Historic and deadly West Virginia Floods of 23-24 June 2016

by

Richard H. Grumm
National Weather Service State College, PA 16803

1. Introduction

Heavy rains (Fig. 1) produced flash flooding and flooding in West Virginia on 23-24 June 2016. The flood waters destroyed over 1200 homes, isolated towns, and killed 23 people. The town of White Sulphur Springs was particularly hard hit by the flooding (CNN 2016; Washington Post 2016). In terms of loss of life, this was the worse flash flooding event since May 2010 (WP 2016). Rivers crested at or above record levels during the event. Total gridded rainfall (Fig. 1) approached 10 inches and spotter reports indicated rainfall amounts over 10 inches were observed.

The heavy rainfall was associated with northwesterly flow around a sharp mid- to upper-tropospheric ridge (Fig. 2). A strong ridge over the southwestern United States was producing intense early season heat wave (Grumm 2016) and a series of waves moved over the ridge into the eastern United States. Strong waves moving over ridges which can and sometime do produce strong convection are often termed “ridge roller” and “ridge runners” (Galarneau et al. 2006). Convective activity on the periphery is also known as “ring-of-fire” convection (Weaver and Nignam 2008). The 10-15 July 1995 Ridge rollers (Galarneau et al. 2006) produced a devastating severe weather event in northern New York and New England. These features are not unique and an event from Australia was presented to demonstrate the presence of ridge roller with many strong subtropical ridges. Galarneau et al (2008) showed the pattern associated with the July 1995 heat wave (see Fig. A1 Galarneau et al 2008). The case study of this heat wave discusses the strengthening jet evolution north of the ridge and the wave-packets coming over the ridge.

The patterns in which significant convective rainfall events develop are relatively well known. However, forecasting these events often is a difficult challenge. Larger scale models which do not allow for convective process often grossly underestimate “rainfall” in their quantitative precipitation forecasts (QPF). Convective allowing models (CAMS) can and often due produce significantly higher QPFs when convection is forecast though they often suffer significant temporal and spatial errors. The evolution of high resolution CAMS has improved short range QPFS (Juanzhen Sun et al. 2014). The evolution of CAM ensembles is also improving high end and extreme QPF forecasts. Currently these ensembles are expensive to run and time lagged ensembles (TLE) are often used a proxy for a true ensemble. Currently, the Global Systems Divisions (GSD) High Resolution Rapid Refresh (HRRR: Benjamin et al. 2016) is used to produce a TLE known as the HRRR-TLE. The future of warn-on-forecast for flash floods will likely be related to the evolution of improved CAMS and CAM ensembles.

The patterns in which significant convectively enhanced heavy rainfall events occur are often recognized by forecasters and generally well predicted by global models. The models and associated ensemble forecast systems can and often correctly forecast the patterns and general areas of rainfall. Though these models are challenged in their ability to produce the extreme
QPF amounts verse the relatively observed extreme rainfall. It will be shown that in this event the NCEP GEFS forecast heavy rainfall in portions of West Virginia. Several runs actually produced an extreme rainfall event relative to the model climatology. However, the QPF amounts were at best 40% of the higher end rainfall observations. The GEFS and other models forecast heavy because they forecast the pattern associated with a Maddox et al. (1979) frontal rainfall flash flood event type.

This paper will present the pattern associated with the historic and devastating West Virginia flash floods of 23-24 June 2016. This paper will also examine the forecast issues in the NCEP models and several more advanced CAMs.

2. Methods and data

The climate forecast system re-analysis (CFSR) data was used to reconstruct the pattern and the standardized anomalies associated with the event. The CFSR is used to show the pattern, which forecasters often use to gain confidence in a potential significant weather event. These same patterns, when forecast may produce high end QPF which may reinforce confidence in the forecast.

The Stage-IV rainfall data (Seo 1998) was used to estimate the rainfall over several 24 hour periods on 21 and 22 May 2016. The rainfall pattern also reveals some interesting information about the track of the 500 hPa cyclone.

