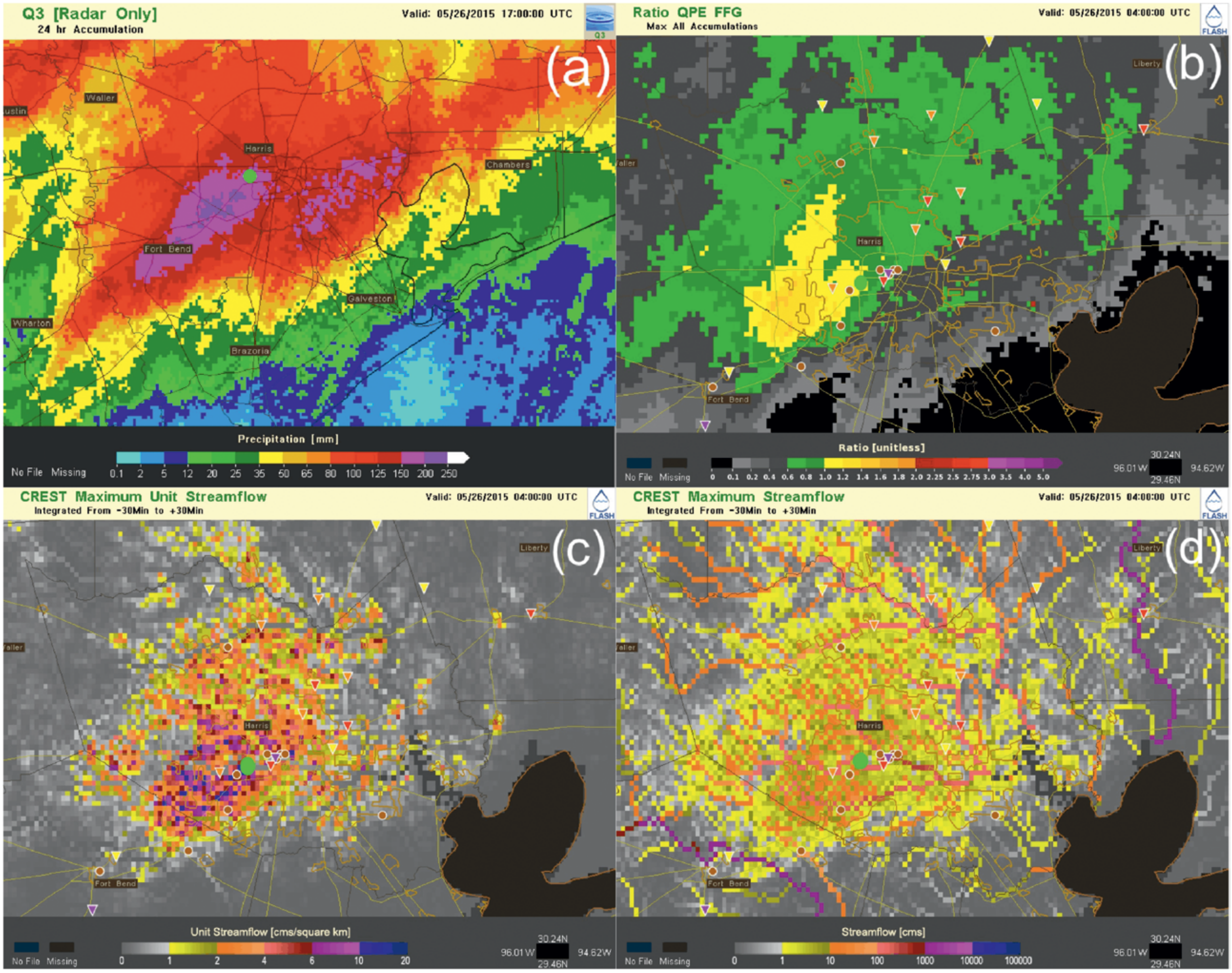

Fig. 5. (a) Accumulated 24-h rainfall estimates from the MRMS system ending at 1700 UTC 26 May 2015; (b) ratio of rainfall to FFG valid at 0400 UTC 26 May 2015; (c) maximum unit discharge forecasts from the distributed hydrologic model from 0400 to 1000 UTC 26 May 2015; and (d) maximum discharge forecasts from the distributed hydrologic model for the same times as in (c). The inverted triangles indicate USGS discharges that exceeded flood thresholds (yellow = action, orange = minor, red = moderate, purple = major), while the brown circles correspond to NWS local storm reports of flash flooding. The green filled circle corresponds to the gauge at Brays Bayou and Beltway 8 with 280 mm (11 in.) of precipitation.

