Mid-Atlantic Heavy Rainfall event of 11 October 2013

Record rainfall in Harrisburg, PA

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1. Overview

A slow moving frontal system and the remnant circulation (Fig. 1) and moisture (Fig. 2) associated with tropical storm Karen produced heavy rainfall (Fig. 1) in the Mid-Atlantic region and record shattering rainfall in southeastern Pennsylvania on 11 October 2013. Rainfall amounts of 6-9.75 inches were common in southeastern Pennsylvania which produced flooding in many low lying areas and mudslides.

The key to forecasting events of this nature require knowledge of the pattern, leveraging this knowledge relative to forecast system predictions of the pattern, and tying in the probabilistic quantitative precipitation forecast (QPF) data. The use of standardize anomalies (Hart and Grumm 2001; Grumm and Hart 2001;Graham and Grumm 2010) often facilitates identifying many high-end and extreme weather events. Junker et al (2008; 2009); Stuart and Grumm (2006); and Grumm (2011a) showed the value of standardized anomalies in predicting heavy rainfall, record breaking East Coast winter storms, and heat waves respectively. Stuart and Grumm (2006) identified low-level (850 hPa) easterly winds and -4 to -6σ easterly wind anomalies as a critical means to distinguish ordinary from extraordinary east coast winter storms (ECWS). Grumm (2011b) showed how both strong easterly wind and southerly wind anomalies can aid in identifying record rainfall events.

Studies on the use of standardized anomalies have shown that the forecast models and ensemble forecast systems (EFS) often produce the patterns associated with heavy rainfall. When these systems produce these pattern they often produce significant amounts of QPF, though the location of the observed precipitation does not always match well with the regions where these forecast systems produce the higher QPF amounts. Thus, the patterns and the probabilities complement each other and provide confidence in the potential for a high impact rainfall event, though the exact location may not be as well predicted.

This paper will document the pattern and forecasts associated with the heavy rainfall over the Mid-Atlantic region on 11-12 October 2013. The focus is on southeastern Pennsylvania where over 5 inches of rain was observed in an area where heavy rain was an extremely low probability forecast. It will be shown, using the SREF, that the pattern was relatively well predicted; the area where the heavy rain was observed was poorly predicted. This is another good example of the complimentary use of standardized anomalies and QPF probabilities in the forecast process.

2. Data and Methods

The large scale pattern was reconstructed using the 00-hour forecast of the NCEP Global Forecast System (GFS) as first guess at the verifying pattern. The standardized anomalies were computed in Hart and Grumm (2001). All data were displayed using GrADS (Doty and Kinter 1995).

The rainfall was obtained from gridded Stage-IV data (Lin et al 2005; Seo 1998) and was plotted in GrADS showing 30 and 6 hour rainfall totals during the period of heavy rain. Other periods were examined though it was determined that there were 5 6-hour periods of 25 to 50mm of rainfall and this window from 0000 UTC 11 through 0600 UTC 12 Octobers is the focus forecast time and pattern time of interest.

The NCEP SREF was used to show the predictability issues associated with this event. Forecasts from 3, 4 and 5 October are used to illustrate the forecast issues associated with this event.

3. Pattern over the region

The evolving 500 hPa pattern over the eastern United States from 6-11 October (Fig. 4) showed a deep trough over the eastern Plains (Fig. 4a) at 06/1200 UTC and an emergent 500 hPa ridge over the next several days. The modest negative height anomalies over the Gulf States, associated with the remnants of TS Karen lumbered up the East Coast during this time, moving beneath the developing larger scale 500 hPa ridge over the northeastern United States and southeastern Canada (Fig. 4b-f).

At the surface (Fig. 1) the weak cyclone was clearly identified in the 24 hour mean sea-level pressure data along with a strong anticyclone at the surface to the north, beneath the 500 hPa ridge. The modest +1s pressure anomalies in the anticyclone to the north and -1σ pressure anomalies with the cyclone produced a strong pressure gradient (Fig. 4c-e) with implied strong low-level easterly flow moving up the East Coast from 8-11 October. In this gradient and implied easterly flow a strong gradient developed in the PW field (Fig. 2) along the East Coast ***after*** the slow moving frontal system to the west interacted with evolving circulation along the coastal plain (Fig. 2a-d). By 09/1200 UTC a strong east-west boundary had developed along the coastal plain with PW values over 50 mm in the warm air and +2 to +3σ PW anomalies.

The 850 hPa winds over the Mid-Atlantic region (Fig. 5) showed strong easterly flow north of the surface (Fig. 4) and 850 hPa cyclone (Fig. 5). The 850 hPa u-wind anomalies were observed at -3 to -4σ below normal from 11/0000 UTC through 12/0600 UTC. A comparison of the strong 850 hPa u-winds and area of more significant u-wind anomalies aligned well with the area of record rainfall in southeastern Pennsylvania.

The high PW and strong low-level easterly winds produced relatively high values of 850 hPa moisture flux (Fig. 6). Moisture flux has been shown to be good ingredients based tool to aid in the prediction of heavy rainfall. The atmosphere was relatively stable over the region where the heavy rainfall was observed. The CAPE of 600 to 1200JKg^{-1} remained well offshore during the event and is thus not shown.

These data imply that the rain fell in a strong east-west frontal boundary with significant low-level easterly wind anomalies, a classic Maddox et al (1979) frontal heavy rainfall event type.

4. Forecasts

The NCEP GFS, NAM, GEFS, and SREF were examined during this event. Each system provided somewhat unique forecasts of the QPF, though all of them produced to little QPF where the heavy rain was observed and each system tended to produce the heavy rainfall south and east of the observed location. For brevity the focus here will be on the NCEP SREF and its ability to predict the ***pattern*** and the ***QPF*** with comparisons to deterministic QPFs.

Six SREF forecasts of the PW pattern (Fig. 7) and 850 hPa winds and u-wind anomalies (Fig. 8) valid at 11/0600 UTC imply that the SREF was able to correctly predicted the larger scale PW pattern and strong easterly winds. The 850 hPa wind forecasts imply that over time the strong low-level easterly jet was forecast farther to the north. The lack of u-wind anomalies in the -4s range was likely the result of averaging the 21-member SREF forecast. Though not shown, individual SREF forecasts produced -4σ u-wind anomalies though the location of the location of the strong 850 hPa winds varied between members.

The resulting SREF QPF from these 6 runs showed that in excess of 50mm of QPF was a low probability event, under about 10% chance until the forecasts issued at 10/0300 UTC when the probability of 50mm or greater QPF was 20-40% (Fig. 9d) and remained high for the next 2 forecast cycles (Figs. 9e-f), though the QPF to the east was somewhat overdone.

The SREF mean QPF and 100mm contour from each member (Fig. 10) showed that the ensemble mean QPF was too far south and east until the forecasts issued around 0300 UTC 10 October when the axis of heavier rainfall shifted to the west (Fig. 10d). The ensemble mean never produced a closed 50mm contour, though several members produced 50 and in this instance, 100mm contours. Interesting, some of the close 100mm contours were well west of the higher QPF in the SREF mean, *a clear indication of considerable uncertainty in these forecasts*.

The pattern in the deterministic models was similar to the mean fields in the SREF though it was easier to visualize in the single model solutions the gradual shift the LLJ in the single solutions. The similar patterns and gradual shift in the LLJ caused the GFS (Fig. 11) to dramatically shift the QPF pattern from forecasts issued at 0600 UTC 11 and 1200 UTC 11 October 2013. These GFS QPFs imply the latter forecast, 11/1800 UTC was the first to predict in excess of 50 mm of QPF in southeastern PA. This is actually quite deceptive as the QPF in Figure 11 do not reflect the temporal shift in the QPF. For example, from 10/1800 UTC through 12/0600 UTC, the GFS forecast would have shown 64mm of QPF just east of the 25mm contour in Figure 11d. The key issue here is that the GFS did not time the QPF well and only the shortest forecast presented the potential for heavy rainfall, over 50mm in the time period of the heaviest rainfall.

The shorter range forecasts NAM (Fig. 12) produced higher QPF amounts and shifted the QPF farther west based on the forecasts issued at 10/1200 UTC. Just about 100-150 km west of where the heaviest rainfall was observed, the 10/1200 UTC had over 75mm of QPF. The NAM had more egregious south and east QPF errors than the GFS in all forecasts produced prior to 10/1200 UTC. Similar to the GFS, the NAM suffered from some temporal issues which make the select time window critical in how to evaluate these data.

