BAMS Article

The 21 August 2021 Catastrophic Flash Flood at Waverly, Tennessee: Harnessing the Warn-on-Forecast System for Confident Prewarning Messaging of Extreme Rainfall

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ABSTRACT: On the morning of 21 August 2021, extreme rainfall spurred a flood wave on Trace Creek that ravaged Waverly, Tennessee, causing 19 fatalities. Peak 24-h rainfall of 526 mm was recorded just upstream at McEwen, setting the Tennessee 24-h state rainfall record. A Slight Risk of excessive rainfall and a Flash Flood Watch were issued 16 and 8 h, respectively, before rain began; however, predicting mesobeta scale extreme rainfall remains an elusive skill for models and humans alike. Operational convection-allowing models not only suggested pockets of heavy rain but also displayed 1) peak values generally less than half of those observed, 2) widely ranging solutions, and 3) erroneous similarly heavy rain elsewhere. Future use of storm-scale ensembles which use rapid data assimilation promises to help forecasters anticipate extrema that may only be predictable at shorter time scales. This work will examine compelling forecasts from a retrospective run of the experimental Warn-on-Forecast System (WoFS). The authors, who include National Weather Service forecasters who worked the event, discuss how WoFS and its probabilistic framework could influence services during low-predictability, high-impact flash floods.

SIGNIFICANCE STATEMENT: This article reports on the occurrence of an extreme rainfall event that set a 24-h record gauge measurement for Tennessee and spurred a flood wave that devastated the city of Waverly on 21 August 2021. Forecasters recognized a flash flood threat as evidenced by a Slight Risk in the Excessive Rainfall Outlook and a local Flash Flood Watch at 16–8-h lead times; however, available operational guidance underforecast the observed amounts by at least half in most instances. The authors review a retrospective run of the Warn-on-Forecast System to explore the potential value of a rapidly updating storm-scale ensemble in capturing the magnitude of such an event with lead time on the order of hours.

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1. Introduction

Flash flood forecasting and risk communication can be very challenging. Flash flooding caused by heavy rainfall[1] may emanate from a wide spectrum of convective modes covering a range of rain rates and spatial and temporal scales. Varying hydrologic response to heavy rainfall adds further complexity. There are numerous cases in recent memory of intense local rainfall which overwhelmed individual hydrologic basins, resulting in deadly and destructive flood waves. Examples include Boulder, Colorado, and surrounding communities in 2013 (Gochis et al. 2015) and Ellicott City, Maryland, in both 2016 (NWS Baltimore/Washington Weather Forecast Office 2016) and 2018 (Viterbo et al. 2020). Some degree of flash flood risk was communicated via traditional outlook and watch products, funneling down to county-level warnings at shorter lead times; however, those efforts in risk communication did not entirely mitigate loss of life. Another such event is studied here: the historic, devastating flood wave[2] that swept through Waverly, Tennessee, owing to the fall of up to 526 mm of rain about 15 km upstream at McEwen, Tennessee, on the morning of 21 August 2021 (hereafter denoted as the Waverly event; Fig. 1).

[1] Other causes of flash flooding include ice jams, for instance.

[2] The rise in (river) stage, culminating in a crest and followed by a recession, associated with a flood.

Extreme rainfall lacks a consistent definition, but Schumacher and Johnson (2005) define extreme 24-h rainfall as surpassing the 50-yr average recurrence interval (ARI) amount at a given location. The 24-h, 50-yr recurrence interval amount throughout west-central Tennessee is approximately 180 mm (via NOAA Atlas 14 at https://hdsc.nws.noaa.gov/pfds/). If we take 180 mm as the minimum rainfall to define an extreme event in this region, at 526 mm, the Waverly event was nearly triple.

In many cases of flash flooding, forecasters and numerical weather prediction (NWP) models may struggle to confidently place heavy precipitation in the correct hydrologic basin(s), and in particular, forecasters may have no NWP that confidently forecasts extreme rainfall totals. The available NWP as of 0000 UTC 21 August 2021 forecast maximum rainfall amounts of 75–254 mm. It would have been difficult to anticipate

Fig. 1. (a) A damage photo taken in Waverly, courtesy of Williamson County, Tennessee, Fire/Rescue. (b) An aerial photo of Waverly after the flood, courtesy of the Nashville, Tennessee, Fire Department.

a >500 mm rainfall and associated devastating flood wave based on models available to meteorologists and hydrologists at the time.

Fortunately, meteorological science is making strides in creating more skillful forecasts, quantifying uncertainty, and acknowledging the full range of possible outcomes. Experimental NWP tools like the National Severe Storms Laboratory Warn-on-Forecast System (WoFS; Heinselman et al. 2024) are built to provide probabilistic forecasts of thunderstorm-related hazards along the watch-to-warning timeline (0–6 h). Some extreme rain events may only become apparent at short lead time and then only toward the upper percentiles of forecasts from the available NWP. Thus, the development of WoFS supports the Forecasting A Continuum of Environmental Threats (FACETs) initiative (Rothfusz et al. 2018) for severe weather and heavy rainfall, aiming to help forecasters identify specific high-impact thunderstorms at greater lead time and with greater confidence.

The extent to which probabilistic information has been incorporated into legacy NWS forecast products varies, as FACETs is still being built. Scientists are identifying needs for training on probabilistic forecast information (e.g., Wilson et al. 2019), and the NWS is striving to meet those needs. Probabilistic forecast topics are increasingly incorporated into services (Novak et al. 2022), emphasized in training for Science and Operations Officers and forecasters, and have been codified via NWS directives (IDSS; NWS 2019) and an accompanying roadmap (NWS 2024). These efforts are aimed at creating an NWS in which forecasters are poised to receive and understand probabilistic NWP output. Once understood, the guidance may inform a forecaster's confidence and influence the scenarios, magnitudes, and potential impacts that can be communicated to users via traditional forecast and warning products and/or IDSS.

A WoFS run was performed retrospectively for the Waverly event and produced compelling output which may have increased forecaster confidence in the possibility of extreme rainfall had it been available. The ensemble depicted convection that was nearly stationary for the entire 6-h projection of many forecast runs, with loops of individual member products suggesting the development of mesoscale convective vortices (MCVs) which anchored the regeneration of cells against the upstream low-level inflow from the west, a process illustrated by Schumacher (2009) for environments very similar to this case. WoFS ensemble maximum 6-h precipitation forecasts notably ranged from 318 to 409 mm in six consecutive hourly forecast runs executed from preconvective initiation to the beginning of the heaviest rainfall; often the point maximum was forecast within 60 km of McEwen and Waverly. These runs provided information with up to 9 h of lead time to the first report of quantifiable flood-related damages per NWS Storm Data (DOC/NOAA/NESDIS/National Climatic Data Center 2023).

The NWS Forecast Office in Nashville, Tennessee (OHX), provided admirable service to Waverly and surrounding communities via a flash flood watch (FFA) issued 8 h prior to the first rainfall and timely Flash Flood Warnings (FFWs). The Weather Prediction Center (WPC) supported OHX with two timely Mesoscale Precipitation Discussions (MPDs) during the event. Still, the notion of an extreme rain event was not communicated in public forecasts and warnings until evidenced by gauge measurements and radar estimates. This paper will examine the operational quantitative precipitation guidance and then explore how WoFS output, had it been available in real time, could have aided understanding and communication of the magnitude and longevity of this extreme rainfall event.

2. Waverly event overview: Meteorology and operations at OHX

Rain began in the early morning of Saturday, 21 August 2021. A quasi-stationary surface front located west of Nashville, Tennessee (Fig. 2d), provided the focus for a prolonged series of heavy rainfall-producing thunderstorms that trained over what is mostly a low-populated

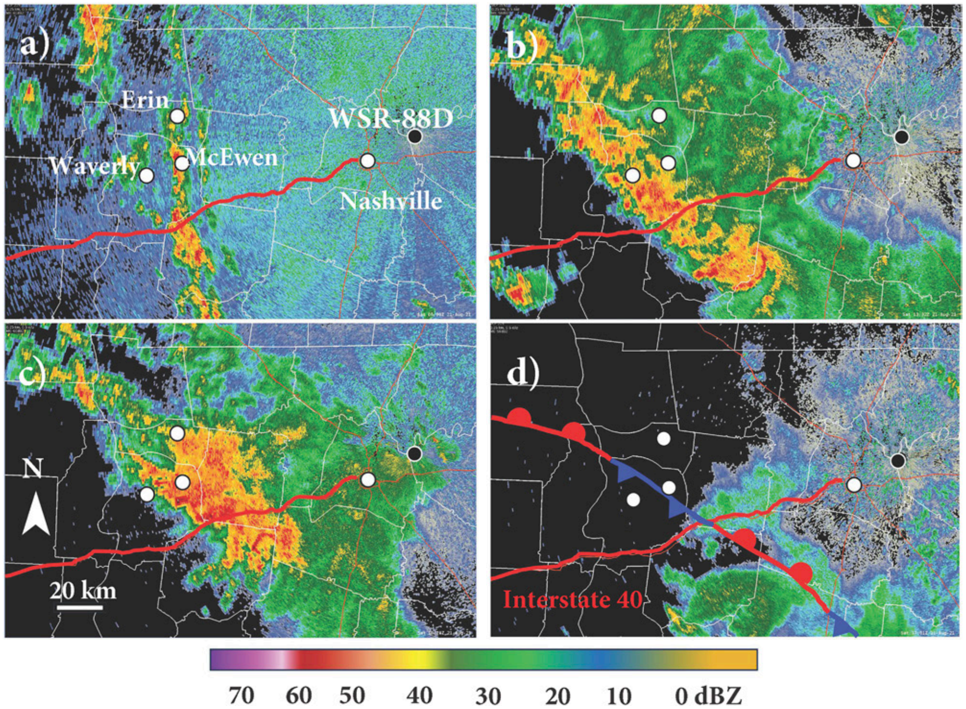

Fig. 2. A sequence of 0.5° reflectivity (dB*Z*) images from the Nashville WSR-88D radar, KOHX, valid at (a) 0600, (b) 1028, (c) 1332, and (d) 1701 UTC, showing the slow southward migration of heavy rain and long residence time over McEwen and vicinity. A manual analysis of quasi-stationary frontal position based on 0300 UTC surface data is overlain on (d) and is adjusted westward from the WPC analysis (not shown).

