Convective Heavy rainfall event of 23 July 2013

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Abstract:
A record rain event affected southern Lebanon County on 23 July 2013. Most of the rain fell in a 3-hour period and the estimated 3-hour rates exceed the value for a 1000 year return period. The 6-hourly amounts were slightly lower than those for a 1000 year return period. The heavy rain produced flooding in the affected area.

The pattern over much of the Mid-Atlantic region contained all the ingredients for a heavy rainfall event including a trough to the west, above normal precipitable water, and strong low-level southerly flow. Early in the event the atmosphere was unstable and late afternoon CAPE values were above 1200JKg-1supporting deep moist convection. Once the thunderstorms developed, the surface based CAPE rapidly decreased.

The numerical guidance indicated the potential areas of heavy rainfall. The focus of the locally heavy rainfall was related to model terrain features and locations where model convective parameterization schemes worked to reduce instability in the model atmospheres. Thus some of the guidance was of value in anticipating the potential for heavy rain; the models were unable to focus on the correct regions. The rapidly updated RAP guidance produced short-range forecasts which provided better clues in both the mass and precipitation fields.

1. Overview

Slow moving showers and thunderstorms brought heavy rainfall and flooding to southeastern Pennsylvania on 22 July 2013 (Fig. 1). The National Weather Service Cooperative Observation Program (COOP) site in Lebanon received 178.05 mm (7.01) in from the event and the local COCORAHS site had 178.56 mm (7.03 in) with most of the rain falling in about a 4-hour period from 2300 UTC 22 July through 0300 UTC 23 July 2013. Hourly data suggest the heavy rain began around 2200 UTC 22 July 2013 and ended shortly after 0300 UTC 23 July. The heaviest 3-hour rain fell from 0000 through 0300 UTC on 23 July 2013. The stage-IV data (Fig. 2) implied that the 6-hour period from 0000 through 0600 UTC 23 July 2013 was the period of heaviest rainfall. The rain produced flash flooding across southern Lebanon County, including the city of Lebanon.

The showers and thunderstorms developed in an area of deep moisture, with precipitable water of 50mm (Fig. 3c), ahead of an approaching short-wave at 500 hPa (Fig. 3a). There were strong low-level southerly winds (Fig. 3b) in the moisture rich air ahead of the 500 hP and surface waves (Fig. 3). Some of the basic ingredients (Doswell et al 1996) favoring heavy rainfall and flash flooding were in place over the Mid-Atlantic region. The basic ingredients include precipitation efficiency and an area where the high rainfall rates can be maintained.

The precipitation efficiency *"law"* requires that a sustained inflow of moisture is available to replace the moisture released by precipitation. The continued influx of moisture into the precipitating system is likely why moisture flux (MFLUX) has been used for identifying larger scale heavy rainfall events. For more intense rainfall rates, deep moist convective potential is a critical ingredient. Sustaining heavy rainfall rates relates to Chappell's rule "*it rains the most where it rains the hardest the longest*" (Chappell 1986). This rule requires slow moving rain bands or training convective elements (Doswell, 1996; Aylward and Dyer 2010).

Aylward and Dyer (2010) used the North American Re-analysis data and the multi-sensor precipitation data to identify heavy rainfall in the eastern United States. The results were similar to those found in previous studies (Schmacher and Johnson 2006) which showed that many heavy rainfall events occurred in a synoptically forced environment but most of these events had embedded convection which produced the heavier rainfall. The synoptically forced events occurred in patterns similar to those identified by Junker et al (1999) and Maddox and Doswell (1982) and recently by Bodner et. al (2012). Key features typically included a trough to the west, a plume of high precipitable water (PW) air into the region, and a low-level jet. Bodner et al (2012) showed the traditional patterns for heavy rainfall including the value of standardized anomalies in identifying potential heavy rainfall events.

The mean PW in Aylward and Dyer (2010) was around 37.1 mm in synoptically forced events and around 42.2 mm for weaker events which they classified as 850 hPa trough-low events (850TL). The pattern for these 850TL included a broad large scale ridge in the mid and upper troposphere, a more traditional warm season convective pattern. They did not examine standardized anomalies of the PW field in there events which has been shown as an effective technique in identifying significant weather events (Stuart and Grumm 2009;Grumm 2011; Junker 2009) and identify potential extreme rainfall events.

This paper will examine the heavy rainfall that affected southern Lebanon County Pennsylvania during the evening hours of 22 July 2013 into the early morning hours of 23 July 2013. The focus is on the pattern in which the rain fell; forecasts of the potential for heavy rain fall; and the character of the rain to include the duration and location of the heavier rainfall amounts. These rainfall data were compared the return periods for heavy rain in the affected region.

2. Methods and Data

The large scale pattern was constructed using the GFS 00-hour forecasts which were compared to the standardized anomalies for key fields as described by Hart and Grumm (2001). For detailed perspectives hourly 13km RAP analysis data were used, the images shown here are increments of 2-hours. All gridded model and forecast data was plotted using GrADS (Doty and Kinter 1995).

Forecasts from the NCEP NAM, GFS, SREF, and RAP were examined. Each of these systems correctly predicted the overall pattern and are not shown. The focus here is on the quantitative precipitation forecast (QPFs) to see what clues these forecast systems provided for the potential for heavy rain.

The NMQ Q2 site was used to extract 1-hourly, 3-hourly, and 6-hourly rainfall estimates which could be compared to the historic rainfall return period data. The larger scale rainfall data were plotted using the mulit-sensor Stage-IV data (Seo 1998).

The evolution of the convection was conducted on AWIPS using archived radar and rainfall estimates collected in real-time at the National Weather Service Office in State College, Pennsylvania.

The return period for the rainfall in 10,100 and 1000 year intervals for this event and comparative events was obtained from the NOAA Atlas-14 data.

3. Pattern Overview

The larger scale patter at 23/0000 UTC (Fig. 3) showed an open 500 hPa trough and surface low to the west classifying this system as an Upper-level trough (ULT) system (Aylward and Dyer 2010). Over southeastern Pennsylvania and New Jersey the PW was over +2 to +3σ above normal and about 50mm, well above the mean value for ULT systems identified by Aylward and Dyer (2010). The 13km RAP showed that the high PW air over southern Pennsylvania (Fig. 4) remained in place from 22/2000 UTC through 23/0600 UTC peaking near 60mm and +3 to +4σ above normal between 23/0200 and 23/0400 UTC (Fig. 4e). The 850 hPa moisture flux (Fig 5) showed high values of MFLUX with the MFLUX peaking between 23/0000 and 23/0400 UTC.

The large scale pattern showed the ingredients were in place over much of eastern Pennsylvania and New Jersey for heavy rainfall. The MFLUX and wind fields in the RAP slowly converged toward southeastern Pennsylvania as the region of the strongest local forcing (Fig. 4 & 5). Another necessary ingredient was the evolution of convection. The RAP analysis of convective available potential energy (CAPE:Fig. 6) showed high CAPE over much of eastern Pennsylvania at 22/2000 UTC to get the initial updraft cores to develop. During the period of heavy rainfall, primarily after 23/0000 UTC, the RAP showed lowered surface based CAPE. The key was the high CAPE before the onset of the heavy rainfall to allow convection to develop and feed of the deep southerly flow.

4. Quantitative Precipitation Forecasts

The larger scale pattern was generally well predicted by the larger scale forecast systems including the NAM, GFS, and SREF and these data are not reproduced here. The focus is on the QPFs produced by the GFS (Fig. 7), NAM (Fig. 8), RAP, (Fig. 9) and the SREF (Fig. 10). The GFS predicted the potential for over 25 mm of QPF for portions of Pennsylvania and at times had locally higher amounts (Fig. 7c & 7f) in excess of 75 mm. and each of the 6 forecast cycles shown indicated areas of in excess of 50 mm of QPF. Several of these GFS forecasts had the higher amounts linked to the model terrain feature comprising the Catskill and Pocono mountains in northeastern Pennsylvania and southeastern New York. The focused areas of heavy rain also suggest that the model convective parameterization scheme (CPS) was focusing the heavy rainfall.