5. Summary

The remnant circulation and moisture associated with tropical storm Karen and a slow moving frontal system produced heavy rainfall in the Mid-Atlantic region. The heaviest rain was observed over southeastern Pennsylvania where many locations received between 5 and 10.5 inches of rainfall[1]. The rain fell on the cool side a low-level boundary with strong easterly flow over the boundary, a classic larger scale "*frontal type*" heavy precipitation pattern (Stuart and Grumm 2006; Grumm 2011b) in the eastern United States.

The heavy rain produced flooding at 5 points along secondary rivers and streams (Table 1). Likely due to relatively dry conditions prior to the rain, minor flooding was observed at 4 of the 5 points and only 1 point experienced moderate flooding. The event of 11 October was relatively unique as the rain fell over about 36 hours and there were 5 6-hour period of rain over 25 to 50mm. Most heavy rain events typically span 4-12 hours, this was an extraordinarily long event and 4 of the 6 hour periods ending at 11/0000 UTC through 12/0000 UTC are shown in Figure 13. The 4 times shown only span 11/0000 through 11/1800 UTC. Each image shows a broad region of 25mm of QPE and each image has at least a small region of over 50mm of QPE. The long period of rainfall likely limited the flash flood aspects of the event.

All analyses presented here imply that the heavy rainfall was associated with a strong 850 hPa LLJ with significant u-wind anomalies. The models and SREF had some difficulty predicting the exact location and intensity of this feature and the associated surge of high PW. This may have contributed to the displacement issues associated with QPF. However, the overall pattern was relatively well predicted by all forecasts systems, which alerted human forecasters to the potential for heavy rainfall in the Mid-Atlantic region. The details as to where the heavy rain would fall were more difficult to ferret out.

The convergence of forecasts toward higher QPF amounts; though far lower than observed; farther west did not occur until about 10/0600 UTC in the GFS (Fig. 11) and after 0900 UTC in the SREF and about 10/1200 UTC in the NAM. From a QPF perspective this event had considerable uncertainty in a pattern that clearly favored heavy rainfall.

[1] Uncertified site had 12 inches.

The rainfall in Harrisburg was 5.72 inches in the 24 hours spanning 11 October 2013 which broke the previous record of 1.47 inches set in 1905 and record daily rainfall of 4.02 inches for 10 October 2013 bet the old record of 1.50 inches set in 1894. The two day total of 9.76 inches pushed the monthly total to 10.48 making October 2013 the wettest October on record beating the old record of 9.87 inches for the month set in 1976. The plots of the station data (Fig. 13) indicate that the rainfall amounts over 4 inches were observed from northern Maryland into southeastern Pennsylvania. The inset map in Figure 13 shows this location. Point data for sites which reported over 5 inches is included in Table 2.

The observations presented here suggest this was an extremely heavy rainfall event and a record breaking event (Capital Cities KCXY) had 10.35 inches of rainfall at many locations. Despite the record nature of the rain, the forecasts with lead-times much more than 12-hours were woeful.

6. Acknowledgements

The Pennsylvania State University for gridded data access and the Mid-Atlantic River fore.

7. References

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October 11 - 13, 2013 Preliminary Flood Summary

Susquehanna (Lower Main Stem)	**Above FS (ft)**	**Crest (ft)**	**Streamflow (cfs)**	**Below FS (ft)**	**Category (ft)**	**Record (ft) - (cfs)**
Camp Hill, Pennsylvania - (CPHP1)	Flood = 7.0	**11.40**	**5,950**	Flood = 7.0	7.0 (minor)	18.77
Yellow Breeches Creek - (WFO CTP)	10/11/2013	**October 12, 2013**		10/12/2013	**9.0 (moderate)**	19,300
Gage & Town/Cumberland County	missing	**1:30 AM**		3:15-3:30 PM	13.0 (major)	September 26, 1975
Hershey, Pennsylvania - (HERP1)	Flood = 7.0	**7.54**	**9,700**	Flood = 7.0	**7.0 (minor)**	27.22
Swatara Creek - (WFO CTP)	10/11/2013	**October 11, 2013**		10/12/2013	10.0 (moderate)	96,900
Gage & Town/Dauphin County	10:30-10:45 AM	**21:30 PM**		6:45-7:00 AM	14.0 (major)	September 8, 2011
Hogestown, Pennsylvania - (HGSP1)	Flood = 8.0	**8.98**	**7,260**	Flood = 8.0	**8.0 (minor)**	17.01
Conodoguinet Creek - (WFO CTP)	10/11/2013	**October 12, 2013**		10/13/2013	10.0 (moderate)	33,700
Gage & Town/Cumberland County	9:45-10:00 PM	**9:15 - 9:45 AM**		7:30-7:45 AM	12.0 (major)	June 23, 1972
Lancaster, Pennsylvania - (LNCP1)	Flood = 11.0	**11.20**	**8,350**	Flood = 11.0	**11.0 (minor)**	27.90
Conestoga River - (WFO CTP)	10/11/2013	**October 11, 2013**		10/11/2013	13.0 (moderate)	50,300
Gage & Town/Lancaster County	7:30-7:45 PM	**9:00 - 9:15 PM**		10:45-11:00 PM	15.0 (major)	June 23, 1972
Southeast PA & Delaware	**Above FS (ft)**	**Crest (ft)**	**Streamflow (cfs)**	**Below FS (ft)**	**Category (ft)**	**Record (ft) - (cfs)**
Chadds Ford, Pennsylvania - (CDFP1)	Flood = 9.0	**9.47**	**5,880**	Flood = 9.0	**9.0 (minor)**	17.15
Brandywine Creek/Christina Basin - (WFO PHI)	10/11/2013	**October 11, 2013**		10/12/2013	11.0 (moderate)	26,900
Gage & Town/Delaware County	2:15-2:30 PM	**19:15 PM**		1:30-1:45 AM	13.0 (major)	September 17, 1999

Crest Statistics

Flooding 10/11/2013 - 10/13/2013
Crests occurred 10/11/2013 - 10/12/2013
First flood of 1 that occurred in October, 2013
Fifthteenth flood that has occurred in 2013
Number of Floods at MARFC **Forecast Points** - **5**
Number of Floods Cresting in **Minor** Range - **4**
Number of Floods Cresting in **Moderate** Range - **1**
Number of Floods Cresting in **Major** Range - 0
MARFC Power Ranking - **9** (Minor = 1 - Moderate = 5 - Major = 10 - Missing =1)

Table 1. Flood data from the Mid-Atlantic River Forecast Center showing the river and stream locations where flooding was observed. Data Include the location, gauge name, stage and flow (cfs) and records. At the bottom of the table a summary of flooding and flooding for 2013 is provided. Date courtesy C. Chillag, MARFC.

WFO	Lon	Lat	Rainfall (in)
CTP	-76.8517	40.2169	10.35
CTP	-76.7636	40.1933	9.73
CTP	-76.8742	39.9181	9.01
CTP	-76.989403	39.919189	8.81
CTP	-76.8703	40.2817	7.83
CTP	-77.360603	39.80106	7.58
CTP	-76.7167	40.1167	7.52
CTP	-76.2833	40.05	7.36
CTP	-77.1894	40.2258	7.10
CTP	-77.3586	39.87	6.97
CTP	-76.562897	40.31876	6.94
CTP	-77.43	39.73	6.90
LWX	-77.4869	38.9764	6.86
CTP	-77.0332	39.7709	6.66
CTP	-76.4667	40.3167	6.54
CTP	-76.3511	39.996	6.49
LWX	-77.380096	38.922131	6.48
CTP	-76.3911	39.9244	6.12
LWX	-76.6694	39.175	6.11
LWX	-77.4572	38.9442	6.10
LWX	-77.459999	38.947498	6.10
CTP	-77.25	39.9333	6.06
LWX	-77.8472	39.6092	5.97
LWX	-77.1134	38.9385	5.84
LWX	-76.8375	39.5001	5.72
CTP	-76.2964	40.1217	5.70
LWX	-76.860497	39.236099	5.70
CTP	-77.5	39.85	5.69
LWX	-76.615303	39.397049	5.69
LWX	-77.691879	39.144821	5.61
LWX	-76.4333	38.15	5.51
LWX	-77.2914	39.6811	5.25
CTP	-77.5167	40.05	5.21
PHI	-75.4153	38.7416	5.18
LWX	-76.808502	39.460999	5.09
LWX	-77.088997	38.73106	5.08
LWX	-76.808998	39.099838	5.07
LWX	-78.2507	38.4549	5.05
LWX	-77.143402	38.918018	5.01
LWX	-77.7222	39.3981	5.00