region of Middle Tennessee between Nashville and the Tennessee River (Figs. 2 and 4b). Radar echoes of developing showers in Humphreys County exceeded 40 dB*Z* by 0440 UTC (Fig. 2a displays radar echoes at 0600 UTC). Moderate to heavy rain fell continuously in parts of the county until 1700 UTC (Fig. 2). OHX had issued an FFA at 2155 UTC the previous afternoon for a broad area of Middle Tennessee that included what would become the flood-ravaged epicenter (Fig. 5d). A social media post published at 2213 UTC stated that

> Models continue to show the potential for heavy showers and thunderstorms … mainly west of I-24 overnight into the morning hours Saturday. 2–4 in. of additional rainfall will be possible … flash flooding will be a concern. Locally higher rainfall amounts will be possible

Worst-case model forecasts from both 1200 UTC 20 August and 0000 UTC 21 August 2021 predicted 178–254 mm in western Tennessee. This prediction does meet the extreme rainfall definition set forth above while significantly underestimating the amount of rain that would eventually fall. The 0600 UTC 21 August 2021 radiosonde[3] from OHX sampled a deeply moist vertical profile illustrated by the skew *T*–log *p* diagram (hereafter skew-*T*) in Fig. 3. Convective available potential energy (CAPE) for a hypothetical parcel lifted near from near the surface was "tall," with an equilibrium level close to 150 hPa and "skinny," with the parcel–environment temperature difference being no greater than 6°C and very consistent throughout the depth of the hypothetical updraft. Radiosondes measured precipitable water of 42.9 mm at 0000 UTC, 47.0 mm at 0600 UTC, and a daily record value of 60.2 mm at 1200 UTC (Table 1). Note that the 1200 UTC sounding was launched during ongoing rain. The skew-*T* consistently had a tall, skinny CAPE profile, and convective cells that formed around 0600 UTC had tropical characteristics. These included persistent areas of moderate reflectivity, an absence of hail indicators, and minimal indication of any outflow despite numerous

[3] Many NWS offices were launching special six-hourly soundings at this time to support forecasts for Tropical Storm Henri in the western Atlantic Ocean.

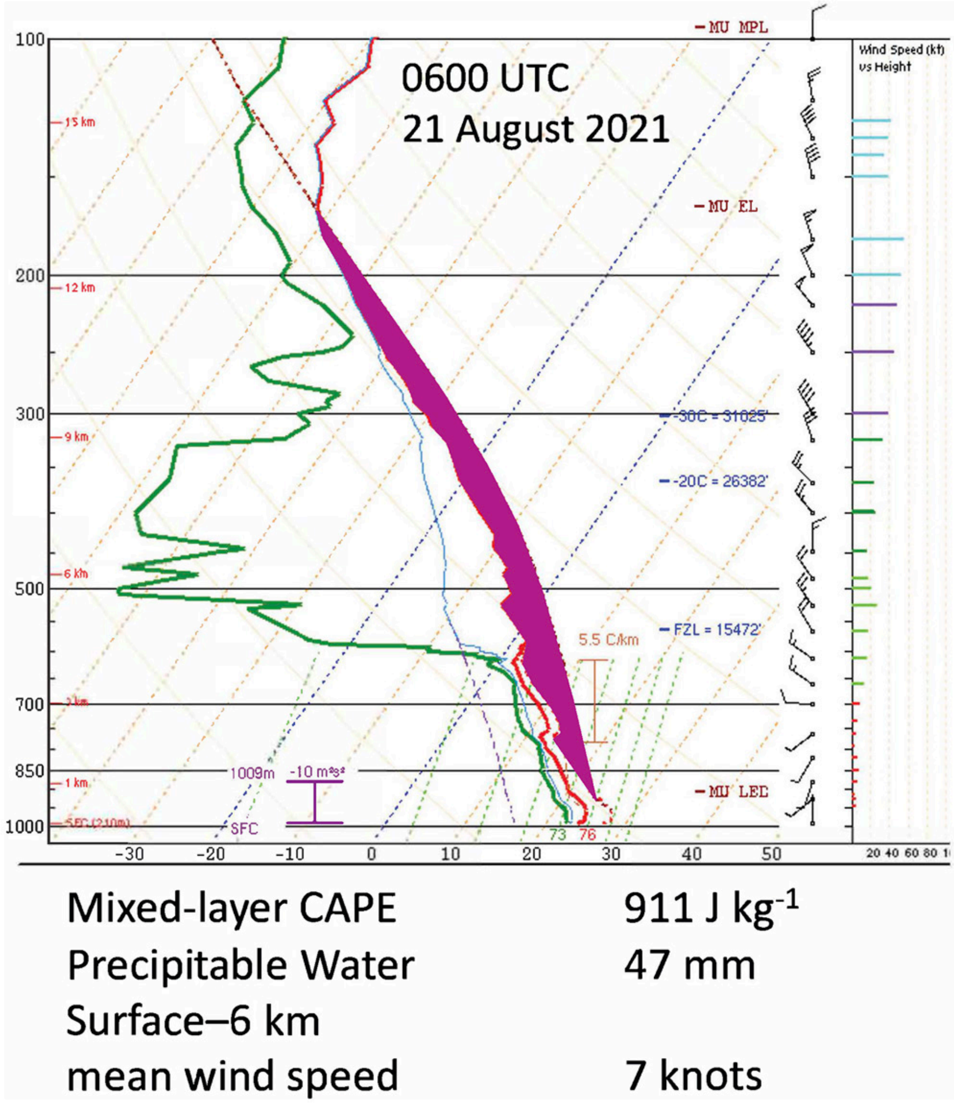

Fig. 3. A skew-*T* plot based on data from a special radiosonde launched at NWS Nashville at 0600 UTC 21 Aug 2021, when the first robust thunderstorms were forming approximately 75 km to the west. Positive CAPE using a parcel based on a virtual temperature correction is shaded in purple.

cell mergers and local upscale growth. Radar-estimated rainfall rates quickly escalated and persisted for several volume scans, suggesting rapid accumulation. An FFW was issued at 0829 UTC. The warning was updated at 1220 UTC to include a “considerable” tag (WMO 2015; Casteel 2016; NWS 2023).[4] An FFW with the rarely used headline “Flash Flood Emergency for...” was issued just 27 min

[4] In 2019, the NWS introduced impact-based FFWs. Each warning is tagged with one of the following characterizations of expected impacts: base; considerable; catastrophic.

Table 1. Measures of the thermodynamic environment, moisture content, and vertical wind profile from successive six-hourly atmospheric soundings conducted at OHX (*Sounding was launched into a precipitating atmosphere.)

Parameter	0000 UTC 21 Aug 2021	0600 UTC 21 Aug 2021	1200 UTC 21 Aug 2021*
Surface CAPE	2738 J kg^{-1}	1167 J kg^{-1}	685 J kg^{-1}
Lifted index	−6	−3	−2
K index	32	34	37
Precipitable water	42.9 mm	47.0 mm	60.2 mm
850–500-hPa lapse rate	5.4°C km^{-1}	5.0°C km^{-1}	4.9°C km^{-1}
Sfc-3-km bulk shear	3.1 m s^{-1}	5.1 m s^{-1}	5.7 m s^{-1}

later at 1247 UTC. OHX received its first report of catastrophic flooding in the town of Erin, located 27 km north–northeast of Waverly (Fig. 2) at 1350 UTC and received its first report of catastrophic flooding in Waverly, where 19 fatalities occurred, at 1501 UTC.

Although heavy rain did fall at Waverly, the catastrophic damages and associated fatalities were caused by a flood wave along Trace Creek owing to the most intense rain of the event which fell about 15-km upstream to the east, in and around McEwen. Figure 4a shows the quantitative precipitation estimate from the Multi-Radar Multi-Sensor (MRMS) dataset, and Fig. 4b maps the 356-mm isohyet to the local topography. Catastrophic flash flooding occurred

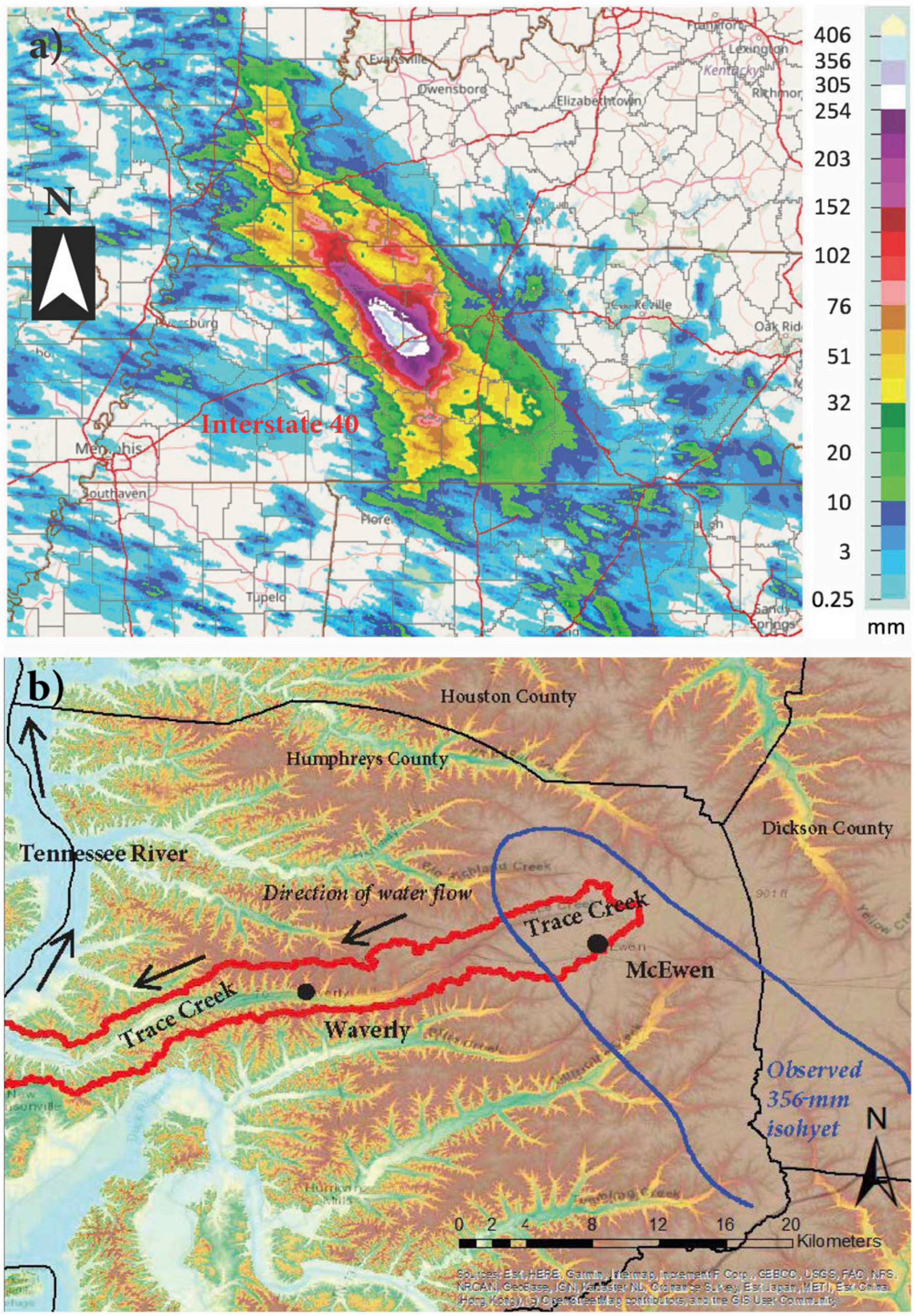

Fig. 4. (a) MRMS quantitative precipitation estimate valid from 0400 to 1700 UTC 21 Aug 2021. (b) Topographical map depicting the direction of water flow along Trace Creek from the area of heaviest rainfall near McEwen, through the town of Waverly, and into the Tennessee River. A blue contour traces the MRMS-based 356-mm isohyet. A black square in (a) outlines the area shown in (b). Map made using ArcMap software from the Environmental Systems Research Institute (ESRI).