Comparative NAM forecasts were less robust (Fig. 8) than those produced by the GFS and showed any rainfall displaced well south of the GFS forecasts. The shorter range RAP forecasts (Fig. 9) showed that the RAP produced locally heavy rainfall amounts near the time window of the Lebanon flood over 100mm at times, though well north. The RAP clearly showed a focus in shorter range forecasts of rainfall over 50 mm along the leading edge of the mountains of eastern Pennsylvania. Perhaps further evidence of the value of high resolution and rapidly updated models at shorter ranges from more convectively driven heavy rainfall events.

The NCEP SREF (Fig. 10) showed a low probability of in excess of 25 mm or rainfall. The 18-hour period ending 1200 UTC 23 July improved the probabilities (Fig. 11), but placed the higher probabilities well west of the area where locally rainfall exceeded 125 mm.

5. Rainfall

The overall pattern of rainfall (Fig. 1) and the 6-hour intervals (Fig. 2) indicated that the heavy rain in most areas fell in relatively short periods of time. Using the NMQ Q2 hourly, 3-hourly and 6 hourly data were extracted to compare to the NOAA Atlas-14 precipitation point frequency

(PF) for return periods. Table 1 shows the data for the Lebanon Flood. The 4.40 and 7.35 rainfall in 3 and 6 hours respectively indicate that the 3-hour amounts exceed the 100 year return period and that the 6-hour amounts were within 0.04 inches of the 1000 return period. It should be noted that the two observed locations received 7.01 and 7.03 inches of rainfall respectively. The radar adjusted estimates in Table 1 and the NMQ image (Fig. 12) were adjusted for observations.

S Lebanon Cty	Observed	1 Year PF Estimate	10 Year PF Estimate	100 Year PF Estimate	1000 Year PF Estimate	Time Window
3 Hour	4.40	1.43	2.55	3.90	5.54	2200-0100 UTC 22-23 July 2013
6 Hour	7.35	1.77	3.15	4.98	7.39	2100-0300 UTC 22-23 July 2013

Table. 1. Lebanon City estimated 3 and 6 hourly rainfall amounts compared to the NOAA Atlas-14 volume 2, 10, 100, and 1000 year return periods. The observations were estimated from NMQ Q2 data. The 3-hour window 2200 to 0100 UTC and the 6-hour window was 2100 to 0300 UTC. Return to text.

The NMQ Q2 data show that the rainfall that the event was a relatively enduring event with heavy rainfall spanning 6-hours[1]. Unlike other recent events in the Mid-Atlantic region, this was a relatively long precipitation event.

Beech Creek Basin	Observed	1 Year PF Estimate	10 Year PF Estimate	100 Year PF Estimate	1000 Year PF Estimate	Time Window
3 Hour	5.43	1.18	2.06	3.15	4.52	2100-0000 UTC 27-28 June 2013
6 Hour	5.43	1.47	2.52	3.83	5.46	1900-0100 UTC 27-28 June 2013

Table 2. As in Table 1 except for Beech Creek 27-28 June 2013.

Comparative rainfall data were extracted for the record the events including Beech Creek, Dubois, and Philadelphia. At Beech Creek data suggested that the 3-hourly rainfall amounts exceeded the 1000 year return period and approached the 1000 year return period for the 6-hour amounts. It should be noted that it did not rain for 6-hours at Beech Creek. The Dubois data showed slightly more extreme rainfall rates and the 6-hour rainfall was well above the 1000 year return period. Similar to Dubois, the Philadelphia rainfall data (Table 4) for 27-28 July crushed the 1000 year return period rainfall for both the 3 and 6-hour intervals.

[1] The scales for the colors are white for 3 and 6 inches in both images.

6. Summary

The 50mm PW value was considerably higher than the mean value of 37.1 mm found by Aylward and Dyer (2010). The more significant issue may have been that the PW was nearly +3σ above normal. The RAP data showed that the high PW air remained in place thus providing constant deep moist air to allow convective elements to feed of constant moisture. The strong southerly flow likely contributed to training and back building convective elements. The winds, persistent moisture and modest CAPE implied all the key ingredients were in place for heavy rainfall and upright convection (Doswell et al 1996).

Dubois Area	Observed	1 Year PF Estimate	10 Year PF Estimate	100 Year PF Estimate	1000 Year PF Estimate	Time Window
3 Hour	5.70	1.19	2.10	3.22	4.61	1700-2000 UTC 27 June 2013
6 Hour	6.27	1.44	2.51	3.85	5.54	1400-2000 UTC 27-28 June 2013

Table 3. As in Table 1 except for Dubois 27-28 June 2013.

KPHL	Observed	1 Year PF Estimate	10 Year PF Estimate	100 Year PF Estimate	1000 Year PF Estimate	Time Window
3 Hour	5.95	1.56	2.73	4.00	5.35	1900-2200 UTC 27 July 2013
6 Hour	7.72	1.93	3.37	5.10	7.14	2000-0100 UTC 27-28 July 2013

Table 4. As in Table 1 except for Philadelphia 27-28 July 2013.

The QPFS in general showed that the NAM produced the lowest QPF amounts and was clearly of limited operational value in this case. The GFS and SREF offered clues that there could be rainfall event, though focusing on where much more than 25 mm of rain would fall was an arduous task. The GFS showed a bias toward terrain features and clearly with point maximum indicated a CPS issue related to the potential higher end QPFs. The SREF signal was of some value as was the GFS signal. The geographic region to be affected by the observed heavy rainfall was beyond the GFS and the SREF to predict. The take-way information from the GFS was the potential for heavy rainfall from southern New York to the Maryland border and that some locations could receive 50 to 75mm or more QPF. The SREF showed a higher potential focused more in Pennsylvania, though forecasts of 50 mm or more at any point (not shown) were generally under a 20% outcome. This is a large region for a flash flood watch and is perhaps a case where forecast needed to indicate that persistent thunderstorms could produce locally heavy rainfall and flooding.

Value of RAP hourly data is demonstrated here as the PW values and standardized anomalies were higher than in 3-hourly GFS data. Experience in flood and severe weather events indicates that these high resolution datasets and short-term forecasts from these datasets can be of value in identifying potential areas of heavy rain and severe weather. The RAP short range QPF fields also showed a signal which was closer to where the rain fall was observed and showed impressive 8-hour rainfall amounts over portions of Pennsylvania and New York. Ultimately, the RAP too could not get the correct geographic area.

Until rapid updated models of higher resolution are available in real-time and storm scale ensembles evolve, the key to these events is knowing the pattern and the potential. Once the convection develops monitoring the situation and then issuing short-fused warnings with limited lead-times is the best overall approach events of this type. The longer range outlook phases for isolated flood events of this nature with the current tools are likely to crude and outlook products would likely be too broad in scope and area to be effective.

The NOAA Atlas-14 data showed that this event and the two events observed 27 June and the Philadelphia event all exceeded the 3-hour rainfall amounts for a 1000 year events and all but the Lebanon event exceeded the return period for a thousand year event. These extreme rainfall events were all associated with deep moist convection. This folds nicely into the work by Schumacher and Johnson (2006) showing the most high end rain events, including those with strong synoptic forcing are convectively driven. Each of the events listed in Tables 1-4 were unique and each was not particularly well predicted by numerical guidance. Each produced local flooding and flash flooding. .

7. Acknowledgements

COOP observers for reports of rainfall data and EM personal for information related to flooding. The NMQ Q2 site for access to data and references.