Table 2. Rainfall by NWS WFO with latitude, longitude and total rainfall (inches) sorted highest to lowest only showing locations with 5 or more inches of rainfall. 69 sites had over 4 inches

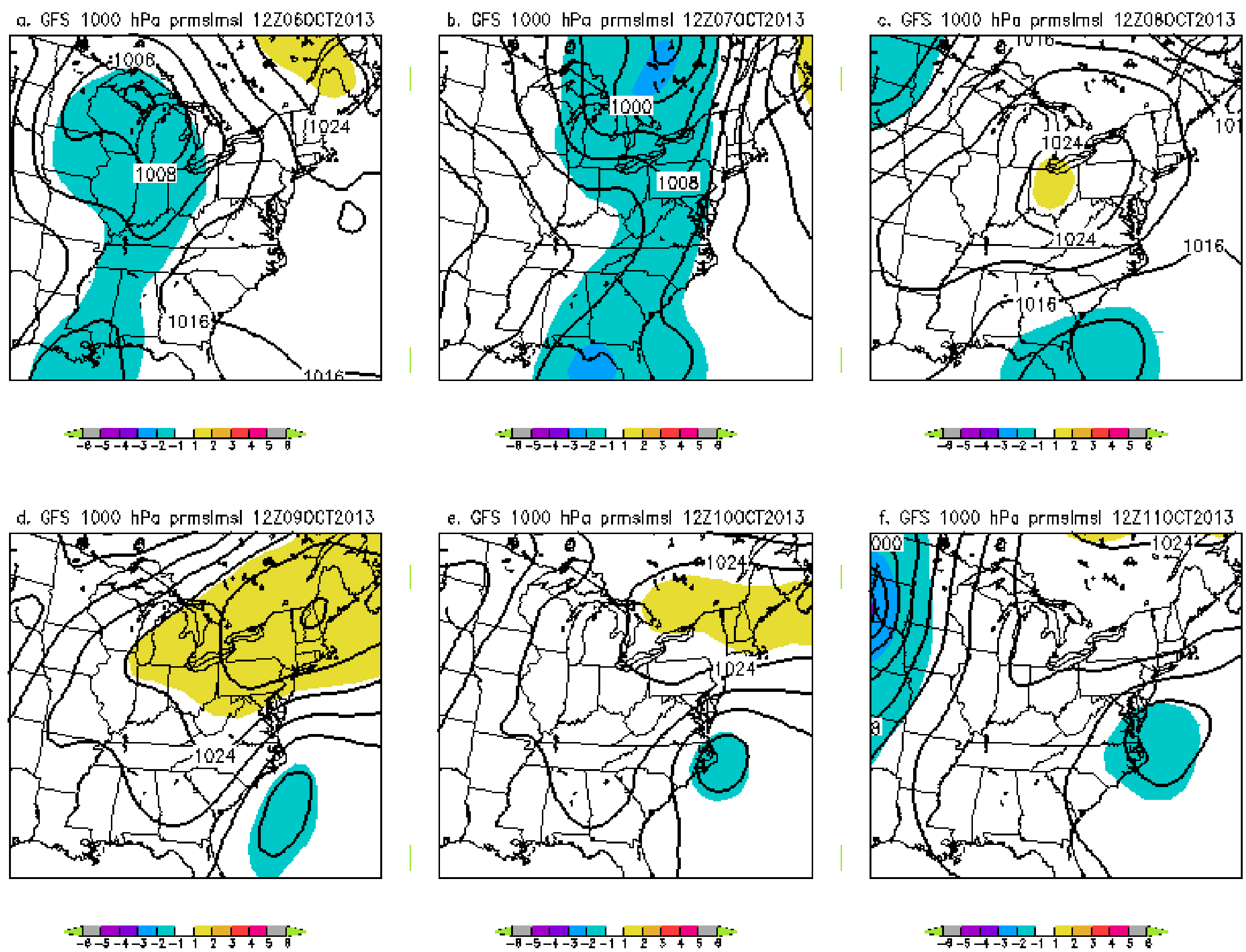

Figure 1. GFS 00-hour forecasts of mean sea-level pressure (hPa) and standardized anomalies (shaded) in 24 hour increments from a) 1200 UTC 6 October 2013 through f) 1200 UTC 11 October 2013. Return to text.

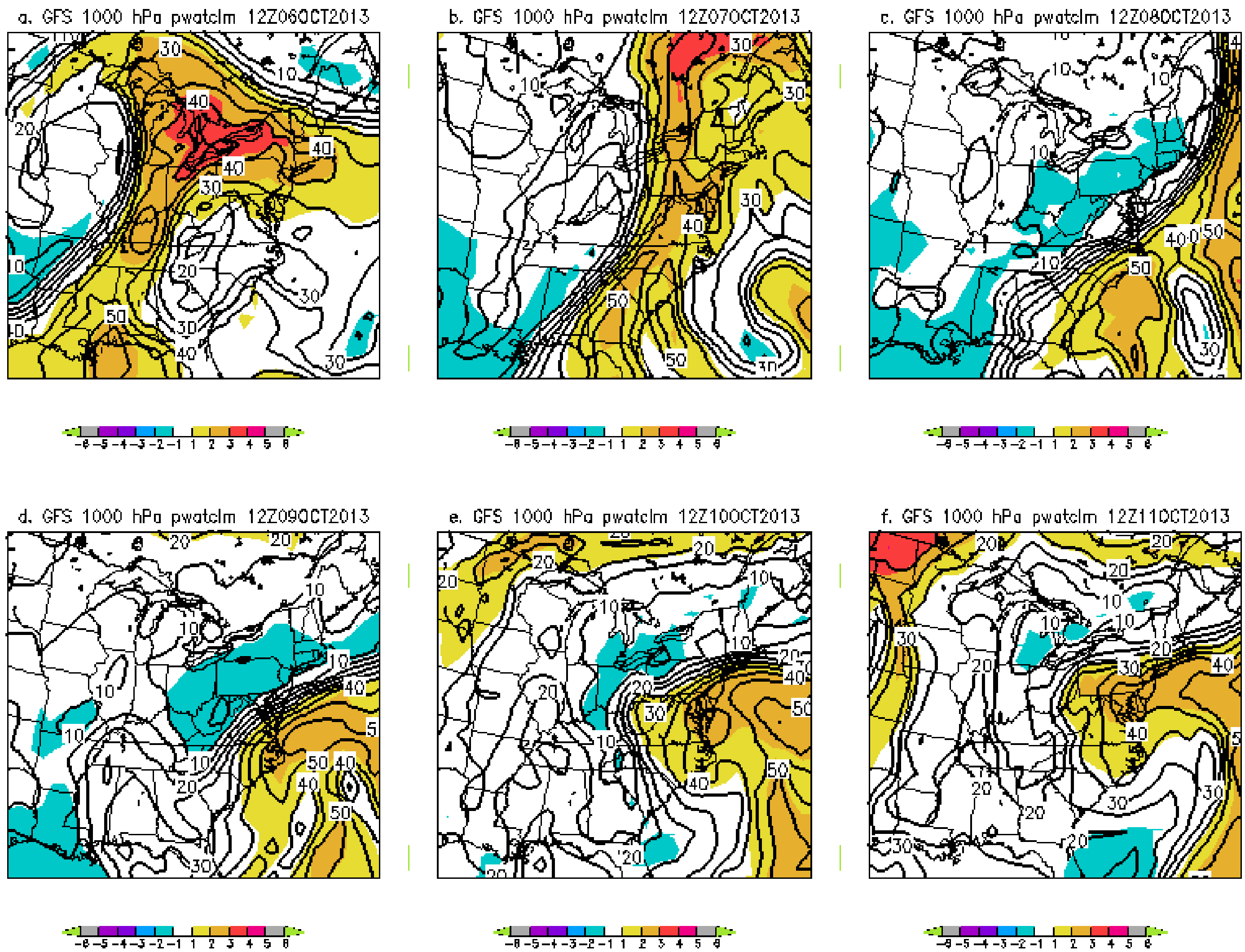

Figure 2. As in Figure 1 except for precipitable water (mm) and precipitable water standardized anomalies. Return to text.