Data was produced locally using archived GRIB files from the CFSRV2, GFS, GEFS, and HRRR. Other data from CAMS were provided by NCEP, GSD, and NCAR.

The Average Recurrence interval images for the GFS were produced using NOAA14 ARI data in GRIB format.

3. Results

a. The pattern

The broader 500 hPa pattern from 0000 UTC 20-25 June (Fig. 1) showed a strong 500 hPa ridge over the western United States. The 500 hPa heights at times exceeded 6000 m (Fig. 2b). The height anomalies in the ridge were on the order of +1 to +2s above normal. Farther north a series of waves eroded the ridge over eastern North America and a strong height gradient, implying a strong jet, developed on the northern and northeastern periphery of the ridge. The 250 hPa winds and u-wind anomalies (Fig. 3) show the evolution of the strong jet on the northeastern Periphery of the ridge. This pattern is very similar to the pattern presented by Galarneau et al. (2008).

The larger scale pattern appeared to suggest that the Gulf of Mexico was cut-off as a moisture source. Despite this, the flow over the ridge brought moisture as shown by the precipitable water (PW) and PW anomalies (Fig. 4). These data show a surge of high PW from the west with above normal PW anomalies over Ohio and West Virginia from about 0600 UTC 23 June through 0000 UTC 24 June 2016 (Figs. 4b-e).
The 850 hPa winds (Fig. 5) showed strong westerly flow in the plume of high PW air. The strongest flow with 850 hPa u-wind anomalies (strong westerlies) moved through the Ohio Valley and West Virginia between 0000 UTC 23 June through about 0000 UTC 24 June 2016. The 6-hour rainfall data (Fig. 6) suggest the heavy rain fell in 3 6-hour periods between 0600 UTC 23 June¹ (Fig. 5b) through 0000 UTC 24 June (Fig. 5d).

The ratio of the QPE to the 100-year 6-hour ARI (QPE/ARI) for the 5 periods is shown in Figure 7a-d and the 24 hour total is shown in Figure 7f. These data are expressed as a percentage. These days suggest that the 6-hour period ending at 0000 UTC 24 June 2016 had rainfall amounts of 80 to 125% of the 6-hour 100 year ARI ratio. The 24-hour total 100 year ARI/QPE ratios were of similar value.

b. GEFS forecasts

The NCEP Global Ensemble Forecast System (GEFS) currently has an approximate horizontal resolution of 33 km. GEFS forecasts were used here to show the pattern and the QPF forecasts from a larger scale model. It is understood that the GEFS used a convective parameterization scheme and thus is incapable of producing extreme rainfall amounts which CAMS are more likely to be capable of producing.

The GEFS correctly forecast the large ridge and attendant heat wave in the western US (not shown) and thus was able to show the plume of high PW air (Fig. 8) which moved over the Ohio. Thus, the GEFS produce QPF over the region (Fig. 9-10) though it grossly underestimated the higher end amounts and lacked the detail of the observed QPE associated with the convection which produced the rainfall.

Despite the low QPF amounts, the GEFS correctly attempted to produce the most significant QPF, relative to the GEFS internal climatology (Fig. 11), near the region where the extreme rainfall was observed.

c. GFS forecasts

The NCEP GFS approximately a 13km resolution model. It is also the model core of the current NCEP GEFS. The overall forecasts of the pattern in the GFS were similar to the GEFS and are not shown. Six GFS QPF forecasts and the ratio of the 24 hour QPF relative to the 24 hour 100 year ARI are shown (Fig. 12). These GFS forecasts correctly produced the higher QPF amounts, generally 1 to 2 inches, over portions of Ohio and West Virginia. A few model runs produced over 3 inches of QPF.

In addition to the higher QPF values, the model also produced ARI ratios (QPF/ARI) on the order of 25 to 75% of the 24 hour 100 year ARI. The wettest run shown, initialized at 1200 UTC 21 June 2016 produced 75 to 100% of the 24 hour 100 year ARI. The GFS got the general area of the higher QPF threats correct.