specifically in Waverly as well as in portions of neighboring counties. Western portions of Middle Tennessee recorded a widespread 203–305 mm of rain with locally higher amounts, including 432 mm measured by the Tennessee Valley Authority in McEwen. A second gauge operated by the McEwen Waste Water Treatment Plant measured 526 mm (20.73 in.) in 24 h (a Tennessee 24-h rainfall record; Tennessee 24-hour Precipitation State Climate Extreme Committee 2021). This gauge records data every 5 min and measured the following rain rates: 14.22 mm (0.56 in. and a rate of 6.72 in. h^{-1}) in 5 min (1130–1135 UTC); 109 mm (4.29 in.) in 1 h (1130–1230 UTC); and 277 mm (10.92 in.) in 3 h (0940–1240 UTC). The bulk of the record-setting 24-h amount occurred from 0400 to 1240 UTC during which the McEwen Waste Water Treatment Plant measured 377-mm rainfall. The rest of this work concerns this roughly 9-h period and will reference McEwen with respect to NWP rainfall forecasts.

Waverly sits on a slope that funnels water toward the Tennessee River to the west of the city. Several creeks carry water westward from the highlands around McEwen; Waverly is the only significant city located along one of these creeks and therefore was quite vulnerable to a quickly moving flood wave. Numerous roads, including Interstate 40, located about 25 km south of Waverly, were shut down or washed away. There was only one way into and out of Waverly during peak flooding. Much of the town was completely destroyed or flooded, including the 911 emergency call center. Multiple eyewitnesses reported that the water rose approximately 1.5 m in 5 min. This was the deadliest flash flood on record in Middle Tennessee; 19 fatalities occurred in Waverly and one additional fatality occurred 12 km south in the town of Hurricane Mills. A full treatment of prediction capabilities for such an event would necessarily include routing of water once it is on the ground (e.g., Cosgrove and Klemmer 2016; Martinaitis et al. 2023). As a first step, this work focuses on anticipating and communicating the magnitude of the rainfall itself, and how a probabilistic storm-scale ensemble, namely, WoFS, can potentially contribute.

3. Rainfall guidance for the Waverly event and associated messaging challenges

a. WPC products. WPC routinely provides guidance products for rainfall. The Excessive Rainfall Outlook (ERO; Burke et al. 2023) estimates risk of rainfall that may lead to flash flooding, debris flows, or generally rainfall-related impacts for events across a spectrum of temporal and spatial scales, including those characterizing the Waverly event. On 20 August 2021, the initial ERO valid for the 24-h period ending at 1200 UTC on 21 August placed Waverly in a Marginal Risk category (Fig. 5a). At Day 2 and then early Day 1 lead time, the associated Excessive Rainfall Discussion noted an anomalous moist plume and low-level mass convergence but cited a lack of distinct upper air features and disparity among the models as reasons not to introduce a higher risk category. The scheduled update issued at 1600 UTC on 20 August did upgrade the area to a Slight Risk[5] (Fig. 5b). Reasons included a wetting antecedent rain event that morning and High Resolution Ensemble Forecast (HREF; Roberts et al. 2019) system forecasts of "...up to 40/45% exceeding 3h FFG..." The discussion also noted "...local amounts of 3–5+ (one model showing isolated maxes of 5–7+)" or 76–127+ and 127–178+ mm, respectively.

WPC quantitative precipitation forecasts (QPFs) represent an areal average and are foremost used as guidance for River Forecast Centers whose QPF drives main-stem-river modeling. WPC forecasters take a conservative approach to QPF magnitude to avoid dramatic run-to-run changes in forecast river stages via changes in QPF placement and magnitude; thus, WPC QPF should not be expected to express potential worst-case scenarios except in extremely rare circumstances at very short lead time. Nonetheless, WPC QPF does represent an expert-adjusted, value-added product (Novak et al. 2014), which we may think of as a

[5] ERO categories available to forecasters include in order of severity: marginal risk; slight risk; moderate risk; high risk. See Burke et al. (2023) for details.

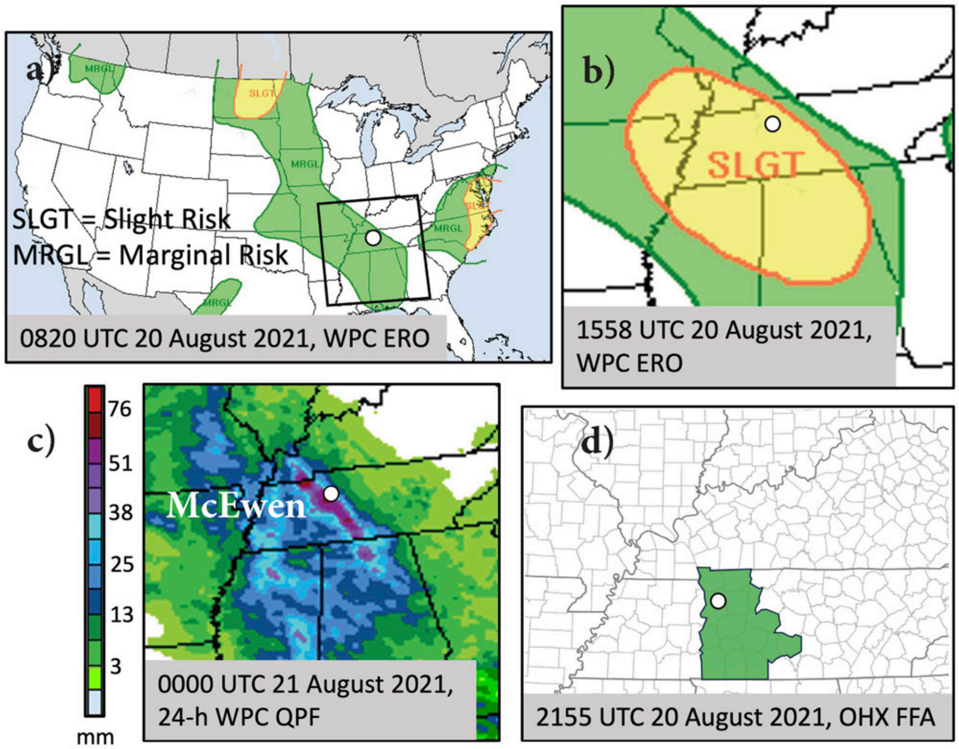

Fig. 5. A chronological graphical depiction of some rainfall-related products from WPC and OHX from around 20–6-h prior to rainfall onset, including (a) 0820 UTC 20 Aug 2021, WPC ERO valid through 1200 UTC 21 Aug 2021, (b) 1558 UTC 20 Aug 2021, WPC ERO valid through 1200 UTC 21 Aug 2021, (c) 0000 UTC 21 Aug 2021 24-h WPC QPF valid through 0000 UTC 22 Aug 2021, and (d) 2155 UTC 20 Aug 2021, OHX counties under an FFA. The inset in (a) depicts the area shown in (b).

proxy for the model QPF guidance that existed at the time. Additionally, WPC probabilistic QPF (PQPF; Sharma et al. 2017) offers a tool for estimating the range of potential QPF magnitudes, with the placement centered on the manually adjusted placement of QPF isohyets in the deterministic QPF product. PQFP model membership, however, is weighted toward global models; convection-allowing models (CAMs) make up just 13% of the 61 members (Weather Prediction Center 2022).

The WPC QPF (Fig. 5c) and PQPF (not shown) trended toward a spatial depiction that was quite accurate for the Waverly event given the national scale on which these forecasts are produced. Twenty-four-hour forecasts from the last regular product suite issued prior to the Waverly event (valid beginning at 0000 UTC on 21 August) placed a narrow stripe of around 50 mm of rain from western Henry County to western Humphreys County to Giles County, Tennessee (Fig. 5c). The real-world rain footprint was eventually laid down from eastern Henry County to eastern Humphreys County to northwestern Maury County, roughly 40 km to the east and not extending quite as far south as the forecast, but the possibility of an exceptional rainfall event was not foretold in the WPC products. The deterministic QPF in this swath was roughly 40–65 mm. WPC PQPF did not express any rainfall scenario that was dramatically heavier than the deterministic QPF. The 99th percentile showed a small area of 75–100 mm; this is much less than fell but was located precisely over McEwen. The QPF swath over Tennessee was roughly equivalent in magnitude to other QPF maxima over Kansas, North Carolina, and northern North Dakota, all sites of additional Marginal or Slight Risk areas in the ERO (Fig. 5a). Little stood out to communicate the relatively greater odds of an exceptional rain event in Tennessee. It was in MPD No. 847 (Fig. 6a), issued during the early onset of rainfall, and in a subsequent MPD No. 848 (Fig. 6c) and two FFWs (Figs. 6b,d) that forecast language ramped up toward higher-end rainfall and impacts. Table 2 tells how expected rainfall amounts were conveyed in OHX and WPC products up to and through the event.