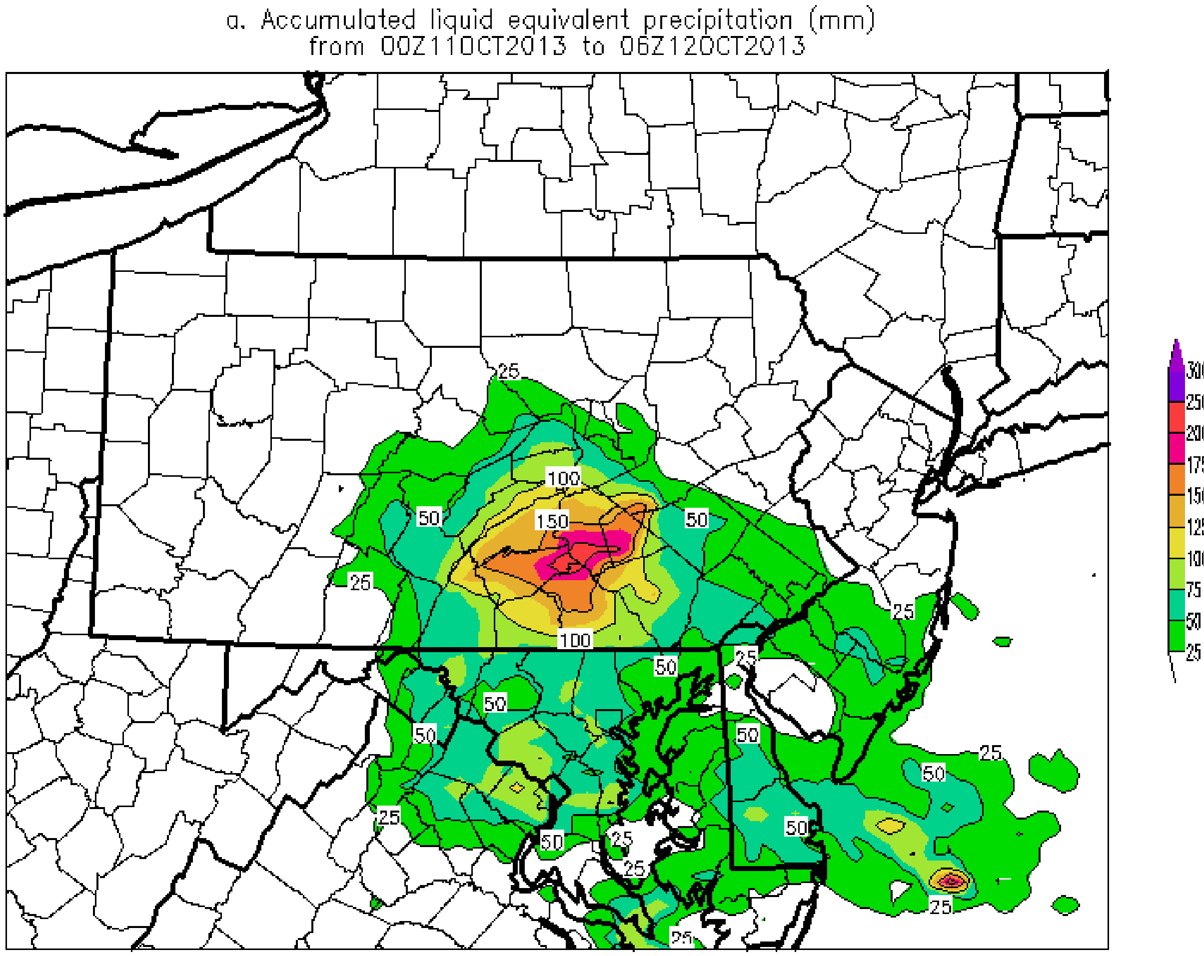

Figure 3. Stage-IV estimated rainfall (mm) for the 24 hour period of 000 UTC 11 through 0600 UTC 12 October 2013. The shading is as indicated by the color bar and contours are 50,100,200,250 mm. **Return to text.**

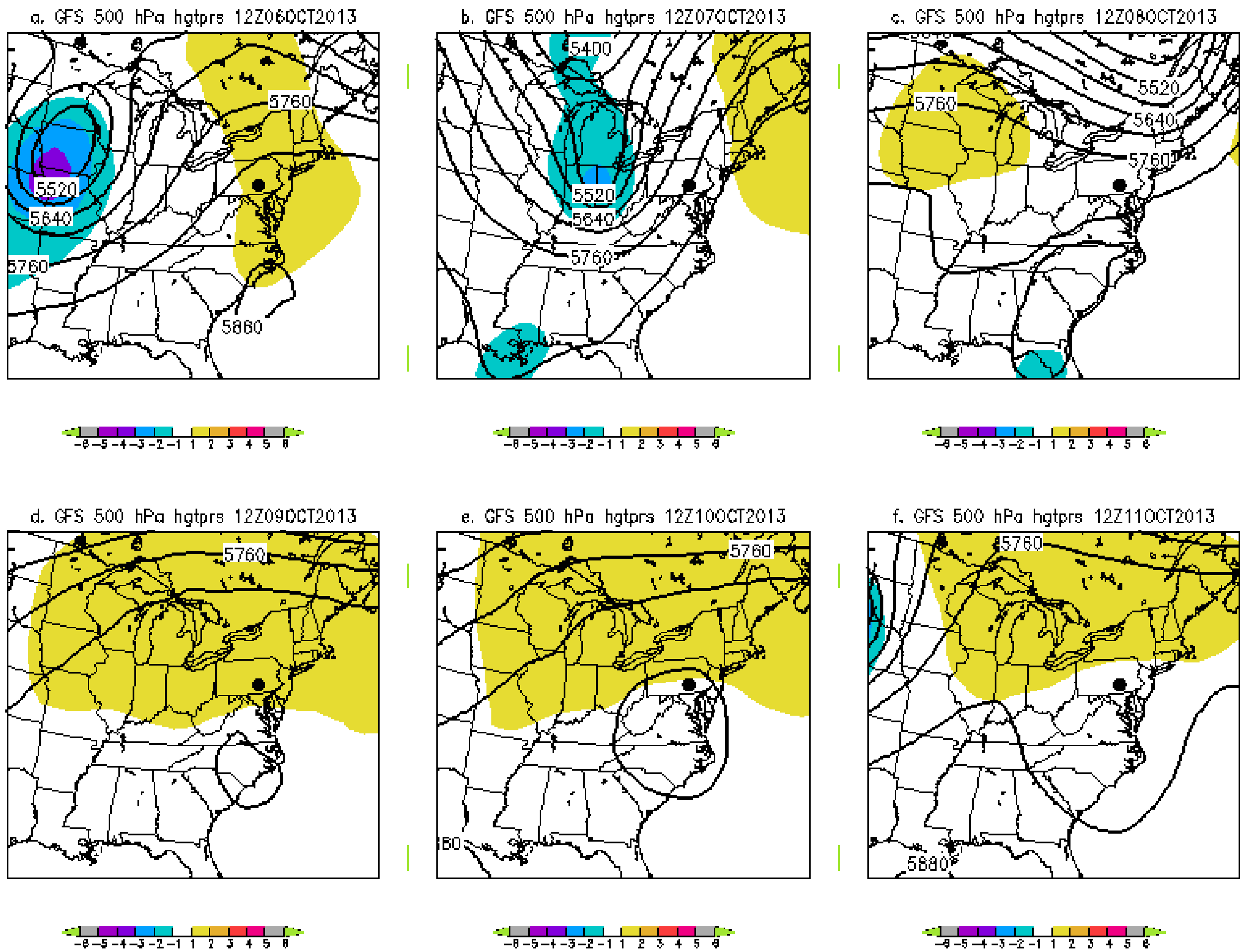

Figure 4. GFS 00-hour forecasts of 500 hPa heights (m) and standardized anomalies (shaded) in 24 hour increments from a) 1200 UTC 6 October 2013 through f) 1200 UTC 11 October 2013. Return to text.