The hydrographs of EF5-simulated discharge at Buffalo Bayou (USGS 08074000, drainage area of 870 km^2) indicate peak discharges exceeding major flood stage according to all three water balance modules (Fig. 6). The simulated peaks overestimated the observed peak discharge and reached maximum values approximately 2 h too early. However, all EF5 model configurations forecasted a major flood, which falls well within the modeling expectations given that the water balance parameters require no discharge-based calibration and thus apply equally to ungauged grid points. The modeling objective of EF5 in the FLASH context is focused directly on flood stage and timing simulation at all grid points in the modeling domain. Improvements in peak flow simulation are envisaged with improved physical representation of the baseflow conditions. In this particular event, Fig. 6 reveals that the simulated baseflow conditions were too high and that improvements in these initial states would have yielded more accurate peak flow simulations.

SUMMARY AND CONCLUSIONS. The MRMS system provides precipitation rate estimates across the CONUS at 1-km resolution with updates every 2 min. Now that MRMS has been transitioned to the NWS for operational use, there is a great opportunity to capitalize on these rainfall rates operating at flash flood scale for hydrologic applications. The FLASH system runs on the back end of MRMS and yields a suite of rainfall and forecast stream discharge products that are designed to advance operational

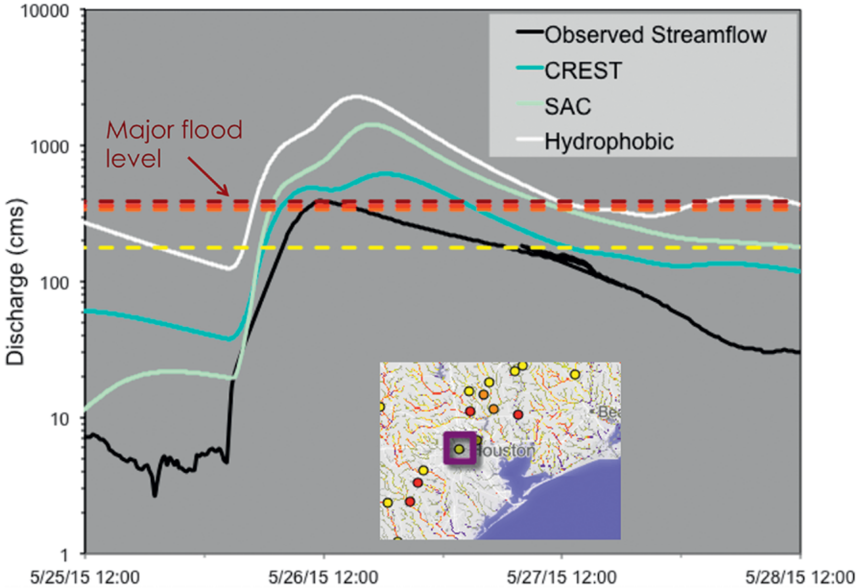

Fig. 6. Hydrographs of simulated and observed discharge in Buffalo Bayou (USGS 08074000, drainage area of 870 km^2) during the Houston flash flood event on Memorial Day 2015. Action, minor, moderate, and major flood stages are shown as horizontal dashed lines colored in yellow, orange, red, and dark red, respectively. The inset shows the location of the stream gauge. All three distributed hydrologic model simulations correctly forecast peak discharges to exceed major flood stage.

flash flood monitoring and prediction to the state of the science. The primary products composing FLASH are comparisons of MRMS rainfall to static thresholds to compute average recurrence intervals and comparisons of MRMS rainfall to dynamic flash flood guidance thresholds to compute the ratio of rainfall to flash flood guidance, peak discharge, unit peak discharge, and soil saturation. A distributed hydrologic modeling infrastructure called EF5 produces 0–6-h forecasts of the discharge and soil saturation products using three different water balance components and a kinematic wave routing scheme. All FLASH products reside on the same 1-km grid as the MRMS products with update frequencies of 2–10 min.