¹ Not the 6-hour QPE is the 6 hour period ending at the valid time. The rain between 06Z and 12Z would be ending at 12Z.
d. Convective allowing model (CAMS) forecasts

CAMS forecasts and experimental CAM ensembles were available for the West Virginia heavy rainfall event. The number of systems and data display formats and concepts were many and only a few examples are shown here. The ensembles produced from these systems had probabilistic, mean products, match-mean products, and new hydrologic products. The matched-mean\(^2\) products (Ebert 2001) were produced to highlight regions where a system might be producing heavy precipitation which an ensemble mean might wash out.

An example match-mean product from the HREF (Fig. 13) shows the 24 hour QPF ending at 1200 UTC 24 June from the HREF initialized at 1200 UTC 23 June 2016. The HREF forecast a broad area of over 2 inches from Ohio into West Virginia with a region of over 7 inches (175 mm) over southwestern West Virginia with locally higher amounts. Relative to verification (Fig. 1) this was extremely promising and successful forecast.

A comparison of 6 different products is shown in Figure 14. These data include the QPE from the MRMS data set (NSSL QPE), calibrated ensemble output from the GEFS, the NCEP SREF, an internal NCEP ensemble, the NAMRR, and the SEFX. It is encouraging that all 5 systems showed the heavy rainfall in and around West Virginia. Each system had its strength and weakness, but properly used these data showed great promise in capturing the potential for extreme rainfall.

Forecasts of the probability of inch or more of accumulated QPF within 25-km from the 3km NCAR ensemble (Fig. 15) and the probability matched mean 21-hour QPF valid at 2100 UTC (Fig. 16) show that the NCAR ensemble was able to forecast the times of heavy rainfall and produce extreme rainfall in close proximity to where the heavy rainfall was observed. Similar to other CAMS during this event the NCAR ensemble probability matched mean products showed clear signals of an extreme rainfall event.

The GSD HRRRV3 time lagged ensemble (HRRR-TLE → hurdle) probability of 3 inches or more QPF in 6-hours is shown in Figure 17. Similar to the NCAR ensemble the HRRR-TLE indicated the potential for in excess of 3 inches of rainfall in 3 hours over West Virginia. Though not shown, several members had greater than 6 inches but lower probabilities and the signal was absent in most ensemble production cycles. Individual HRRRV3 members like the NCAR ensemble also showed significant QPF amounts (not shown) with several HRRRV3 cycles showing over 6-8 inches for the 24 hour period covering the entire event.

4. Conclusions

A large scale frontal system with flow over a strong subtropical ridge (Grumm 2016) set up a nearly classic Maddox frontal rainfall event (Maddox et. al. 1979) over the Ohio Valley on 23 June 2016. The larger scale pattern was relatively well predicted in the NCEP global forecast.

\(^2\) Probability matched mean—combines the spatial pattern of the ensemble mean QPF with the frequency distribution of the rainfall rates to provide a more realistic ensemble rainfall intensity forecast (Ebert 2001)
systems and thus these models showed a signal for the potential rain event. However, lacking the ability to produce convection these models failed to produce the QPF amounts relative to observed extreme rainfall. Several CAMS produced significantly higher QPF amounts in close proximity to the general locations where the heavier rainfall was observed. The probability matched mean products showed great promise in forecasting future extreme rainfall events.

The NCEP GEFS (Fig. 11) correctly forecast the overall pattern and thus produced lift, as indicated by its QPFs in the correct geographic location. However; relying on convective parametrization schemes and the coarse resolution; the GEFS was incapable of forecasting the extreme rainfall as observed during this event. Despite these limitations, comparing the GEFS QPF to the internal GEFS QPF climate (M-Climate) it is clear that the GEFS was producing an extreme rainfall event within its climate space. It takes some experience for correctly use the GEFS and GEFS M-climate to identify potential extreme QPF events. These data, based on where the model has both lift and moisture, can indicate where in a specific pattern the ensemble thinks the QPF will occur. In this event it was on the warm side of the ensembles frontal boundary (based on 850 hPa temperatures and PW fields not shown).