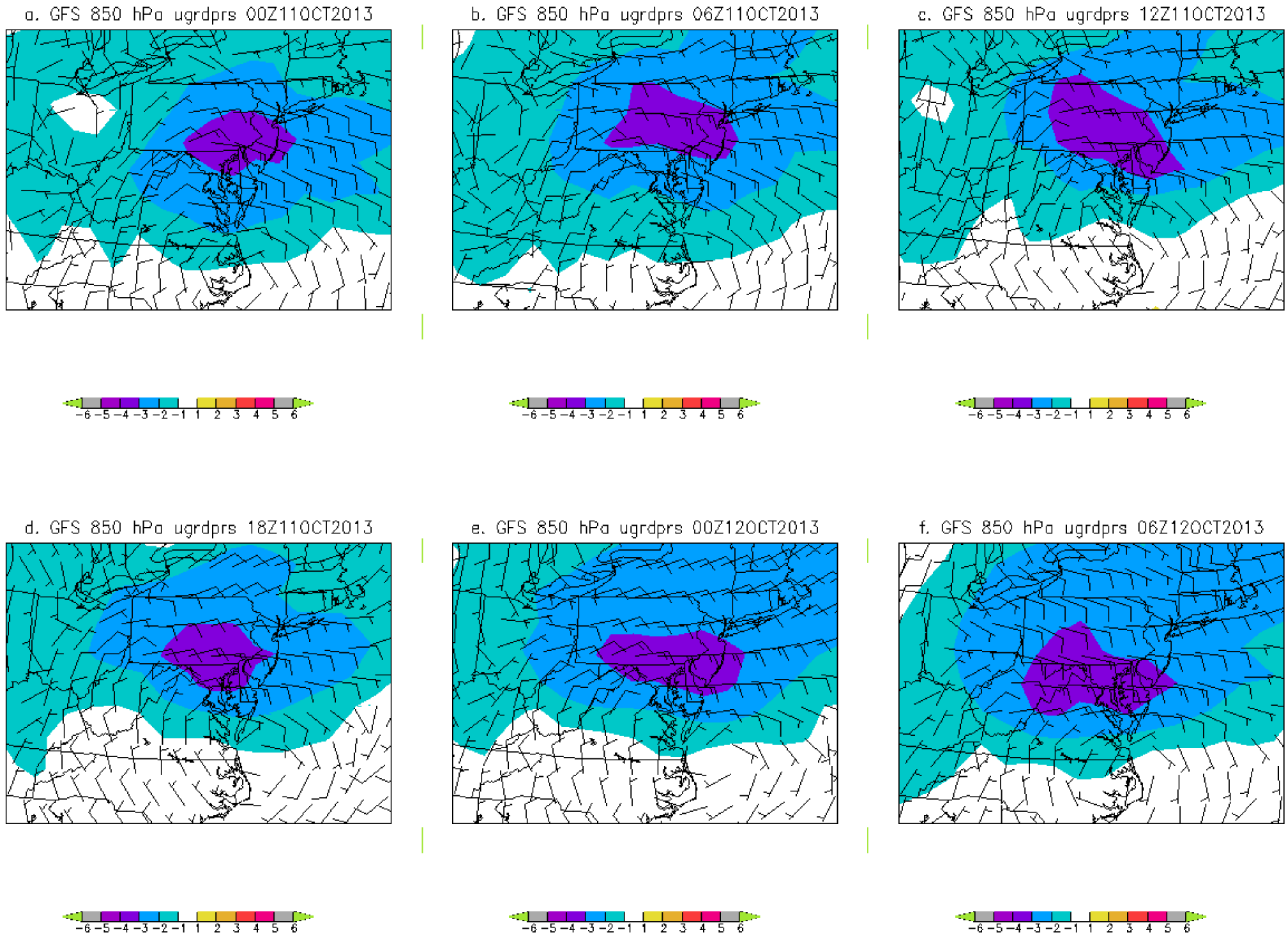

Figure 5. As in Figure 4 except for 850 hPa winds (kts) and u-wind anomalies in 6-hour increments from a) 0000 UTC 11 October 2013 through f) 0600 UTC 12 October 2013. Return to text.

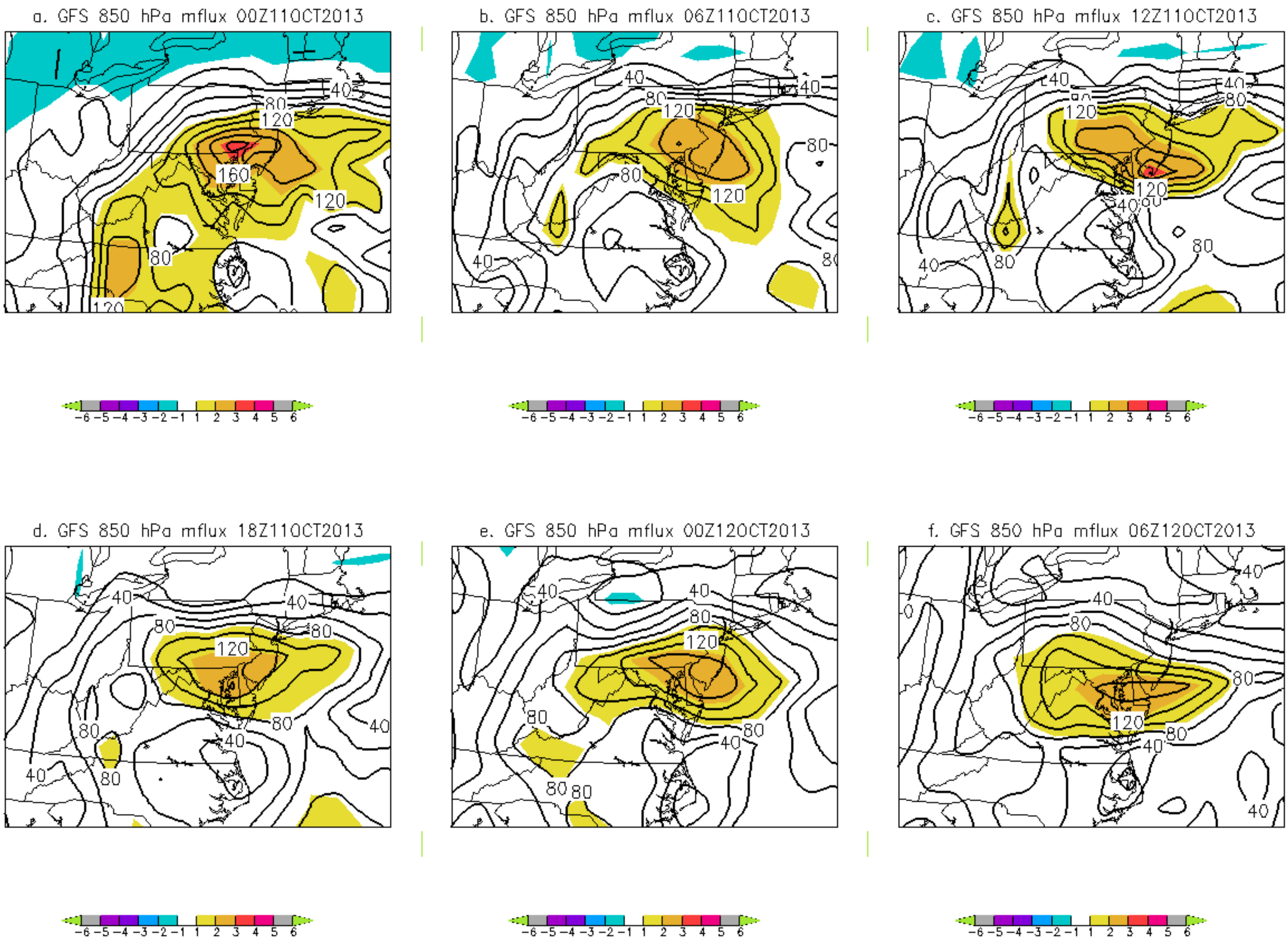

Figure 6. As in Figure 4 except for 850 hPa moisture flux and moisture flux anomalies. Return to text.