8. References

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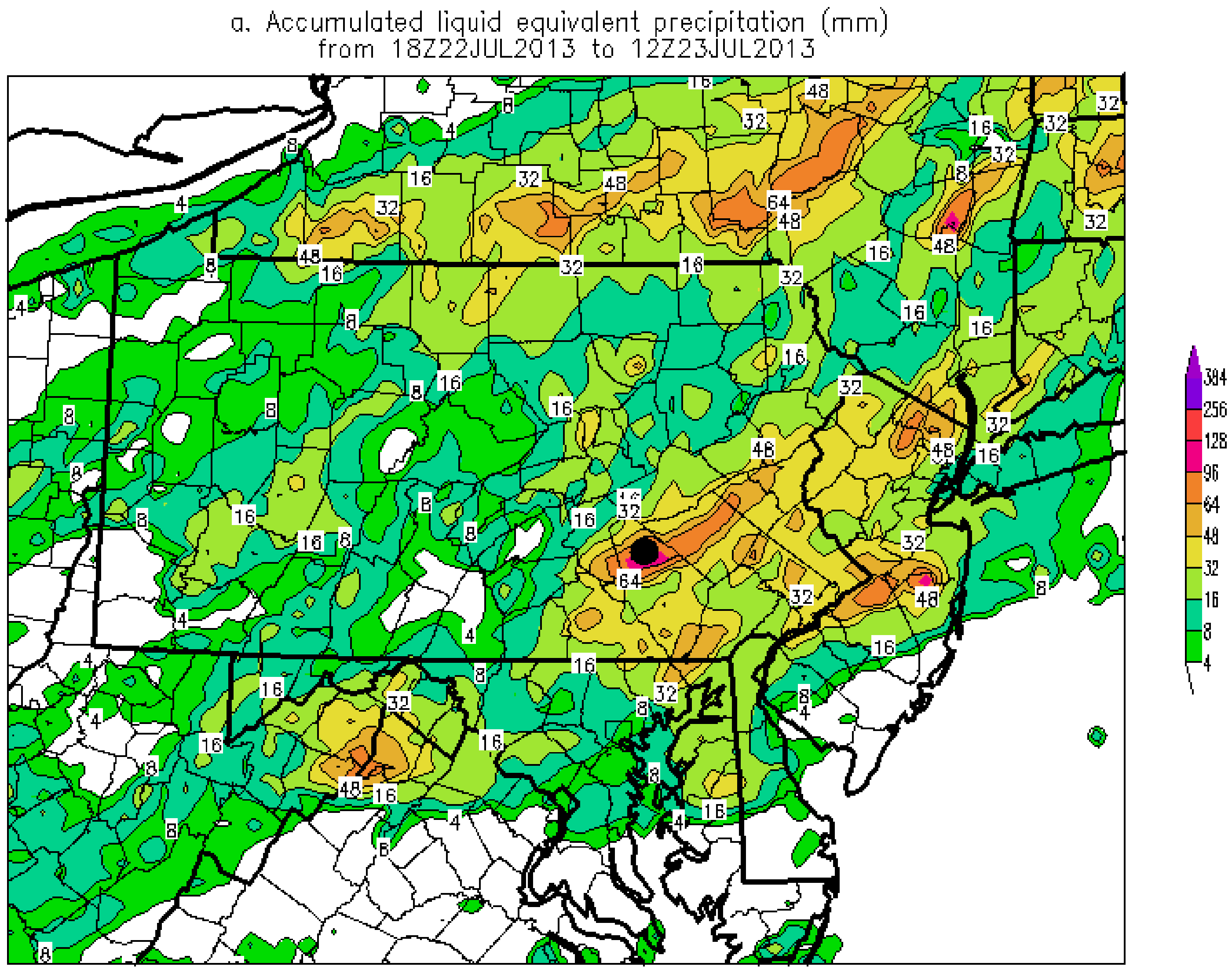

Figure 1. Stage-IV gridded rainfall data for the 24 hour period ending at 1200 UTC 23 July 2013. Return to text.

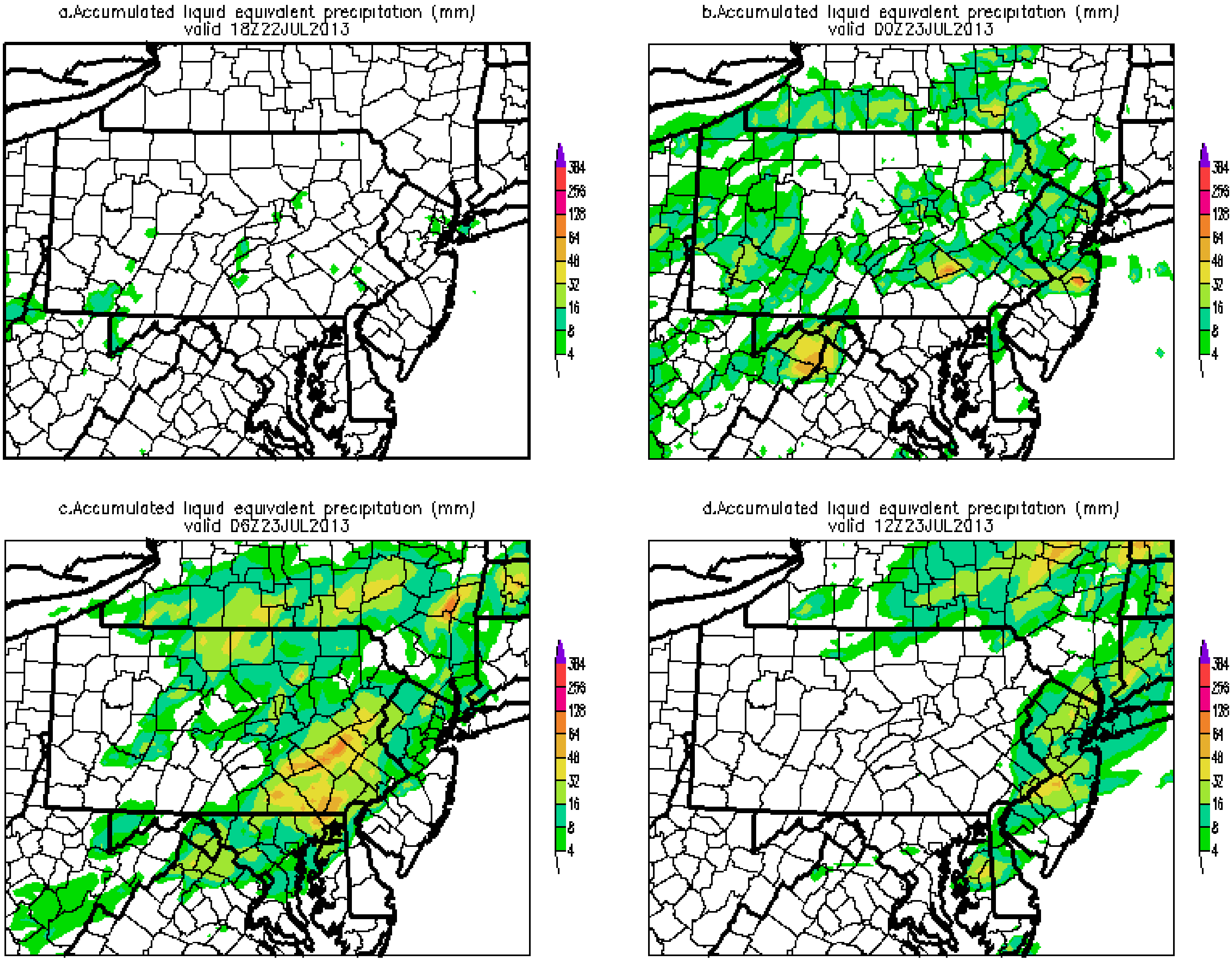

Figure 2. As in Figure 1 except for the rainfall in 6-hour increments for the periods ending at a) 1800 UTC 22 July, b) 0000 UTC 23 July, c) 0600 UTC 23 July and d) 1200 UTC 23 July 2013**. Return to text.**