We evaluated unit peak discharges from EF5 for 33,726 events across the United States and found that they correlate well with observed discharges (linear and rank correlation = 0.64 and 0.79, respectively). The water balance components of EF5 rely on parameters based on physical properties of the Earth and are not adjusted using streamflow observations. This means we can expect the EF5 maximum unit discharge forecasts to have similar skill in ungauged basins, which compose 99.9% of FLASH's 10.8 million grid cells. Errors in the timing of peak discharges predominantly fall within 2 h. The urban flash flood cases in Oklahoma City, Oklahoma, and Houston, Texas, on Memorial Day weekends of 2013 and 2015, respectively, showcased the FLASH product suite, while the discharge-based objective evaluation focused on the EF5 distributed hydrologic model outputs.

FLASH encompasses a variety of rainfall and forecast discharge products because each of them provides valuable information about the magnitude and spatial extent of flash flooding (see Martinaitis et al. 2017 for details). We are using the ensemble of products to develop flash flood recommendations available in the Hazard Services software (Argyle et al. 2017). Guided by NWS forecaster inputs, we will optimize these recommenders so that they take full advantage of the products that work best for their areas of responsibility. NWS forecasters remain a critical component in testing new concepts, such as flash flood recommenders using the HMT-Hydro experiment, a vital research-to-operations conduit and training mechanism.

The FLASH system provides new tools in the NWS forecaster toolbox for warning on dangerous flash floods, but there are limitations. All products depend on the accuracy of the MRMS radar–only rainfall-rate estimates. The quality declines in the Intermountain West, where intervening mountains inhibit low-level radar coverage. Also, the EF5 distributed hydrologic model products provide forecasts out to 6 h, but they are normally based on observed rather than forecast rainfall. Forecasters should also note that flash flood impacts can take place at scales that are typically unresolvable by continental-scale models including EF5. Examples include flooding from clogged storm drains, low-water crossings, and dam and levee breaches. The hydrologic modeling concepts employed in EF5 do not necessarily apply to flood prediction in all geomorphological settings. For instance, the kinematic wave routing scheme has limited applicability in flat areas, including the low-lying Gulf Coast, Mississippi delta, the southern part of Florida, and the Central Valley of California (see Vergara et al. 2016 for details). Finally, we have designed the discharge simulations in EF5 very specifically for flood detection, magnitude, and timing estimation; the model outputs may not be applicable to all facets of hydrologic forecasting, such as baseflow conditions or flood recessions.

The implementation of FLASH represents a first step toward modernizing flash flood products and services in the NWS. Our ultimate goal is to advance the state of flash flood forecasting to realize quantifiable reductions in losses of life and property. Several enhancements are underway. The MRMS precipitation forcing will improve with more use of dual-polarization radar variables, probabilistic quantitative precipitation estimates, and satellite-aided precipitation in regions with poor low-level coverage. We will continue to evaluate the potential of using rainfall forcing from short-term radar-based extrapolations and NWP forecasts. The hydrologic model forecasts will improve through assimilation of surface water extent, depth, and velocity from spaceborne and airborne radars, soil moisture from passive microwave radiometers, and stream discharge from on-site gauges and remote sensing platforms. Future enhancements to the model physics include improved snow water equivalent estimation and snowpack modeling. Finally, error models will be employed in order to identify and correct region-dependent errors resulting from a combination of forcing errors and model physics limitations.

Being able to forecast overland and stream discharges at ungauged locations is a necessary but insufficient condition to determine whether there is an impending flash flood. We are developing flood severity thresholds based on relationships between observed flood stages and discharge, regionalized to ungauged grid cells using spatially distributed maps of geomorphology, hydroclimatology, soil types, and land use/land cover. Further refinements of these thresholds will occur by providing forecasts to local emergency managers and receiving feedback about local "trouble spots." EF5 discharge forecasts will be compared to these thresholds to identify local flooding hazards. The next step is to incorporate the hydrologic hazard forecasts with dynamic societal vulnerability factors in order to anticipate specific impacts. For instance, a flash flood has a much greater potential to cause a vehicle-related fatality when there is a flooded roadway at night (Terti et al. 2017). We will use factors such as time of day, day of the week, road and population density, proximity to a stream, etc., to produce impact-specific products. Provided probabilistic NWP guidance and precipitation forcings (described in Kirstetter et al. 2015), the FLASH system will also yield probabilistic flash flood products in coming years.

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