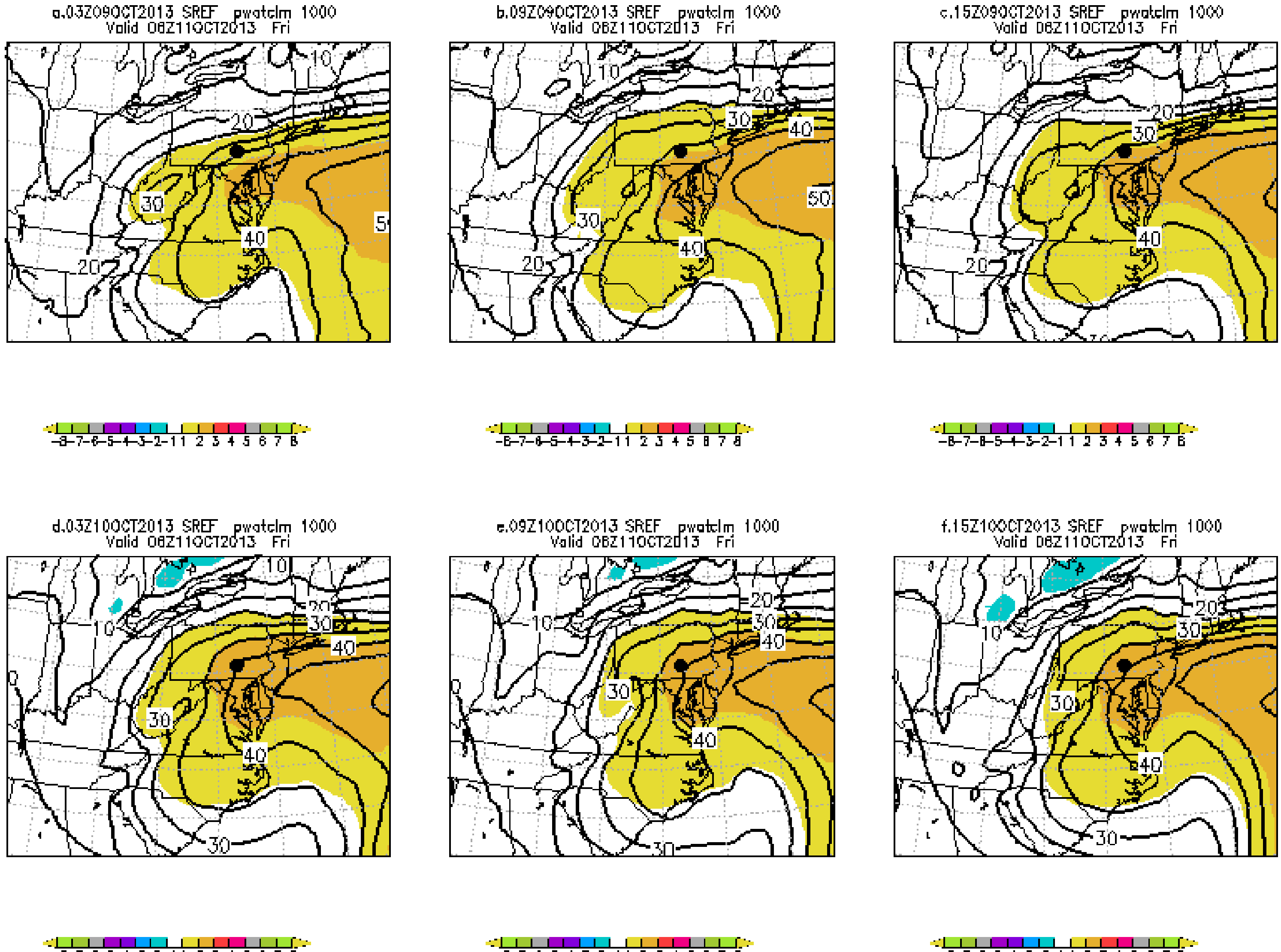

Figure 7. NCEP SREF forecasts of precipitable water (mm) and standardized anomalies valid at 0600 UTC 11 October 2013 from SREF initialized at at a) 0300 UTC 9 October, b) 0900 UTC 4 October, c) 1500 UTC 9 October, d) 0300 UTC 10 October, e) 0900 UTC 10 October, and f) 1500 UTC 10 October 2013. Return to text.

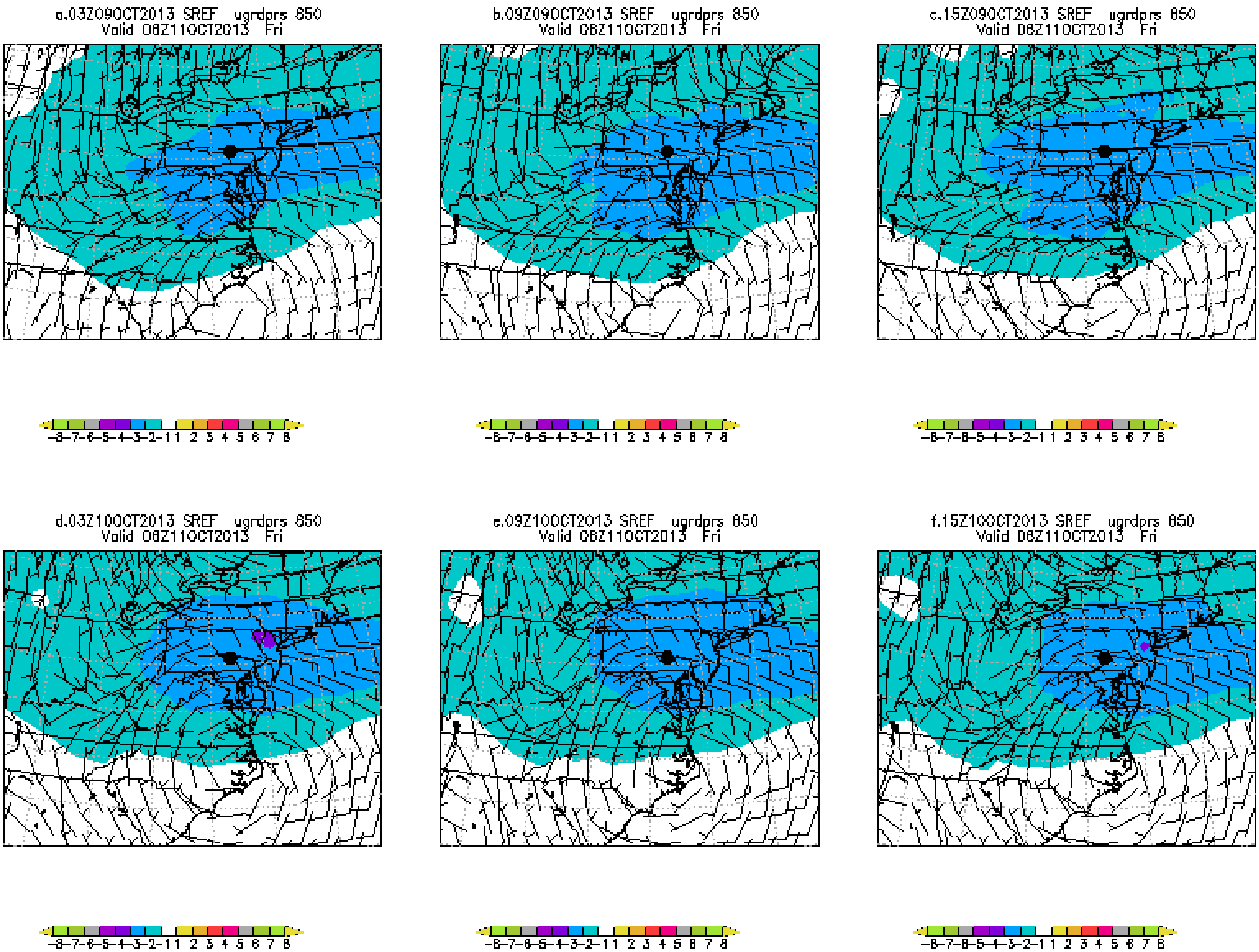

Figure 8. As in Figure 7 except for 850 hPa winds and 850 hPa u-wind anomalies. Return to text.