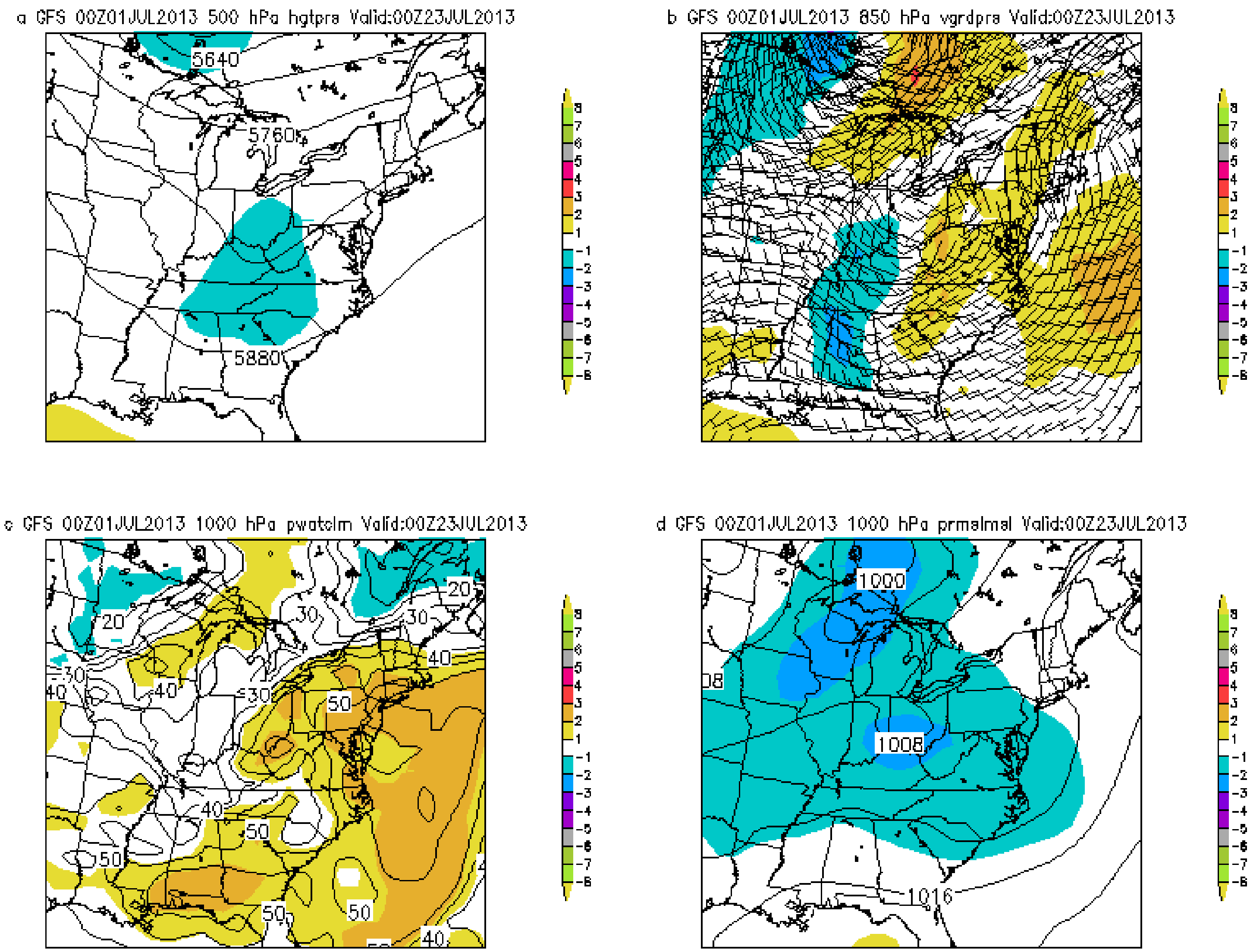

Figure 3. GFS 00-hour forecasts valid at 0000 UTC 23 July 2013 showing a) 500 hPa height and height anomalies, b) 850 hPa winds and wind anomalies, c) precipitable water and precipitable water anomalies, and d) mean sea-level pressure and pressure anomalies. **Return to text.**

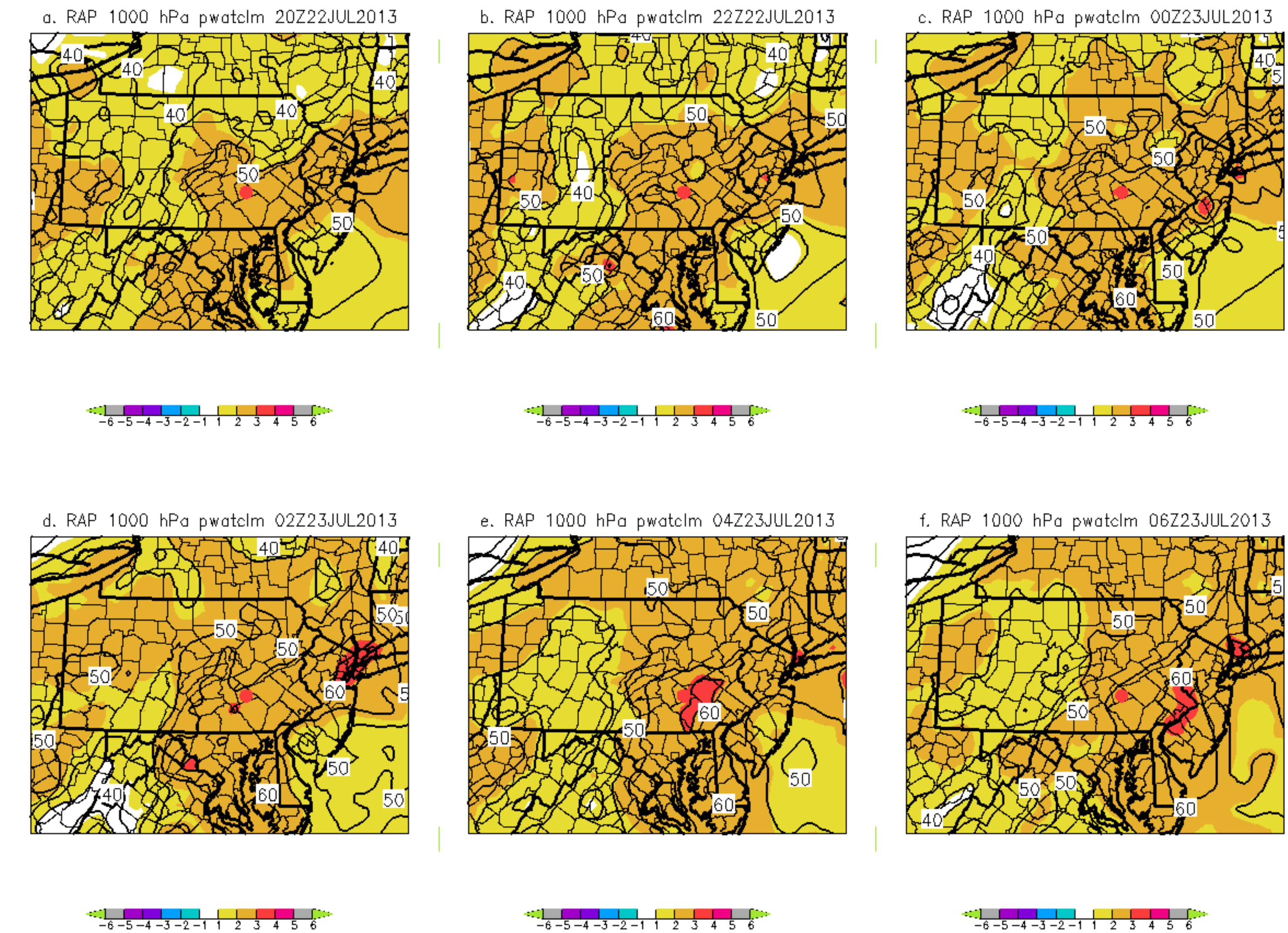

Figure 4. RAP 13km analysis of precipitable water (mm) and precipitable water anomalies in 2-hour increments from a) 2000 UTC 22 July 2013 through f0 0600 UTC 23 July 2013. Red dot is near Lebanon, PA where over 125mm of rain was observed. Return to text.