The NCEP GFS (Fig. 12) also produced a significant rainfall event in the Ohio valley. These data were displayed using the QPE/ARI ratios. Relative to the observed QPE (Fig. 7) the GFS had the correct idea of a heavy rainfall event and a weak signal in the QPF/ARI ratios showing ratios in the 50 to 70% of a 24-hour 100 year rainfall event. The observed QPE/ARI ratios reached as high as 125 to 150% of the 24-hour 100 year ARI in some areas of West Virginia. The GFS like the GEFS had a useful signal but could not generate the QPF relative to observed rainfall. The CAMS which are not as widely used had a better signal. The key point here is that the NCEP GFS was able to correctly forecast the larger scale area favorable (Fig. 12) for heavy rainfall. But like all models which cannot produce convection but rely on CPS’s, it was unable to forecast the higher amounts observed.

The CAMS shown here including the HREF, HRRR, and NCAR Ensemble all showed great promise for the long term forecasting of extreme rainfall events. Using probability matched mean products these forecast systems correctly produced extreme rainfall amounts relative to forecast systems such as the GFS and GEFS. They also produced some extreme rainfall amounts in the general geographic area where it was observed. This event was strongly forced by a strong frontal system and sharp subtropical ridge. A strong 250 hPa jet was also present. Thus the overall success during this event may be related to the combination of the convective allowing systems and the stronger background synoptic signal. It is unclear how these systems will perform in weaker more convectively based events. These systems show great potential in improving flash flood forecasting the 18 to 30 hour window when there is strong forcing and the system has upright convection.

Short-term forecasting of this event indicated that there was considerable training along a weak quasi-stationary frontal boundary. This training contributed to the heavy rainfall and combined with flow into the mountainous of West Virginia, the orography served to focus the extreme rainfall amounts where 200 to 250 mm of rain was observed. During this phase of the event, the rapid refresh models, like the HRRR had an advantage. As the event wound down on 24 June
2016, the HRRRV1 and HRRRV2 limited convection in and around the rain cooled areas of West Virginia\textsuperscript{3}. CAMS initiated during the ongoing convection at 0000 and 0600 UTC 24 June had too much QPF and a potential lingering rainfall threat in West Virginia. Correctly leveraging the power of rapid updating and CAMS could help provide improved short-term forecasts as the event reaches its peak and equally aid in better forecasting when the threat for heavy rainfall has passed.

5. Acknowledgements

The Pennsylvania State University for real-time data access. Matt Pyle (NCEP/EMC) for HREF forecasts in image format, Curtiss Alexander for information on the GSD HRRR and facilitating use of the GSD HRRR-TLE website. Thanks to NCAR for access to their high resolution ensemble. The Albany MAP for insights and information on the flood.

6. References


CNN, 2016: West Virginia floods devastate 1,200 homes, many lives, 28 June 2016 and similar stories.


\textsuperscript{3} Personal observation and discussion during the 2016 FFAIRE at NCEP on 24 June.

**WP 2016:** West Virginia flood was 'one in a thousand year event,' Weather Service says; more heavy rain forecast. Washington Post June 27 1969.