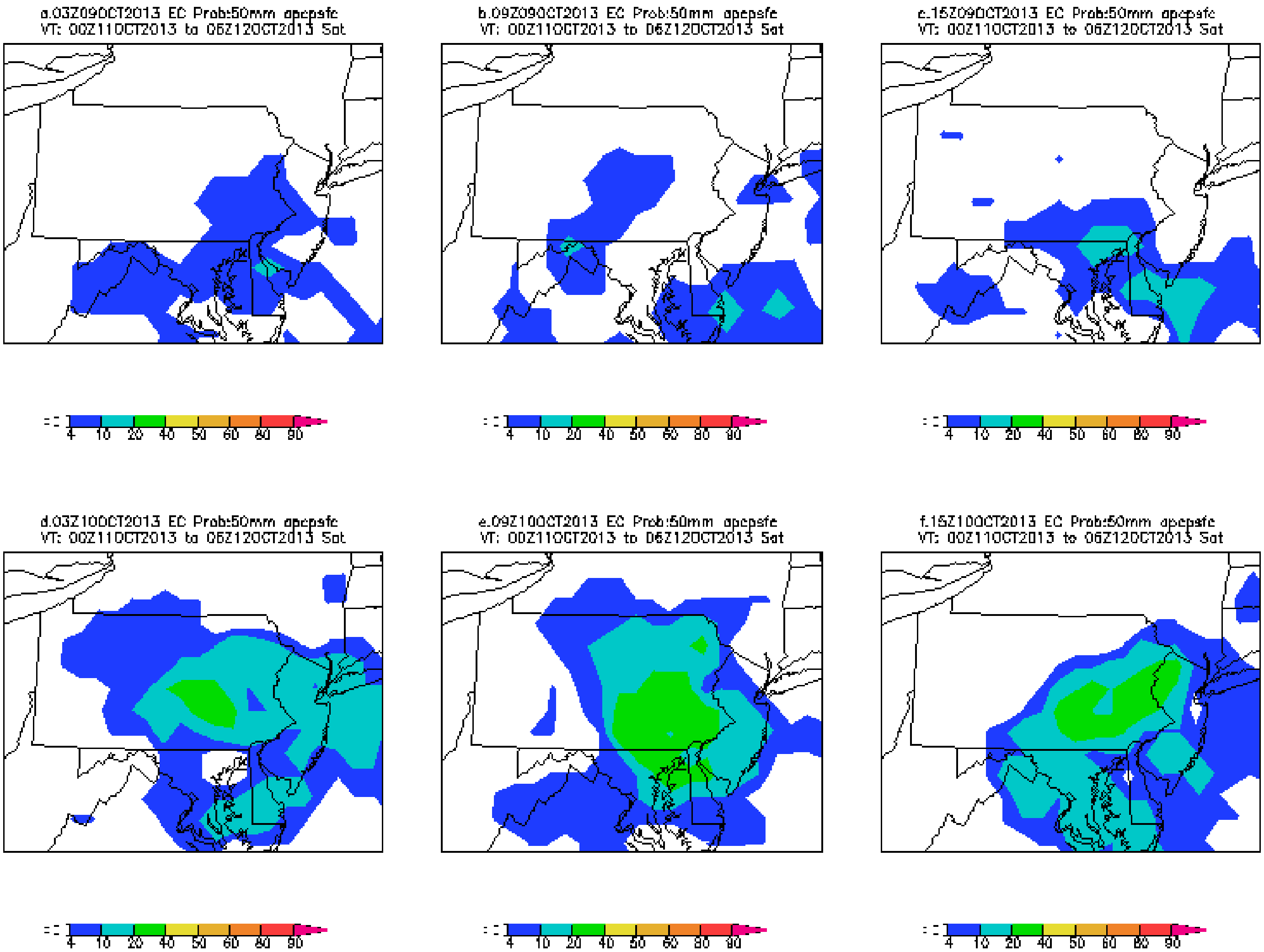

Figure 9. NCEP SREF ensemble probability of 50mm or more QPF (shaded) for the 30 hour period ending at 0600 UTC 12 October 2013 and each member's 50 mm contour (thin lines) from NCEP SREF initialized at a) 0300 UTC 9 October, b) 0900 UTC 4 October, c) 1500 UTC 9 October, d) 0300 UTC 10 October, e) 0900 UTC 10 October, and f) 1500 UTC 10 October 2013. **Return to text.**

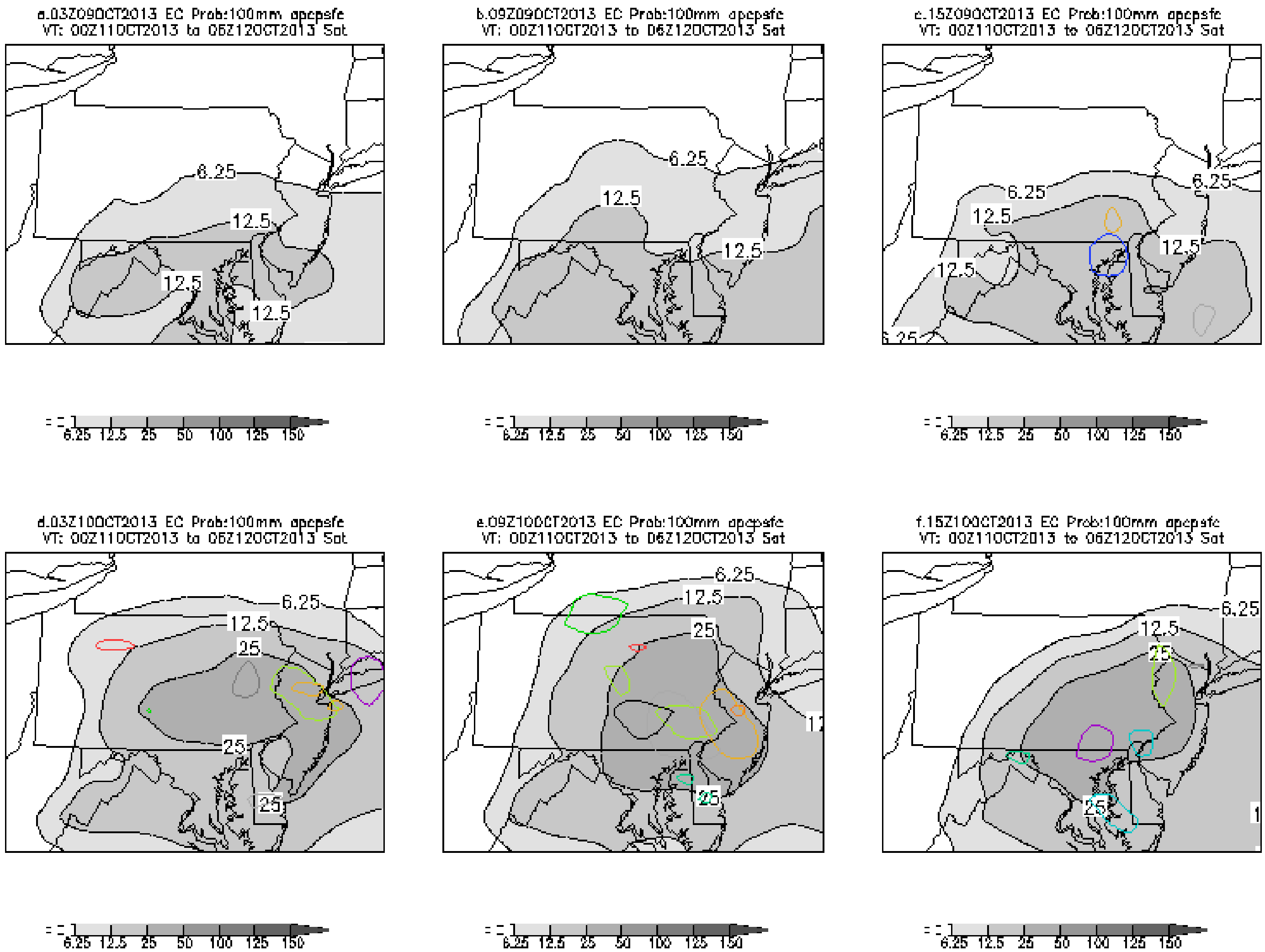

Figure 10. NCEP SREF ensemble mean QPF (shaded) for the 30 hour period ending at 0600 UTC 12 October 2013 and each member's 50 mm contour (thin lines) from NCEP SREF initialized at a) 0300 UTC 9 October, b) 0900 UTC 4 October, c) 1500 UTC 9 October, d) 0300 UTC 10 October, e) 0900 UTC 10 October, and f) 1500 UTC 10 October 2013. **Return to text.**