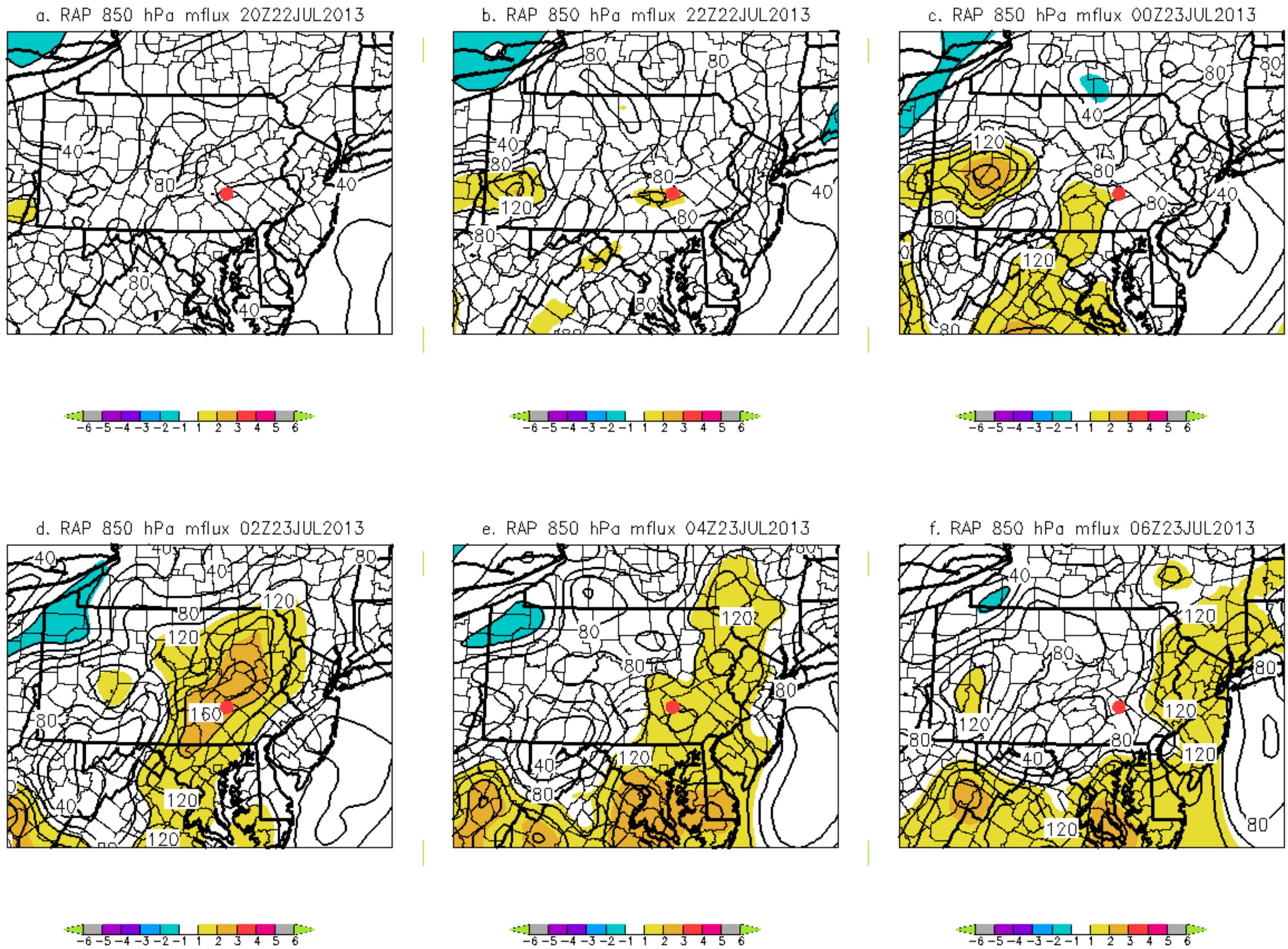

Figure 5. As in Figure 4 except for RAP 850 hPa moisture flux and moisture flux anomalies. **Return to text.**

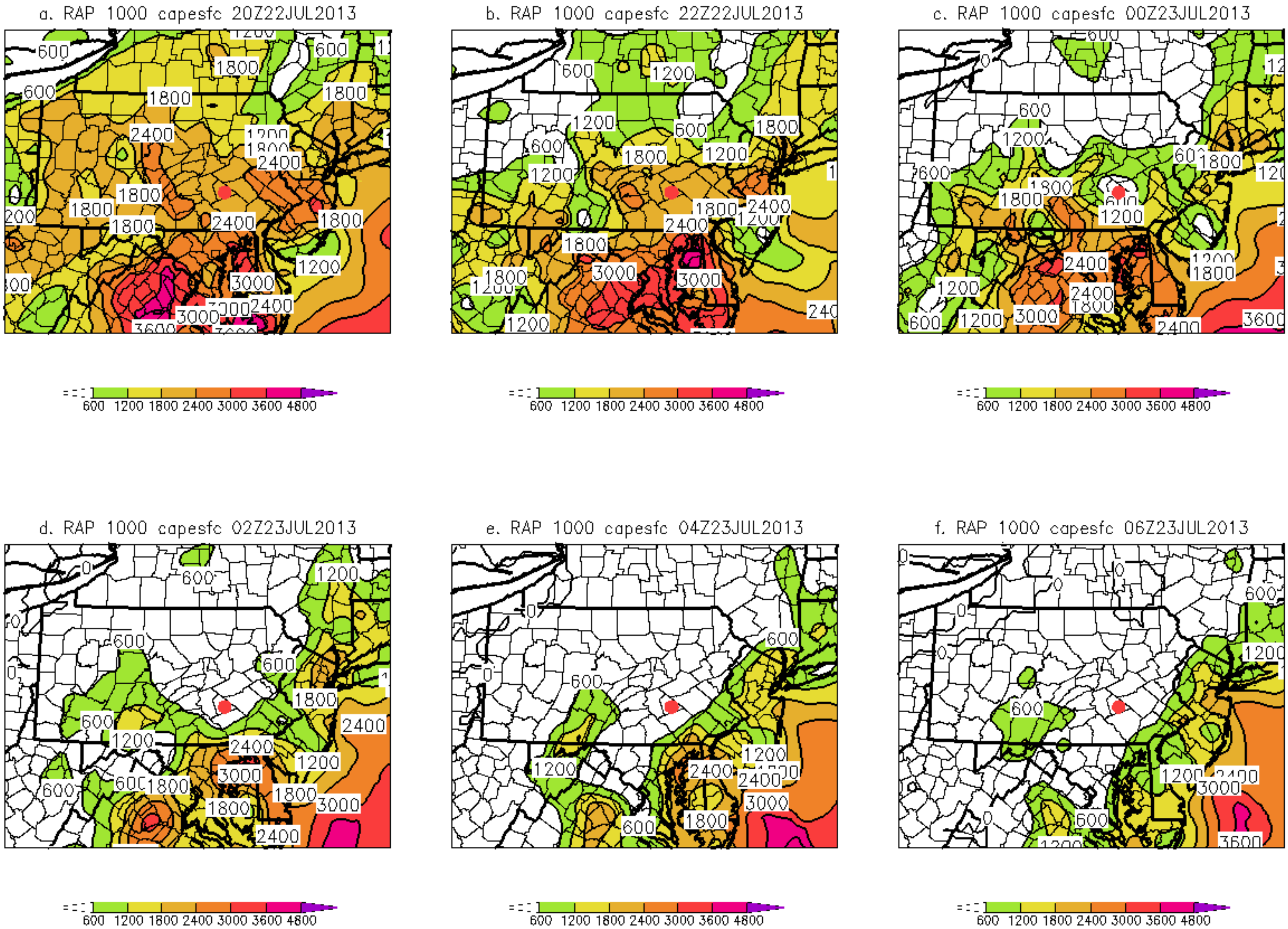

Figure 6. As in Figure 5 except for RAP CAPE (JKg-1) in contours of 600JKg-1 with shading as in the color key. **Return to text.**