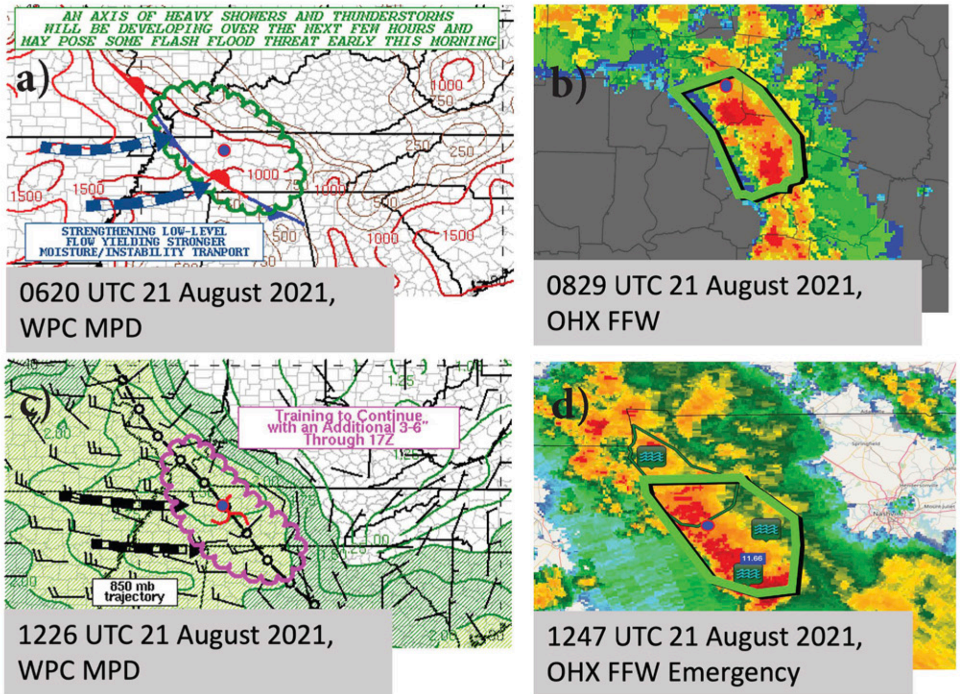

Fig. 6. **A chronological graphical depiction of some rainfall-related products from WPC and OHX from the onset of rainfall until the issuance of an FFW with emergency headline, including (a) 0620 UTC 21 Aug 2021, WPC MPD, (b) 0829 UTC 21 Aug 2021, OHX FFW, (c) 1226 UTC 21 Aug 2021, WPC MPD, and (d) 1240 UTC 21 Aug 2021, OHX FFW. A blue dot with red border marks the location of McEwen, Tennessee. FFW image courtesy of Iowa State University.**

b. Model QPFs.

1) HREF ensemble. Neither WPC forecasts nor model QPFs signaled an extreme rainfall event. Derived products from the HREF did contain a potentially actionable probabilistic forecast. The HREF is an “ensemble of opportunity,” composed of individual deterministic CAMs used to derive ensemble products on a 3-km grid over the contiguous United States (CONUS). The HREF suite of products is provided twice daily, at 0000 and 1200 UTC, projected forward 48 h. HREF, version 3, membership is shown in Table 3. HREF member QPFs may be used to derive the probability of rainfall exceeding the ARI; the ARI is defined as the average number of years between exceedances of a given rainfall amount over a given duration at

Table 2. **Reporting of how rainfall magnitude or potential magnitude in central Tennessee was discussed in various WPC and OHX products from 24-h lead time up to the issuance of an FFW with emergency headline.**

Issuance time	Issuing office and product	Rainfall magnitude description in product
0816 UTC 20 Aug 2021	WPC 24-h QPF (not shown)	6–13-mm areal average
0828 UTC 20 Aug 2021	WPC ERO (Fig. 5a)	Not discussed
1558 UTC 20 Aug 2021	WPC ERO (Fig. 5b)	127–178+ mm
2020 UTC 20 Aug 2021	WPC 24-h QPF (Fig. 5c)	51–64-mm areal average
2155 UTC 20 Aug 2021	OHX FFA (Fig. 5d)	51–102-mm w/higher amounts possible
0036 UTC 21 Aug 2021	WPC ERO (not shown)	60% probability of >76 mm
0620 UTC 21 Aug 2021	WPC MPD No. 847 (Fig. 6a)	Spotty 76–102+ mm
0640 UTC 21 Aug 2021	OHX FFA (identical to Fig. 5d)	51–102-mm w/higher amounts possible
0810 UTC 21 Aug 2021	WPC ERO (not shown)	Not discussed
0829 UTC 21 Aug 2021	OHX FFW (Fig. 6b)	Up to 89 mm
1226 UTC 21 Aug 2021	WPC MPD No. 848 (Fig. 6c)	Isolated 178–356-mm totals implied
1247 UTC 21 Aug 2021	OHX FFW (Fig. 6d)	229-mm observed; no additional forecast amounts mentioned

Table 3. Listing of HREF, version 3, members, their respective titles, sources of initial and lateral boundary conditions, microphysics and planetary boundary layer schemes, and horizontal grid spacing.

HREF member	Initial conditions	Lateral boundary conditions	Microphysics	Planetary boundary layer parameterization	Horizontal grid spacing (km)
HRRR (and 6-h time lag)	RAP-1 h	RAP-1 h	Thompson	MYNN	3.0
HRW-ARW (and 12-h time lag)	RAP	GFS-6 h	WSM6	YSU	3.2
HRW-FV3 (and 12-h time lag)	GFS-6 h	GFS-6 h	GFDL	GFS EDMF	3.0
HRW-ARW2 (and 12-h time lag)	NAM	NAM-6 h	WSM6	MYJ	3.2
NAM Nest (and 12-h time lag)	NAM	NAM	Ferrier-Aligo	MYJ	3.0

a point location. HREF ARIs designed and employed at WPC use a 40-km radius around a point to define ARI exceedance probabilities.

The HREF run at 1200 UTC 20 August produced ARI probabilities exceeding 30% for the 10-yr value and 20% for the 100-yr value (Fig. 7b). The 100-yr ARI at McEwen is 200 mm (Bonnin et al. 2004). The period of reliable observations is short on a climatological scale; thus, a 90% confidence range of 182–227 mm is provided. It is also worth noting that rainfall of 200 mm does not appear to be exceptionally uncommon, but its occurrence at a specific point location is exceptionally uncommon.

A forecast of a 20% chance to exceed a threshold that is, on average, exceeded every 100 years, or alternately in the Annual Exceedance Probability (AEP) framework, has a one percent chance of occurring in a given year, may have helped forecasters frame the potential rarity of even a 200-mm rainfall, should that transpire. The degree to which NWS forecasters are practicing use of ARIs in operations is uncertain. The extreme precipitation monitor (Stovern et al. 2020), an operational product from WPC, reframes WPC QPF in the ARI and AEP frameworks. HREF ARIs are often used in forecasting at WPC, but the product does have noteworthy shortcomings. Signals may be driven by one or two member models with wet biases and/or by easily achievable 100-yr values in dry climates like the western CONUS. ARI signals in the eastern CONUS generally fall into two regimes: the HREF members are nearly unanimous (e.g., 70% for Post Tropical Cyclone Ida in the mid-Atlantic in 2021) or the probability is 10%–20% and driven by just one to two HREF members. The Waverly event fell into the latter regime via the 1200 UTC model cycle. HREF 100-yr ARI did increase with a very small area of 40% probability in the 0000 UTC cycle (Fig. 7d). Forecaster weighting of the 100-yr ARI signal was tempered by inconsistency in the hourly High-Resolution Rapid Refresh (HRRR; Benjamin et al. 2016; Dowell et al. 2022) runs after 0000 UTC 21 August (see Fig. 9). Though the ARI was one factor supporting the issuance of an MPD at 0620 UTC, lack of agreement among different model sources was one reason the MPD used "possible" rather than "likely" language and did not speak to the potential for extreme rainfall.

(i) Forecasts from 1200 UTC 20 August. Several models did forecast heavy rain in western Tennessee (Fig. 8). Of the 1200 UTC 20 August suite, the HRRR (Fig. 8a) and North American Mesoscale 3-km CONUS nest (NAM Nest; Fig. 8b) forecast particularly heavy rain with good placement near McEwen. Importantly, this area was among the one or two heaviest rain areas in those respective model forecasts over the Southeast (i.e., they were eye catching). These two models helped boost the signal in the HREF local probability-matched mean (LPMM; Fig. 7a). HREF mean forecasts produced a good spatial match to the extent of the

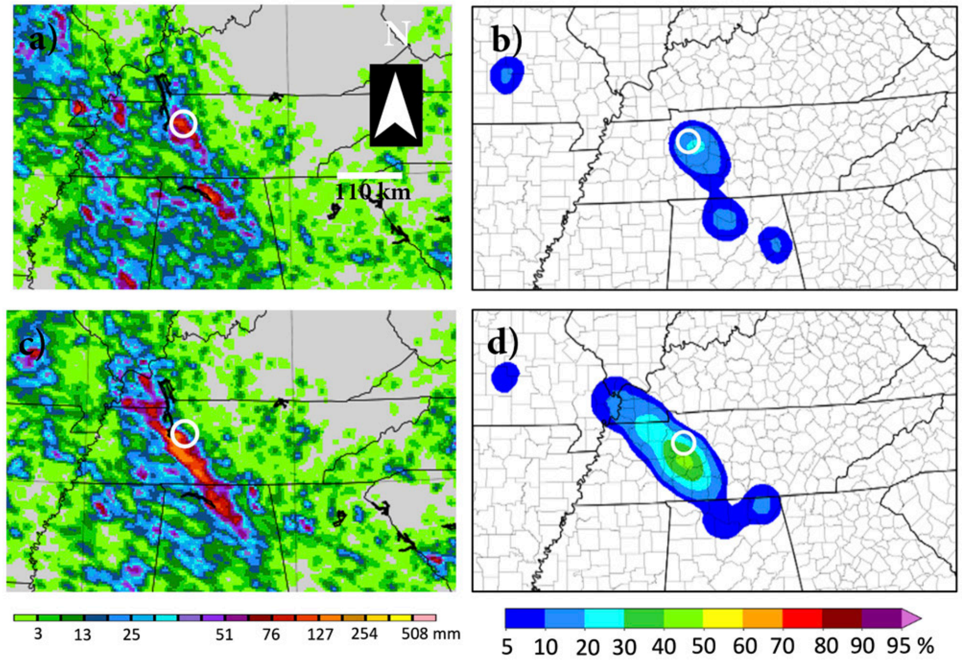

Fig. 7. **HREF LPMM 24-h QPF valid ending 0000 UTC 22 Aug 2021, for runs initialized at (a) 1200 UTC 20 Aug 2021 and (c) 0000 UTC 21 Aug 2021. HREF-derived 1% AEP for the 24-h period ending 0000 UTC 22 Aug 2021, for runs initialized at (b) 1200 UTC 20 Aug and (d) 0000 UTC 21 Aug. McEwen, Tennessee, the site of 526 mm of observed rainfall, is indicated by a white ring. Model forecast graphics courtesy of the Environmental Modeling Center.**

McEwen precipitation, and the LPMM had the heaviest amounts (101–127 mm); however, the magnitude does not speak to the potential of an extreme event, and other similarly heavy signals were located elsewhere in the domain.