Figure 1. Stage-IV estimated quantitative precipitation for the 24 hour covering the rainfall. Data are in mm as indicated in the color bar. Return to text.
<table>
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<th>County</th>
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Figure 2. Climate Forecast System re-analysis data of 500 hPa heights and 500 hPa height anomalies in 24 hour increments from a) 0000 UTC 20 June 2016 through f) 0000 UTC 25 June 2016. Heights are every 60 m and standardized anomalies are as in the color bar in standard deviations from normal. Return to text.
Figure 3. As in Figure 2 except for the CFSR 250 hPa wind vectors and the u-wind anomalies (shaded) in 6-hour increments from a) 0000 UTC 23 June 2016 through f) 0600 UTC 24 June 2016. Return to text.
Figure 4. As in Figure 2 except for precipitable water (mm) and precipitable water anomalies (sigma) in 6-hour increments from a) 0000 UTC 23 June 2016 through f) 0600 UTC 24 June 2016. Return to text.
Figure 5. As in Figure 3 except for CFSR 850 hPa wind vectors and the u-wind anomalies (shaded) in 6-hour increments from a) 0000 UTC 23 June 2016 through f) 0600 UTC 24 June 2016. Return to text.
Figure 6. As in Figure 1 except for Stage-IV QPE in 6 hour increments from a) 0600 UTC 23 June through e) 0600 UTC 23 June and the summation of the 5 times in panel f. Values in mm based on the color key. Return to text.
Figure 7. As in Figure 6 except for the ratio of the 6-hour Stage-IV QPE to the 6-hour 100 year recurrence interval data a-e and relative to the 24 hour 100 year recurrence interval in panel f. Values of the QPE/ARI ratio are expressed as a percentage of the ratio as per the color bar. Return to text.
Figure 8. NCEP GEFS forecasts of precipitable water (mm) and precipitable water anomalies valid at 0000 UTC 24 June 2016 from 6 successive GEFS forecasts initialized at a) 0000 UTC 19 June, b) 0000 UTC 20 June, c) 0000 UTC 21 June, d) 0000 UTC 22 June, e) 0000 UTC 23 June, and f) 1200 UTC 23 June 2016. Return to text.
Figure 9. As in Figure 8 except for GEFS forecasts of the probability of 25 mm or more QPF for the 24 hour period ending at 0600 UTC 24 June 2016. Return to text.
Figure 10. As in Figure 9 except for GEFS mean QPF and each members 50 mm contour if forecast. Return to text.
Figure 11. NCEP GEFS 24 hour QPF valid at 0600 UTC 24 June 2016 (inches) and the forecast ensemble mean QPF relative to the GEFS internal 24 hour QPF climatology. Return to text.
Figure 12. NCEP GFS forecasts of QPF (contours in inches) and the ratio of the QPF to the 24 hour 100 year ARI values as a percentage (shaded). All forecasts are valid at 0600 UTC 24 July 2016 and are initialized at a) 0000 UTC 21 June, b) 1200 UTC 21 June, c) 0600 UTC 22 June, d) 1200 UTC 22 June, e) 1800 UTC 22 June, and f) 0000 UTC 23 June 2016. Contours are in inches showing each full inch of QPF.
Figure 13. NCEP HREF forecasts initialized at 1200 UTC 23 June 2016 showing 24 hour QPF for the 24 hour period ending at 1200 UTC 24 June 2016 showing top) the matched mean QPF and bottom) the probability of 6 inches or more QPF in 24 hours. Return to text.
Figure 14. The verification and forecasts of QPE and QPF valid at 1200 UTC 24 June 2016. Data include a) MRMS QPE, b) Calibrated ensemble mean QPF from the NCEP GEFS, c) NCEP SREF mean QPF, d) NCEP internal ensemble blend, e) NCEP NAMRR, and f) the SSEFX probability match-mean QPF. Refer to text.
Figure 15. **NCAR** 10 member 3km Ensemble initialized at 0000 UTC 23 June 2016 showing the hourly probability matched mean of 1 inch or more QPF for the 1 hour periods ending 20 and 22 UTC 23 June 2016. The second yellow color appears to be bleached out in these images. Return to text.
Figure 16. As in Figure 15 except for the matched mean accumulated rainfall (mm) for the period ending 2200 UTC 23 June 2016. Values in inches as per the color bar. Return to text.
Not Used  http://www.emc.ncep.noaa.gov/mmb/mpyle/href_ffair/wvcase/

Python linkable address for wget for loops:
http://rapidrefresh.noaa.gov/hrrrtle/for_web/hrrr_tle_jet/2016062306/full/pqpf6_300_f16.png
Figure 17. Experimental HRRRV3 time-lagged ensemble from 23 June showing the probability matched QPF of 3 inches or more QPF within 40 km of the location. Upper panel is the 0600 UTC forecast ending at 0900 UTC and the lower panel is the 0000 UTC 23 June forecast valid at 1300 UTC. Return to text.