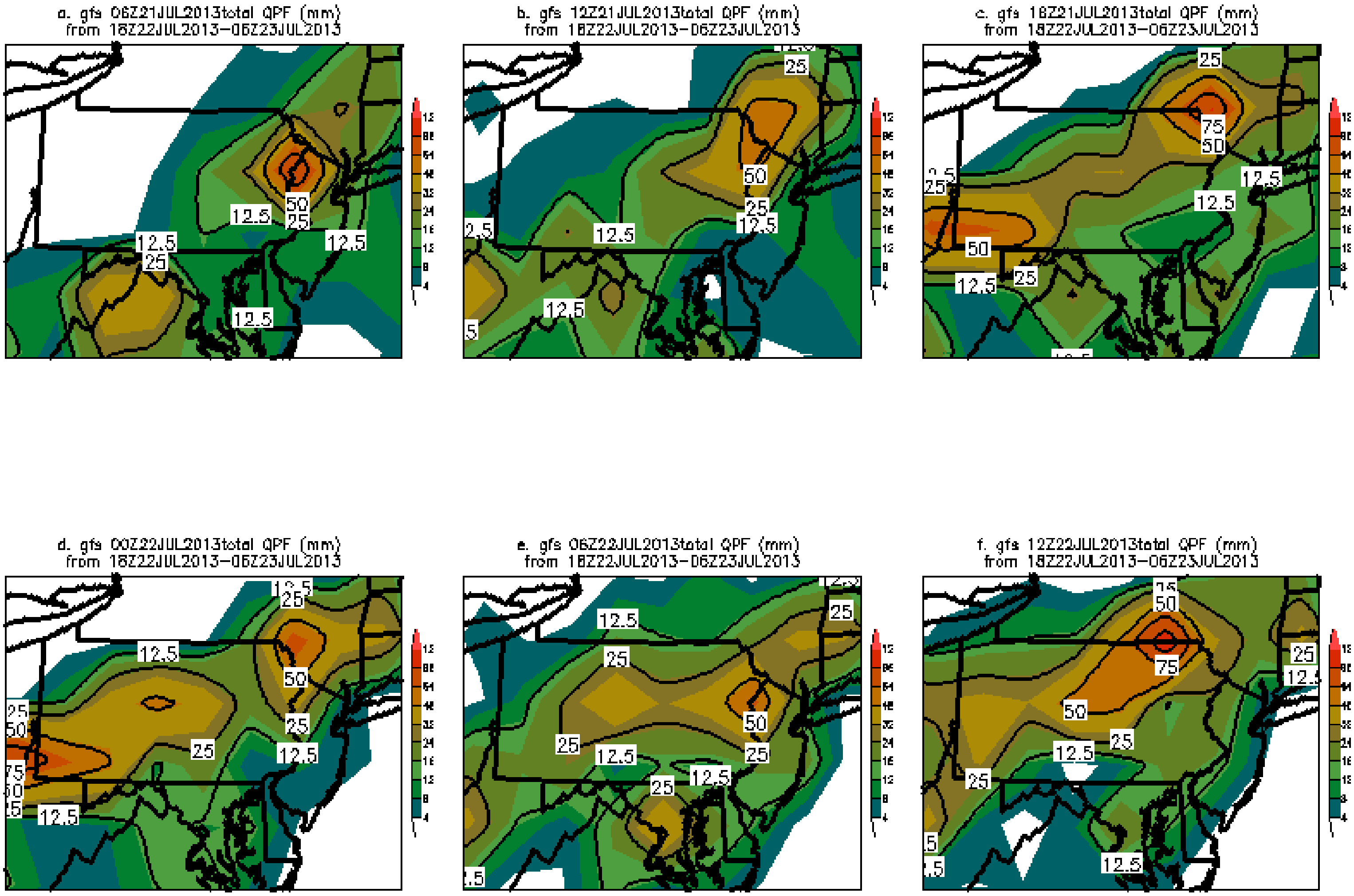

Figure 7. NCEP GFS quantitative precipitation forecasts valid for the 12 hour period ending at 0600 UTC 23 July 2013 from forecasts initialized at a) 0600 UTC 21 July, b) 1200 UTC 21 July, c) 1800 UTC 21 July, d) 0000 UTC 22 July, e) 0600 UTC 22 July, and f) 0000 UTC 22 July 2013. Values in mm shaded as per color bar and contoured every 12.5, 25, 50, 75, 100 and 125 mm. [Return to text.]