The HRRR and NAM Nest had good placement of a sizable >100 mm rainfall area near McEwen, while other CAMs offered very different forecasts. The Weather Research and Forecasting (WRF) Advanced Research WRF 2 (ARW2) Model (Fig. 8c) and the HREF member running the Finite Volume Cubed-Sphere Dynamical Core (HRW-FV3; not shown) predicted relatively light (sub-50 mm) rainfall displaced in opposite directions from McEwen and surrounded by larger, heavier, erroneous rain areas throughout the Southeast.

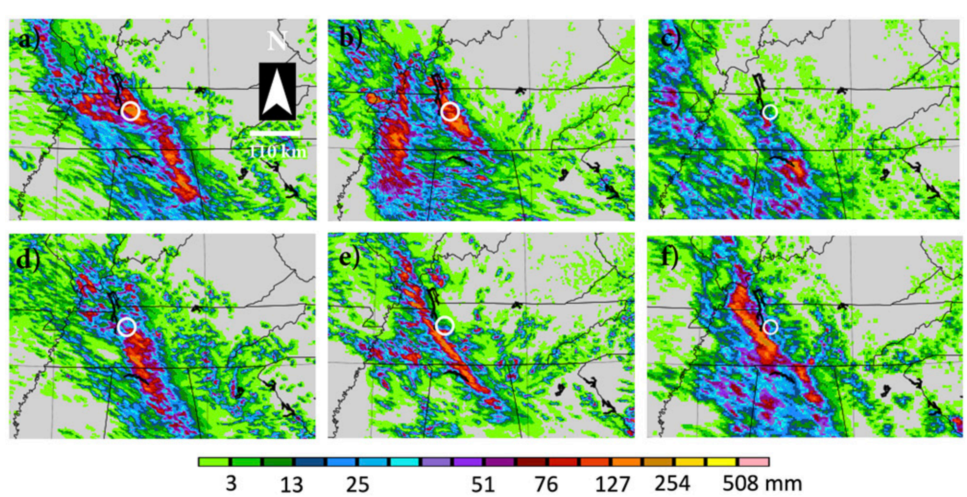

Fig. 8. **Select HREF member model 24-h QPFs valid ending 0000 UTC 22 Aug 2021, including (a) HRRR, (b) NAM Nest, and (c) WRF-ARW initialized 1200 UTC 20 Aug 2021 and (d) HRRR, (e) NAM Nest, and (f) WRF-ARW initialized 0000 UTC 21 Aug 2021. McEwen, Tennessee, the site of 526 mm of observed rainfall, is indicated by a white ring. Model forecast graphics courtesy of the Environmental Modeling Center.**

(ii) Forecasts from 0000 UTC 20 August. The signal for placement and relative magnitude of the McEwen rainfall compared to other QPF areas improved substantially in the 0000 UTC model cycle. The largest and heaviest rainfall area in the Southeast was in western Tennessee in all models studied here (Figs. 8d–f). Improvement was most stark in the WRF-ARW (Figs. 8c,f), WRF-ARW2 (not shown), and FV3 (not shown) which forecast very little heavy rainfall in western Tennessee at 1200 UTC and instead forecast one or more pronounced swaths of >125 mm rainfall at 0000 UTC. The subjective performance trend since 1200 UTC was positive with only two minor exceptions. The HRRR shifted the heaviest rain out of the McEwen vicinity by about 50 km to the south (Figs. 8a,d), and the NAM Nest shifted its very accurate 1200 UTC heavy rain swath erroneously westward by about 40 km (Figs. 8b,e).

The magnitude of QPF had also increased, and this increase was fairly consistent across models. Using the 0000 UTC suite, it may have been reasonable to have high confidence in seeing 127–178 mm and moderate confidence in seeing 178–254 mm. The WRF-ARW (Fig. 8f) predicted a few grid cells in the 254–381 mm range ~ 50 km northwest of McEwen. Most 0000 UTC models were in error to the west on the order of 50 km. Placement of the event was slightly better in the 1200 UTC runs, but model agreement and forecast magnitude increased in the vicinity of McEwen in the 0000 UTC runs. Taking action on such signals is not trivial. The event was of such small scale when considering regional or national plots of QPF that forecasters would likely need to dedicate substantial time and thought to analyzing the signal and drawing conclusions.

2) HRRR forecasts. The operational HRRR launches new runs hourly, and these project forward at least 18 h. This study examined HRRR 18-h QPFs for runs made between 0100 and 0600 UTC on 21 August (Figs. 9a–d). For runs made between 0700 and 1000 UTC, the accumulation period was truncated, always ending at 0000 UTC 22 August. The 0100–0400 UTC runs were marked by inconsistent rainfall placement and coverage over Tennessee (Figs. 9a–c). Eighteen-hour run-total precipitation in the vicinity of McEwen was predicted below 130 mm during this time. The HRRR produced a more consistent and more accurate depiction of the precipitation swath beginning at 0500 UTC (Fig. 9d). Amounts of 75–100 mm with localized values of 130–180 mm were forecast in a relatively narrow zone surrounding the quasi-stationary front, including over Humphreys County and McEwen. A further

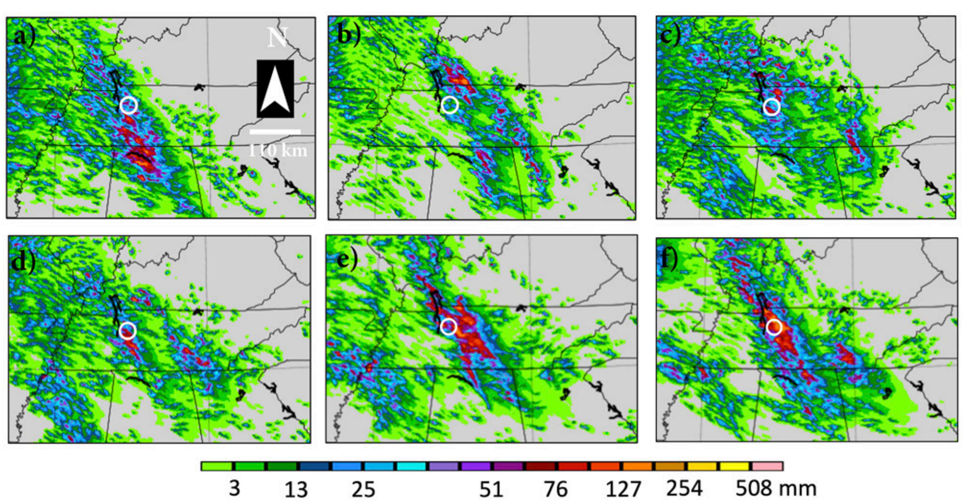

Fig. 9. HRRR 18-h run accumulated precipitation from (a) 0100, (b) 0200, (c) 0400, (d) 0500 UTC, 16-h run accumulated precipitation from (e) 0800 UTC, and 14-h run accumulated precipitation from (f) 1000 UTC 21–22 Aug 2021. McEwen, Tennessee, is circled by a white ring. HRRR forecast graphics courtesy of the Environmental Modeling Center.

improvement to HRRR performance is noted starting at 0800 UTC (Fig. 9e), likely owing to radar data assimilation producing accurate analyses of ongoing deep convection. A more coherent area of 130–180 mm was predicted in the 0800 UTC run, increasing to 180–255 mm at 0900 UTC and 254–381 mm at 1000 UTC (Fig. 9f).

The consistent and steep trend in HRRR QPF from 0800 to 1000 UTC, corroborated by real-time radar analysis, had potential to alert forecasters to the increasing likelihood of at least a 254–381 mm event. Forecasters at WPC and OHX do not recall the specific influence that HRRR forecasts had as the event unfolded, and note that the increase to HRRR QPF occurred in between MPD issuances. The forecasters focused primarily on mesoanalysis, observed data such as radar trends, and task-specific tools like the Flooded Locations and Simulated Hydrograph (FLASH) Complete Routing and Excess Storage (CREST; Gourley et al. 2017; Wang et al. 2011) maximum unit streamflow. HRRR forecasts were not directly cited within the text of either of the two WPC MPDs issued during the Waverly event.

4. WoFS guidance for the Waverly event

Experimental WoFS guidance was not available to forecasters in real time, but a retrospective run was performed to include WoFS runs launched half-hourly from 0300 to 1200 UTC 21 August 2021. Top-of-hour runs project 6 h and bottom-of-hour runs project 3 h. WoFS emphasizes probabilistic prediction by providing numerous probability and percentile products (Skinner et al. 2023). Unlike the HREF, WoFS does not yet reframe QPF as ARI exceedance probabilities.

First real-world radar echoes occurred around 0400 UTC, and the first robust (>40 dB*Z*) core in Humphreys County was noted at 0440 UTC. The WoFS runs from 0400 UTC (Fig. 10a) to 0500 UTC (Fig. 10b), launched prior to the onset of heavy rainfall accumulation and largely prior to the initiation of robust thunderstorm cells, were already predicting a broad heavy rain footprint and larger potential rainfall magnitudes than had been forecast by the operational CAMs (Table 4). The point maximum forecast anywhere in the WoFS domain is plotted as a cross hair on the plan-view QPF products and circled in yellow in Fig. 10. The point maximum in the 90th percentile product at 0500 UTC was 229 mm, approximately

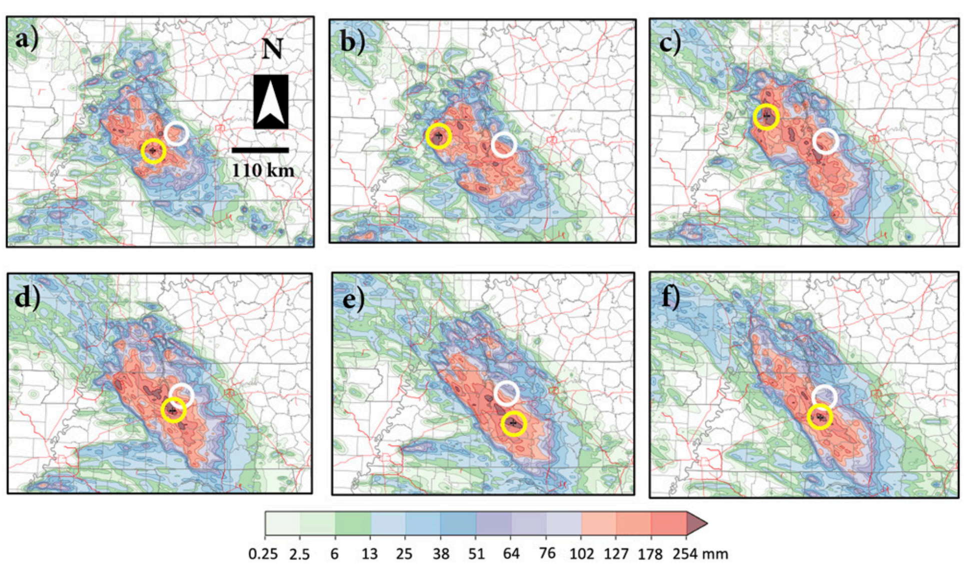

Fig. 10. WoFS ensemble maximum 6-h rainfall from six consecutive top-of-hour runs made retrospectively at (a) 0400, (b) 0500, (c) 0600, (d) 0700, (e) 0800, and (f) 0900 UTC 21 Aug 2021, over Tennessee and surrounding area. In all panels, a white ring circles McEwen, Tennessee, and a yellow ring circles a cross hair that is present on each panel and which denotes the highest QPF value in the WoFS domain. Cross hair locations and their values are reported in Table 4.

Table 4. Magnitude and location relative to McEwen, Tennessee, of the maximum single point value for both the 90th percentile and 100th (maximum) percentile WoFS QPFs for 6-h forecasts issued from 0400 to 0900 UTC.

WoFS rainfall accumulation period	WoFS 6-h point maximum of the 90th percentile (mm)	Location of the data in the preceding column	WoFS 6-h point maximum of the 100th percentile	Location of the data in the preceding column	MRMS maximum during the 6-h window (mm)	McEwen waste water treatment plant gauge (mm)
0400–1000 UTC	170	~56-km SW McEwen	340	~56-km SW McEwen	152–177	130
0500–1100 UTC	229	~35-km SW McEwen	344	~110-km NW McEwen	254–304	219
0600–1200 UTC	227	~28-km SW McEwen	409	~115-km NW McEwen	304–356	304
0700–1300 UTC	289	~28-km SW McEwen	353	~32-km SW McEwen	356–406	376
0800–1400 UTC	283	~48-km S McEwen	350	~48-km S McEwen	356–406	366
0900–1500 UTC	230	~48-km W McEwen	318	~35-km SW McEwen	304–356	348

35 km southwest of McEwen, and in the max percentile product was 344 mm, approximately 110 km northwest of McEwen (Fig. 10b). The point maximum in the 90th percentile product between 0500 and 0900 UTC ranged from 227 to 289 mm and was always within 28–48 km of McEwen. The point maximum in the max percentile product during this time ranged from 318 to 409 mm (Figs. 10b–f). The magnitude of the point maximum in the max percentile product was within or very close to the range of observed values in the MRMS quantitative precipitation estimate (Table 4). The location of the point maximum in the WoFS max percentile product was more variable, but the shape of the 100-mm isohyet encompassing the mesoscale rain event remained consistent and generally accurate (Fig. 10). The point maxima in the max percentile QPFs were indicative of the potential for a particularly extreme event to occur within that broader region—even sometimes indicating that this extreme could occur within 50 km of where it did occur.

WoFS successes are most often tied to its unique rapid data assimilation at 15-min intervals, particularly when assimilating ongoing thunderstorms (Guerra et al. 2022). This certainly played a role here, but success in the early runs prior to robust convective initiation suggests there was some predictability on a larger scale. Cold pools were very weak for several hours, and latent heat release in the deep convective updrafts was focused in a narrow zone. Loops of observed radar data and WoFS output (see Figs. 11e–h) suggest this allowed MCV formation. WoFS employs NSSL fully double-moment microphysics (Table 5; Mansell et al. 2010; Mansell and Ziegler 2013), a scheme not currently employed in operational CAMs, and its influence on these successful forecasts would be a good topic of study.

WoFS offers numerous probabilistic and deterministic outputs that forecasters may use to vet or corroborate scenarios suggested in any single product. In the case of extreme rainfall from stationary or training cells, loops of simulated radar reflectivity and simulated satellite imagery at 5-min resolution over 6 h can act as a powerful visualization tool. Numerous ensemble members from the 0600 UTC WoFS run, for example, depicted strong radar echoes, large rain rates, and infrared wedge signatures, all of which were nearly stationary and/or quickly reforming over the same location for the entirety of the forecast period (Figs. 11 and 12). The 5-min rain rate (Figs. 11a–d) and composite reflectivity (Figs. 12e–h) products showed nearly stationary and back-building convection over the course of 6 h. Loops of these products gave visually crisp indications of storm-scale and mesoscale vortex formation, likely owing to latent heat release. This notion is supported by the development of 8–15-knot (kt; 1 kt ≈ 0.51 m s^{-1}) westerly inflow into the thunderstorm region at 700 hPa after a

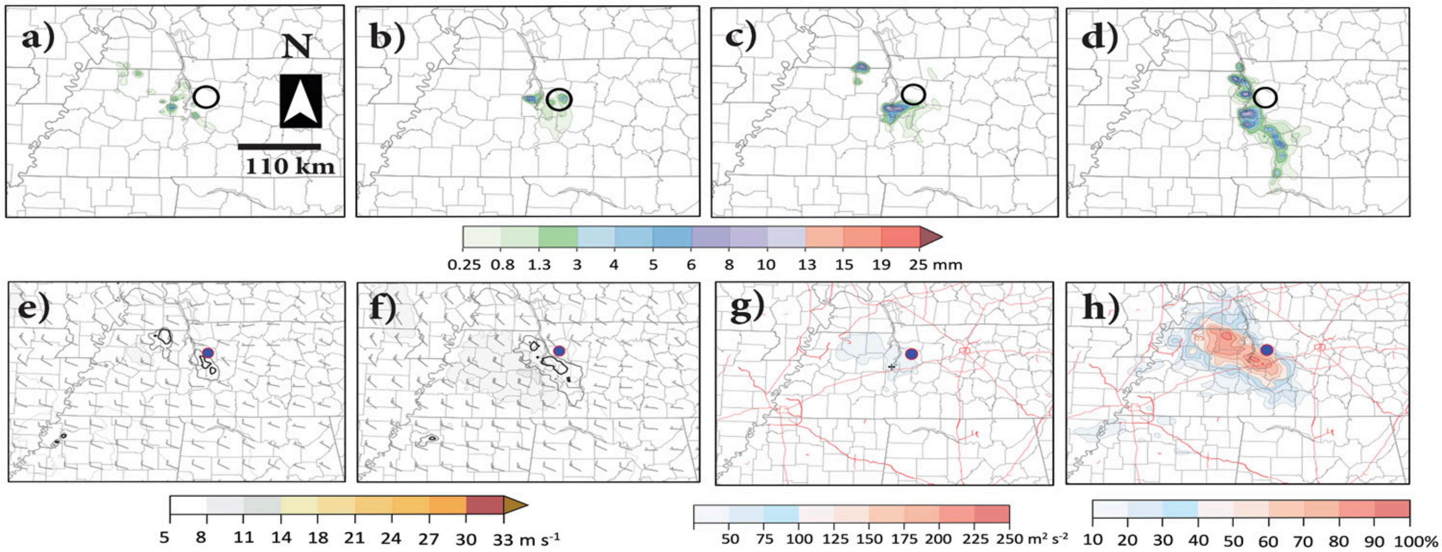

Fig. 11. All from the WoFS 0500 UTC run, WoFS member-10 5-min rain rate valid at (a) 0500, (b) 0700, (c) 0900, and (d) 1100 UTC. WoFS ensemble mean 700-hPa wind barbs (kt) and color-filled isotachs (plotted in kt on the WoFS real-time viewer, but with color scale converted to m s^{-1} for the figure) valid at (e) 0700 and (f) 0900 UTC. Hollow gray and black contours in (e) and (f) are the probability-matched mean of composite reflectivity at 35 and 50 dB*Z*, respectively. (g) WoFS ensemble maximum 2–5-km updraft helicity valid 0500–1100 UTC, and the (h) WoFS probability of 0–2-km vertical vorticity exceeding 0.003 s^{-1} from 0500 to 1100 UTC. McEwen, Tennessee, is marked by a black ring in (a)–(d) and a blue dot with red border in (e)–(h).

few hours of latent heat release in the 0600 UTC WoFS run (Figs. 11e,f), along with the appearance of nonzero values of maximum 2–5-km updraft helicity (Fig. 11g) and moderate probabilities of 0–2-km vertical vorticity exceeding 0.003 s^{-1} (Fig. 11h) coincident with the ongoing storms in the ensemble. These circulations in the WoFS member simulations are seen focusing the growth and training of new robust convection on the low-level inflow side of the vortices. One might recognize that additional latent heat release would further strengthen the vortices, creating positive feedback (Schumacher 2009).

This focused and long-lasting release of instability did not produce any definable cold pool that could potentially dislodge the anchor point for newly developing cells. Two-meter temperatures from the 0600 UTC WoFS showed negligible change throughout the domain during the 6-h forecast projection (Figs. 13b,d,f). Forecast soundings for the grid box nearest to McEwen showed the maintenance of a tropical profile that is completely saturated – especially below 500 hPa and at later hours above 500 hPa, and yet instability was never exhausted; member mean most unstable CAPE only decreased from 1730 J kg^{-1} at 0600 UTC to 732 J kg^{-1} at 1200 UTC (Figs. 13a,c,e). This suggests the stabilizing influence of convective overturning was partially offset by synoptic ascent acting to cool the middle levels.

Even when the environment and early observations are supportive of the potential for very large rainfall amounts, it can be useful for forecasters to consider extreme model output relative to that model system. One example is the NAM Nest, which is perceived to have a high QPF bias; thus, an extreme forecast amount from that model would not necessarily invoke forecaster confidence in an impending extreme event. Forecasters may not yet have enough experience with WoFS to understand its precipitation strengths and biases, although WPC

Table 5. Listing of WoFS sources of initial and lateral boundary conditions, microphysics and planetary boundary layer schemes, and horizontal grid spacing.