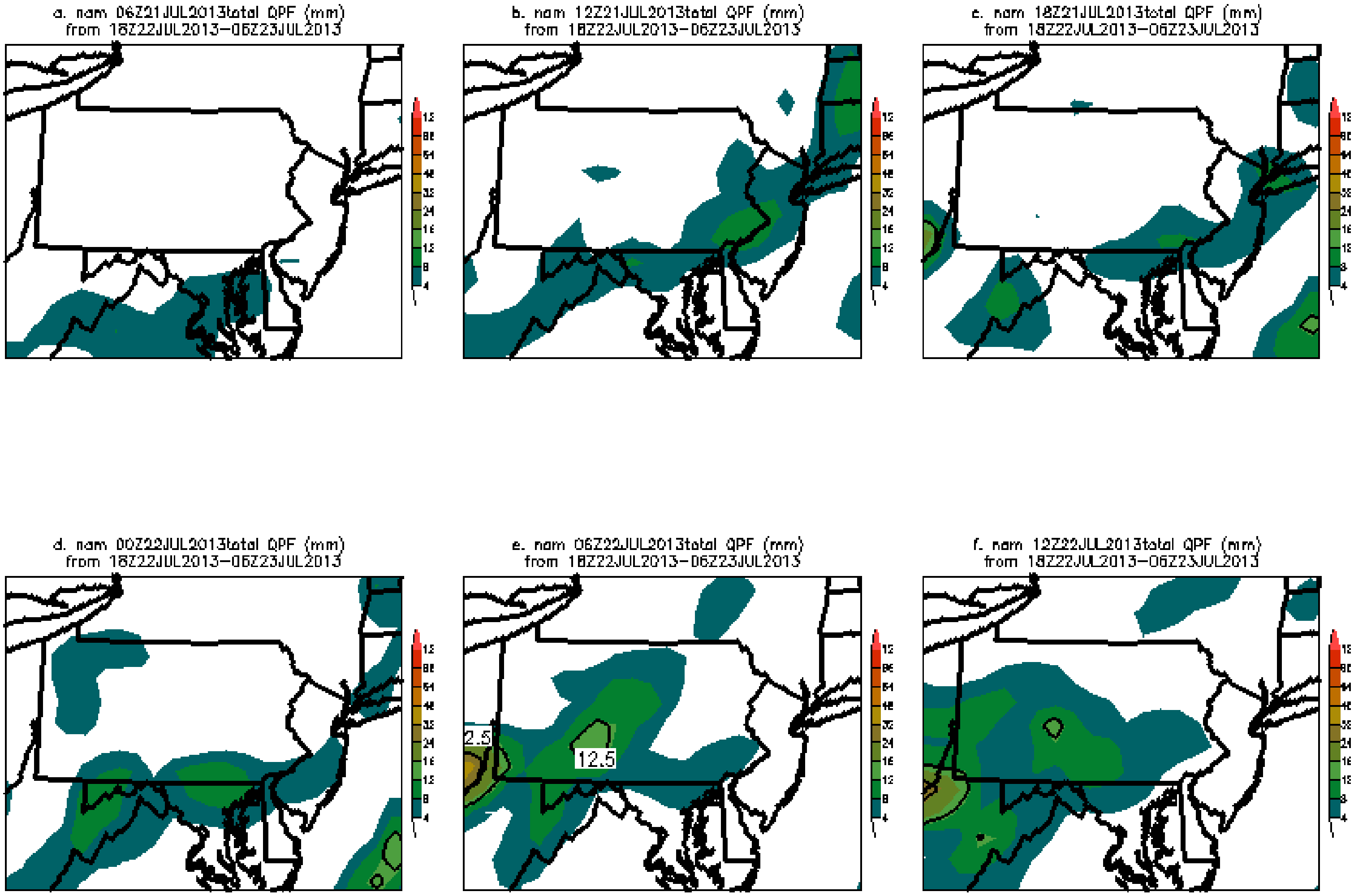

Figure 8. As in Figure 7 except for the NCEP 12km NAM. **[Return to text.]()**

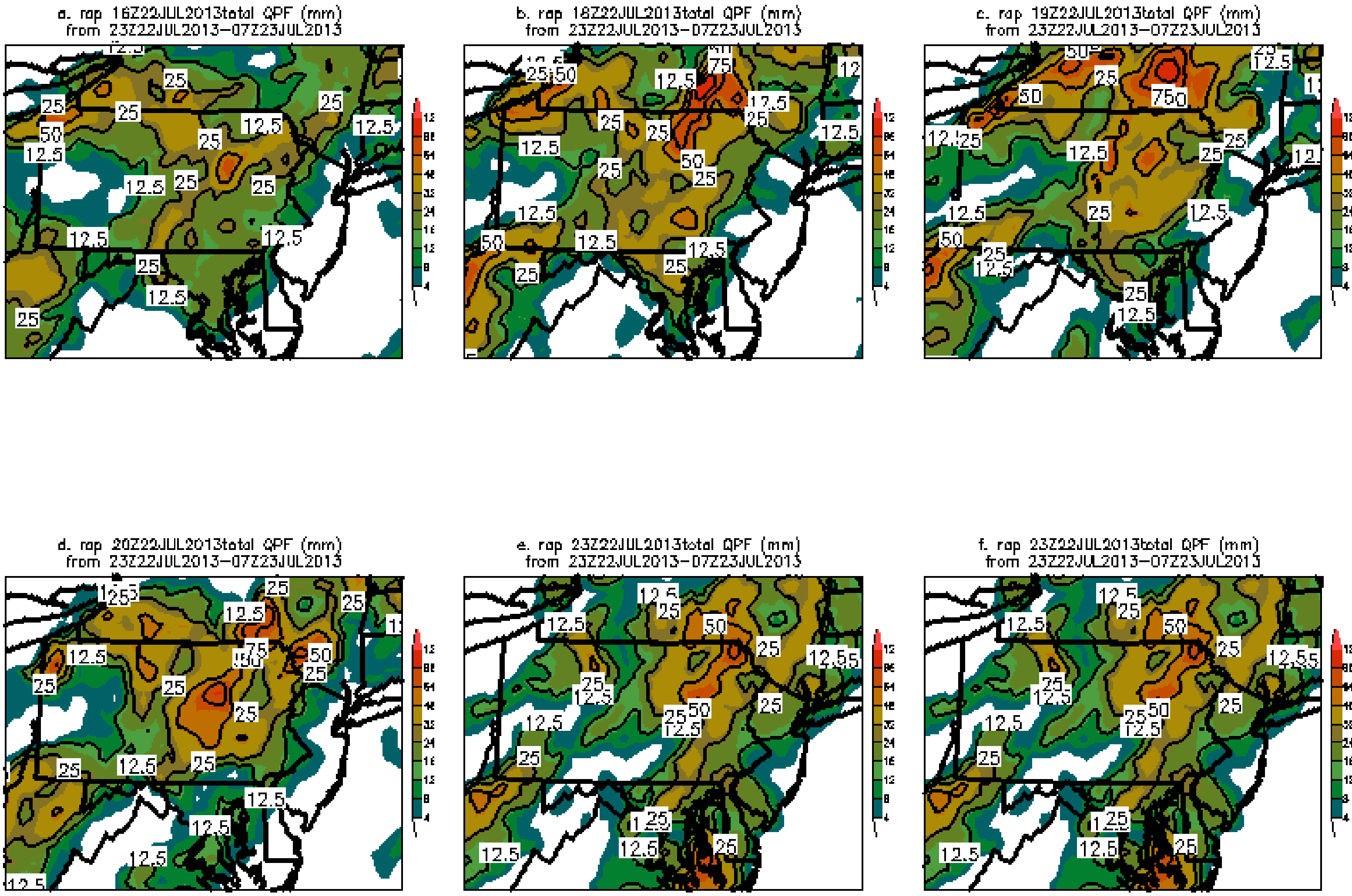

Figure 9. As in Figure 7 except for 13km RAP with rainfall valid 2300 UTC 22 June through 0700 UTC 23 June from RAP initialized at a) 1600 UTC 22 July, b) 1800 UTC 22 July, b) 1900 UTC 22 July, d) 2000 UTC 22 July, e) 2300 UTC 22 July. **Return to text.**

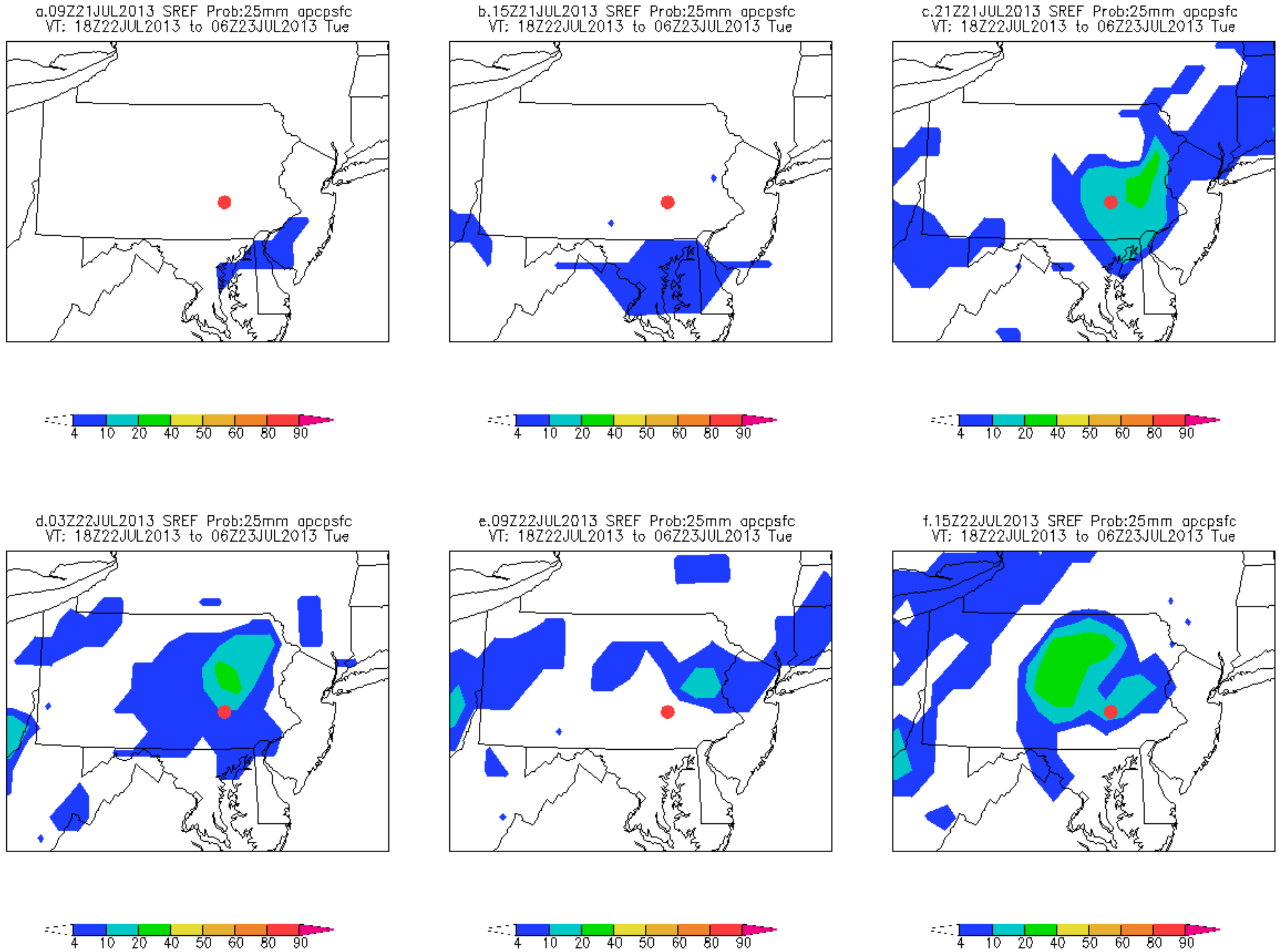

Figure 10. NCEP SREF forecasts sowing the probability of 25mm or greater QPF for the 12 hour period ending at 0600 UTC 23 July 2013 from forecasts initialized at a) 09000 UTC 21 July, b) 1500 UTC 21 July, c) 2100 UTC 21 July, d) 0300 UTC 22 July, e) 0900 UTC 22 July, and f) 1500 UTC 22 July 2013. If predicted a thick black contour would show the ensemble mean. **Return to text.**

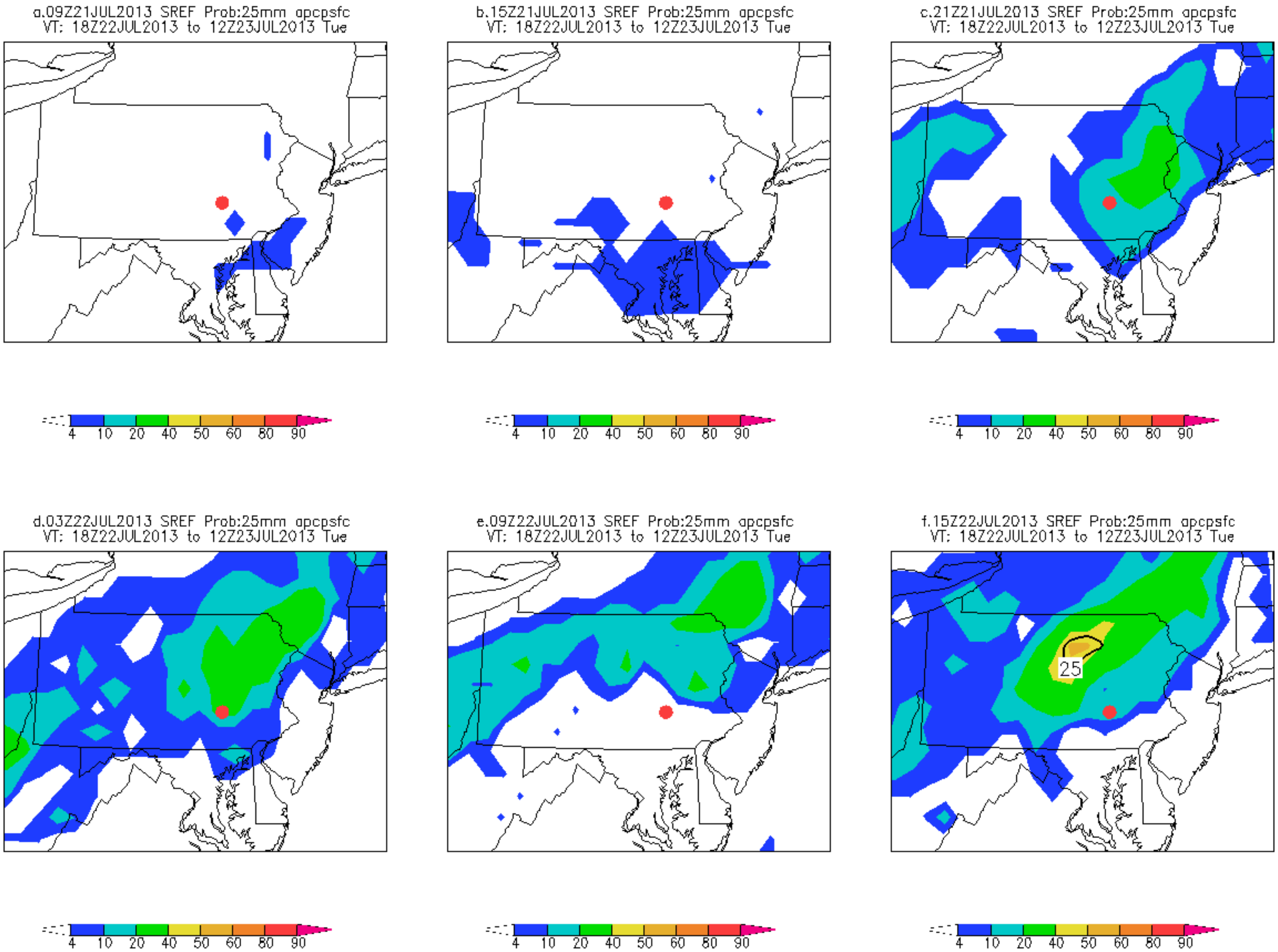

Figure 11. As in Figure 10 except for an 18 hour window ending 1200 UTC 23 July 2013. **Return to text.**

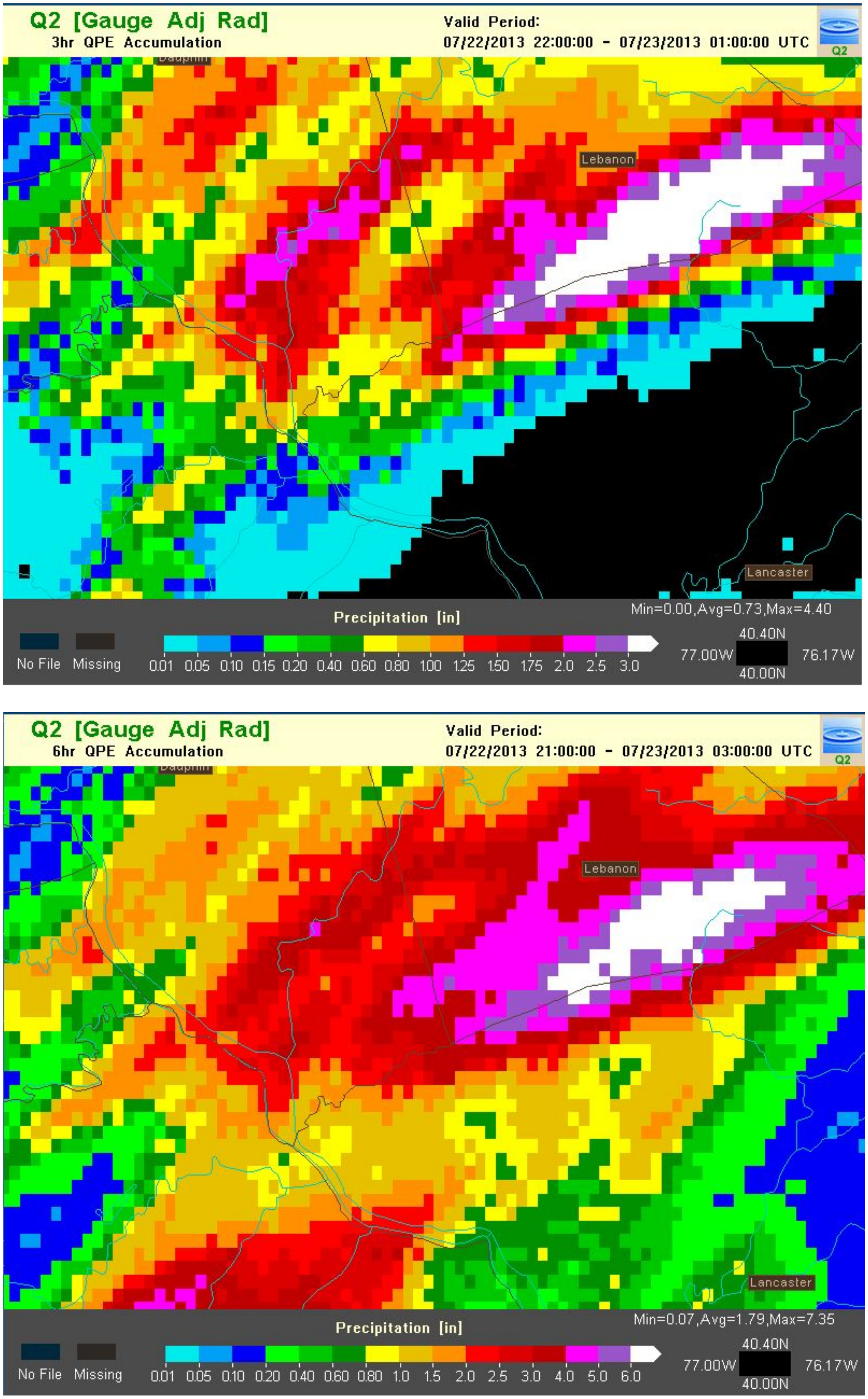

Figure 12. NMQ Q2 precipitation data showing radar and gauge adjusted data for the periods valid (top) 200 through 0100 UTC 22-23 July, and (bottom) 2100 to 0300 UTC 22-23 July 2013. Return to text.