Model system	Initial conditions	Lateral boundary conditions	Microphysics	Planetary boundary layer parameterization	Horizontal grid spacing (km)
WoFS (18 members, varied PBL)	HRRR	HRRR + GEFS	NSSL 2-moment	YSU, MYJ, MYNN	3.0

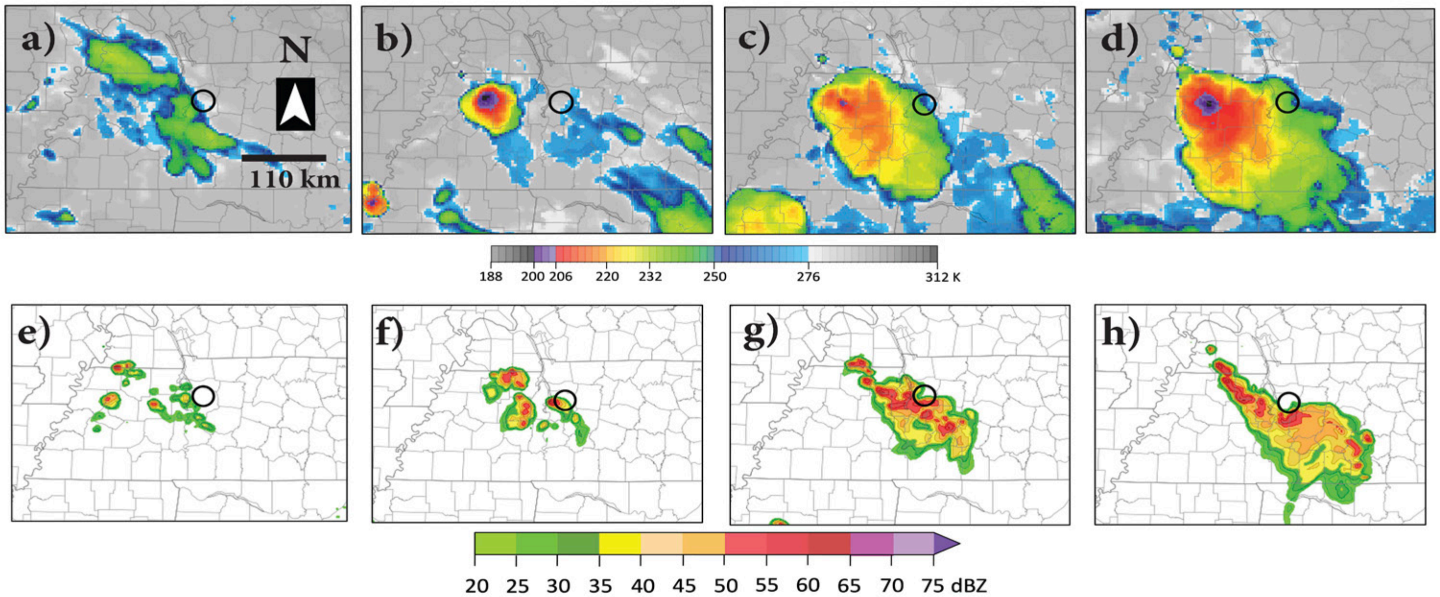

Fig. 12. All from the WoFS 0500 UTC run, member-16 simulated infrared brightness temperature (K) valid at (a) 0500, (b) 0700, (c) 0900, and (d) 1100 UTC and member-12 simulated composite reflectivity valid at (e) 0500, (f) 0700, (g) 0900, and (h) 1100 UTC. McEwen, Tennessee, is encircled by a black ring in all panels.

forecasters have been studying WoFS output in real time since 2018 (Wilson et al. 2023). This study can provide some context for WoFS output by examining the point maximum QPF within the WoFS domain in the max percentile data. The location of the point maximum is denoted by a cross hair on the web-based WoFS plots (see examples in Fig. 10), and its value is printed beneath the color bar legend; this is one tangible value that forecasters can skim without estimating based on shading. The Waverly event produced the eighth largest point maximum among 76 nontropical events occurring over the spring and summer seasons of 2021–23; this represents the 90th percentile of the resulting distribution (Fig. 14).

5. Discussion

Forecasts for the early-morning Waverly event indicated some potential for flooding rains at ~8–16-h lead time, with an Excessive Rainfall Outlook upgrade to Slight Risk the morning before and an FFA issued during the afternoon. Messaging became more specific and carried an increasing sense of urgency with a mesoscale discussion from WPC during the onset and the upgrade of an FFW to a Flash Flood Emergency from OHX at the height of the event. Operational prediction tools, however, underforecast the rainfall amounts by at least half, and any existing signals of a potentially extreme rainfall event were buried amongst inconsistent signals.

Operational forecasters at OHX and WPC, including those who worked the event, have discussed whether and how a real-time WoFS run could have increased confidence in the likelihood of extreme rainfall just ahead of and during the early stages of the Waverly event. Internal collaboration between forecasters at OHX during the evening, several hours before the onset of rain, revealed confidence that 2–4 in. (51–102 mm) and locally higher amounts would be likely within the FFA. Were output from WoFS available and viewed just ahead of the event, forecasters would have seen the half-hourly arrival of storm-scale ensemble guidance consistently predicting worst-case scenario amounts about 4 times greater than what was being messaged in the FFA, at several hour lead times to the heaviest rainfall. Multiple WoFS runs starting at 0400 UTC showed the potential for extreme rainfall–ensemble maximum amounts of 318–409 mm. This type of consistency from a rapidly updating storm-scale ensemble alone would have increased forecaster confidence that extreme rainfall was a

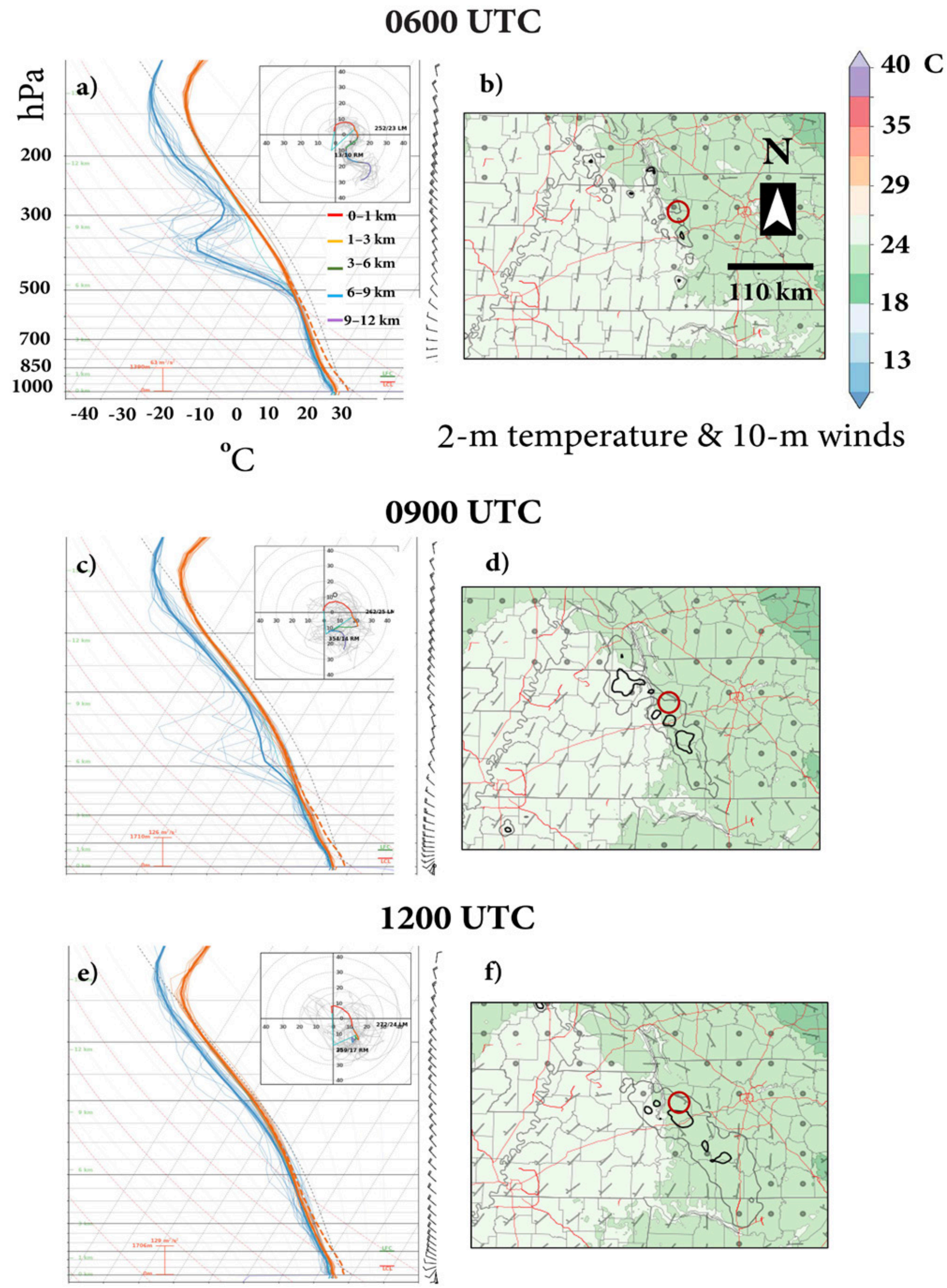

Fig. 13. Thermodynamic and kinematic information from the retrospective 0600 UTC run of WoFS on 21 Aug 2021, based on data available more than 2 h before the first FFW and more than 6 h before the issuance of an FFW with emergency headline. Pairs of images show WoFS forecast soundings and associated hodographs for a point near Waverly and the plan view of 2-m temperature and 10-m wind forecasts over the WoFS domain at (a),(b) 0600, (c),(d) 0900, and (e),(f) 1200 UTC. Hodograph axis values are plotted in knots; a hodograph legend is included on (a). The ensemble mean hodograph data are plotted in bold and colored; individual member hodographs are plotted in gray. Hollow gray and black contours on (b), (d), and (f) are the ensemble probability-matched mean of 35 and 50 dB*Z* composite reflectivity, respectively. McEwen, Tennessee, is encircled by a red ring in (b), (d), and (f).

possibility. A plausible forecaster response would be to ramp up IDSS messaging to some degree, especially forecast rainfall amounts, late in the evening and prior to the event onset. The eventual increase of HRRR forecast rainfall amounts from 0800 to 1000 UTC would then exist in a new context, representing model agreement that could build forecaster confidence in an impending extreme event. Forecasters at OHX would have had more model support to message greater flash flood risk and greater expected impacts to partners and the public from 0400 to 1000 UTC.

The value of WoFS is commonly seen as a numerical-guidance-based bridge to influence specificity and uncertainty being expressed during IDSS between the watch and warning time frame (Wilson et al. 2024). Area-focused IDSS is commonly provided to emergency managers and in this case could have been directed toward Humphreys County, where Waverly and McEwen are located, before the onset of flooding. Forecasters hypothetically operating with increased confidence from viewing the 0400 and 0500 UTC runs of WoFS could have engaged emergency managers in one-on-one briefings and provided collaborative chat messages to media and other partners with 3–4 h of lead time prior to the first FFW. Well-established relationships with OHX area emergency managers and increased exposure to WoFS output would have allowed OHX to contact those emergency managers by phone even at such a late hour. WoFS output showing much higher rainfall amounts during the overnight time frame would provide emergency managers with advanced notice of potentially catastrophic flooding, as well as keeping the communication open during the overnight hours with any updates to WoFS output and radar data. The strong relationships OHX has with area emergency managers not only allow for late-hour communication of potential weather threats but are also part of the future of IDSS and improved watch-to-warning technology.

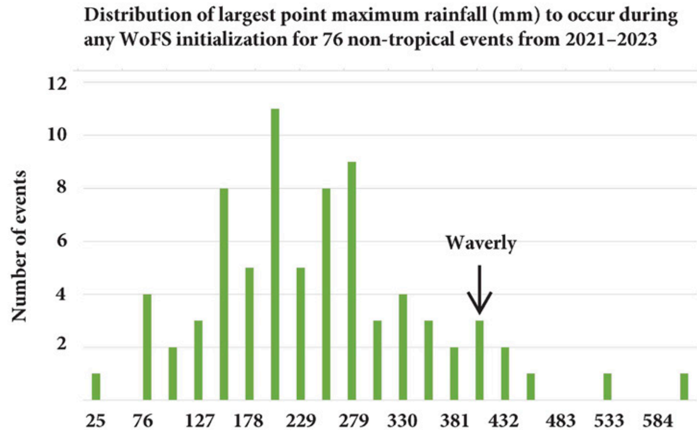

Fig. 14. Number of cases in which the greatest 6-h point maximum QPF for any WoFS initialization fell into respective 25–26 mm or 1-in. bins.

WPC issued the first of two MPDs for the event at 0620 UTC. The MPD, made without the benefit of seeing WoFS forecasts, included the magnitude-related statements, "...rainfall rates that may locally approach or exceed 2 in. h^{-1}" (i.e., 51 mm h^{-1}) and "...generally the expectation is for some spotty 3–4+-in. totals for this time frame, and then a threat for additional rainfall beyond 12Z..." (i.e., 76–102 mm and 1200 UTC, respectively).

The synoptic environment featured a slow 0–6-km mean wind speed, veering low-level wind profiles, and modest westerly low-level inflow from a moist and unstable source region over western Tennessee. Back-building and training would be plausible in this environment, but the uncertainty in the degree of convective organization led to initial caution with respect to the messaging of rainfall amounts and ultimately the flash flood threat. WPC forecasters noted that the two MPDs issued during this event represented a mix of HRRR guidance and nowcasting based on satellite, radar, and observations, and that WoFS output would have been very helpful given its favorable handling of other flash flood events over the years. WoFS would have provided a much clearer picture of the potential for extreme rainfall amounts and resultant threat of high-end flash flooding. Integration of the 0400 and 0500 UTC WoFS QPF percentile products, as well as the hourly probabilities of 2- and 3-in. rainfall (51 and 76 mm), would have especially influenced the decision-making process. WoFS simulated radar reflectivity, storm-object paintball plots of reflectivity >40 d*BZ*, and simulated satellite imagery contained very useful information on the convective mode, organization, storm motions, and event duration. Collectively, these WoFS products likely would have contributed to MPDs that messaged heavier rainfall amounts, and when including heavier amounts, it is not uncommon for WPC to draw a connection to the potential severity of impacts within the MPD text.

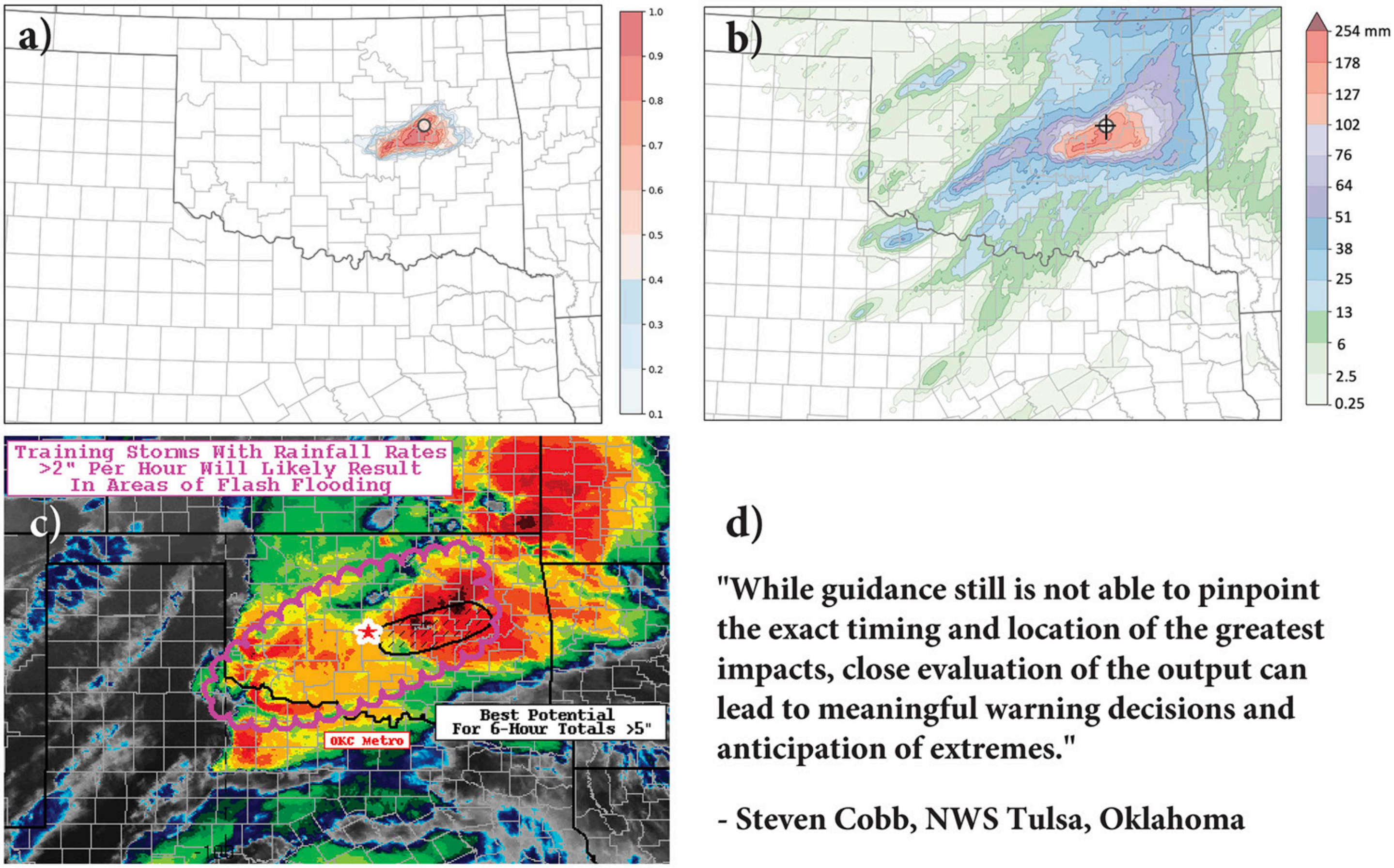

Fig. 15. Real-world application of WoFS on 4 May 2022 illustrated by (a) WoFS 6-h probability of rainfall exceeding 127 mm from 0100 UTC 5 May 2022, (b) WoFS 6-h swath of 50th percentile QPF from 0100 UTC 5 May 2022, (c) an MPD issued 0200 UTC 5 May 2022, and (d) a quote from Steven Cobb of NWS Tulsa, Oklahoma, based on their use of WoFS to inform FFWs. A white circle in (a) and (b) denotes the location where event maximum rainfall of around 280 mm was observed. A black cross hair in (b) denotes the location of 208 mm, the highest forecast value in this WoFS product.

Real-time, real-world WoFS usage in the style hypothesized here has occurred and was first reported by Heinselman et al. (2024). On 4 May 2022, WoFS directly influenced an MPD (Fig. 15c) and the timing and content of FFWs issued during an event with 250–300-mm peak rainfall in eastern Oklahoma. The MPD cited unusually high (200 mm) amounts in the 50th percentile QPF (Fig. 15b) and >60% probabilities of 51 mm h^{-1} rates in successive hours of the forecast output between 0200 and 0500 UTC (not shown). In addition to the summary quote in Fig. 15d, NWS Tulsa reported that "...earlier indications of 2" or greater (increasing probabilities) and max accumulations of 5" likely led to a quicker acceptance of the events eventually bulls-eyed farther east (i.e., 51 and 127 mm, respectively) and "The data was critical in helping us maintain situational awareness of the impending flash flood threat including the anticipation of a flash flood emergency."

Extreme rainfall is notoriously difficult to predict, especially at smaller scales and under weak synoptic forcing (e.g., Weisman et al. 2008). Minutes and hours gained in forecaster confidence of an impending extreme rainfall can directly translate to real-world actions such as one-on-one briefings to emergency manager partners and use of stronger language in public products. Forecasters need tools that are rapidly updating and which express the uncertainty inherent in storm-scale processes (Heinselman et al. 2024; Stensrud et al. 2009); WoFS can serve this need. The utility of WoFS in severe storm and flash flood prediction has been documented (e.g., Jones et al. 2019; Yussouf and Knopfmeier 2019; Yussouf et al. 2020; Burke et al. 2022; Heinselman et al. 2024; Wilson et al. 2023), and transitioning it to operations can be an important step in enabling forecasters to provide more lead time for extreme local rain events.

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Data availability statement. The data used to support graphics and textual statements presented in this paper come from public-facing and readily available sources. Many are referenced as they are first encountered within the paper and include the National Weather Service Nashville Forecast Office, the Weather Prediction Center, the Environmental Modeling Center, the Tennessee 24-h Precipitation State Climate Extreme Committee, and NWS Storm Data. Warn-on-Forecast System data used here can be gleaned from the archived forecast graphics available at cbwofs.nssl.noaa.gov.

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