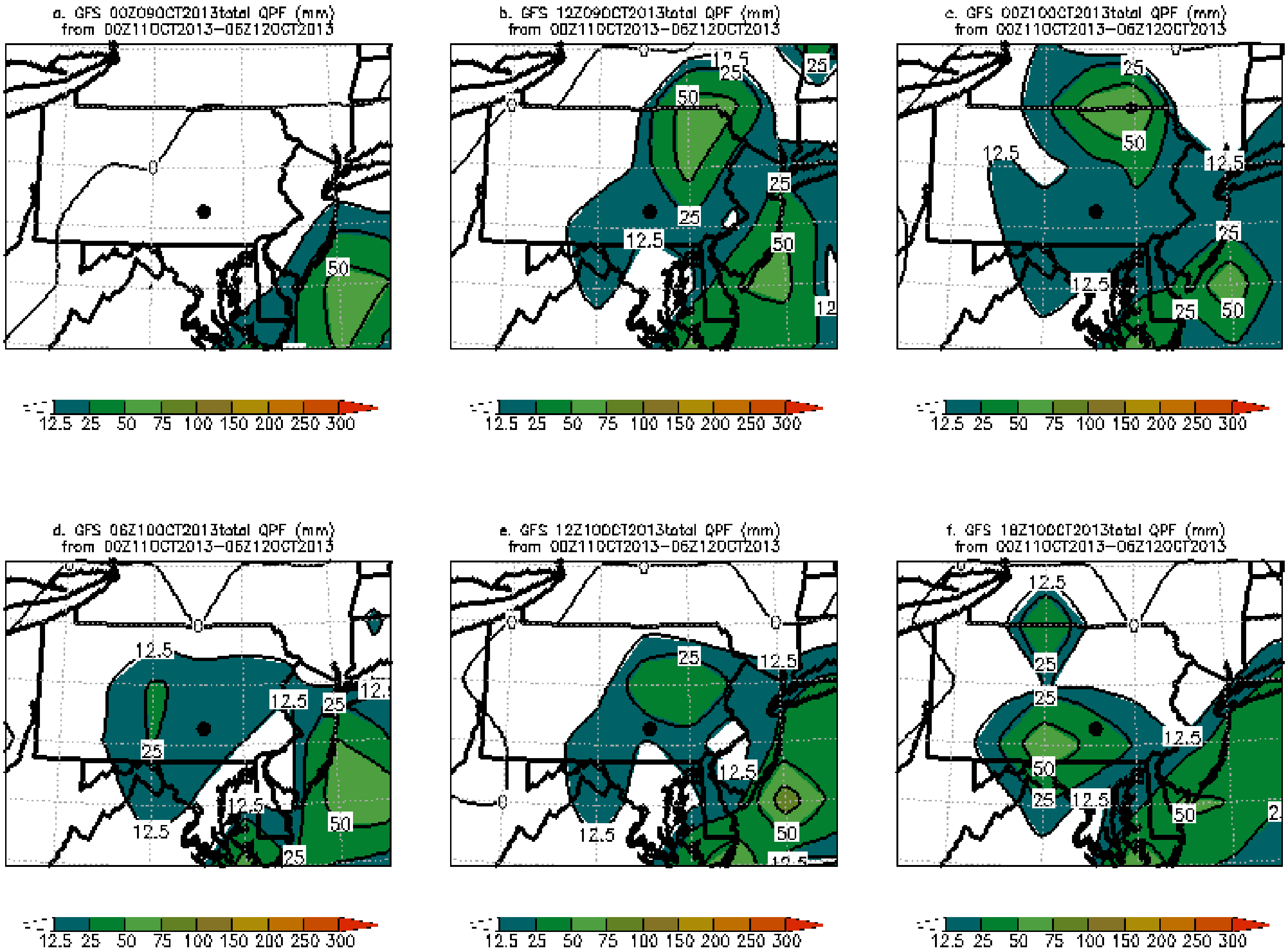

Figure 11. NCEP GFS QPF (mm) for the 30 hour period ending at 0600 UTC 12 October 2013 from forecasts initialized at a) 0000 UTC 9 October, b) 1200 UTC 9 October, c) 0000 UTC 10 October, d) 0600 UTC 10 October, e) 1200 UTC 10 October, f) 1800 UTC 10 October 2013. **Return to text.**

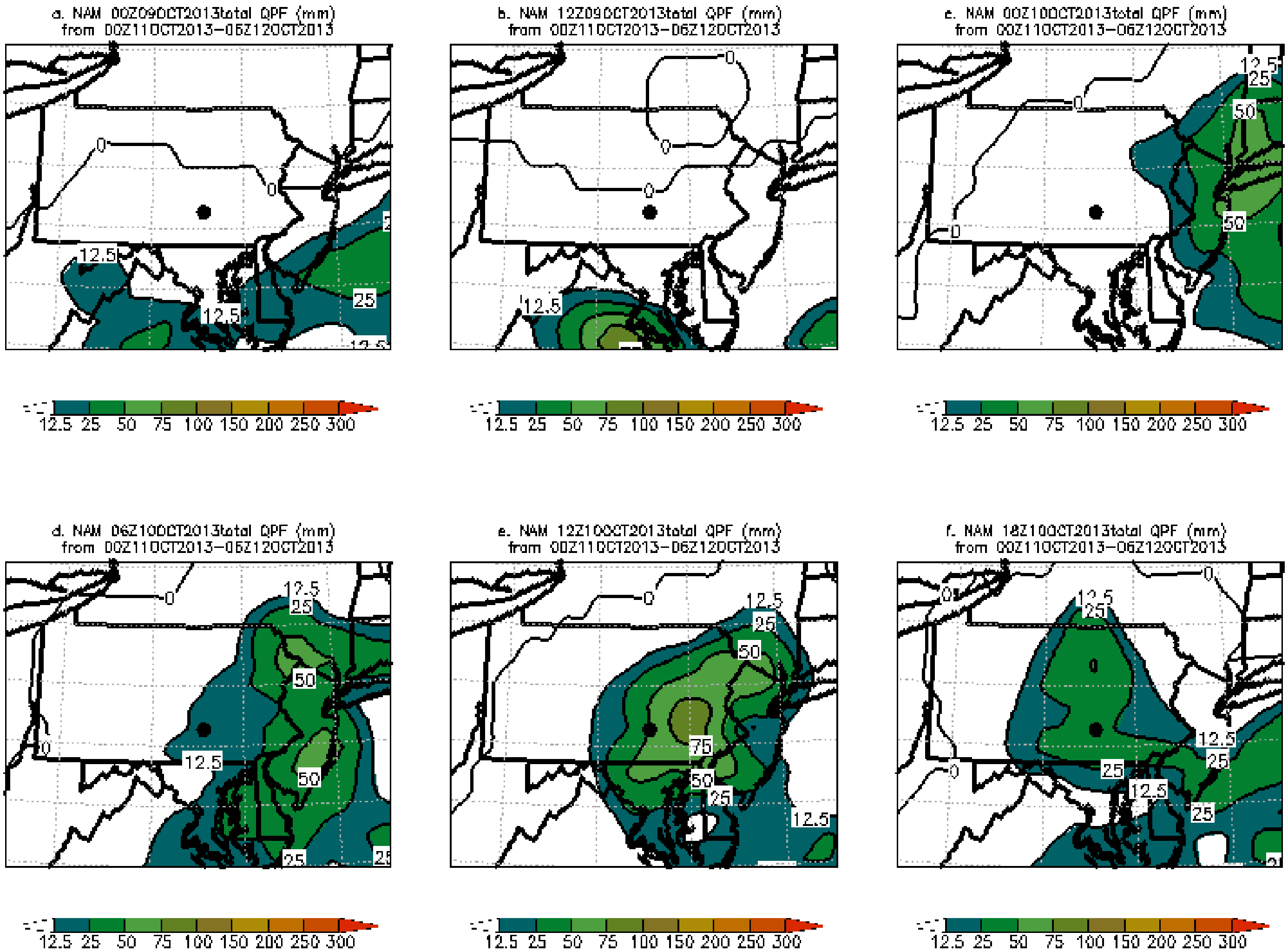

Figure 12. As in Figure 11 except for the NCEP NAM. Return to text.

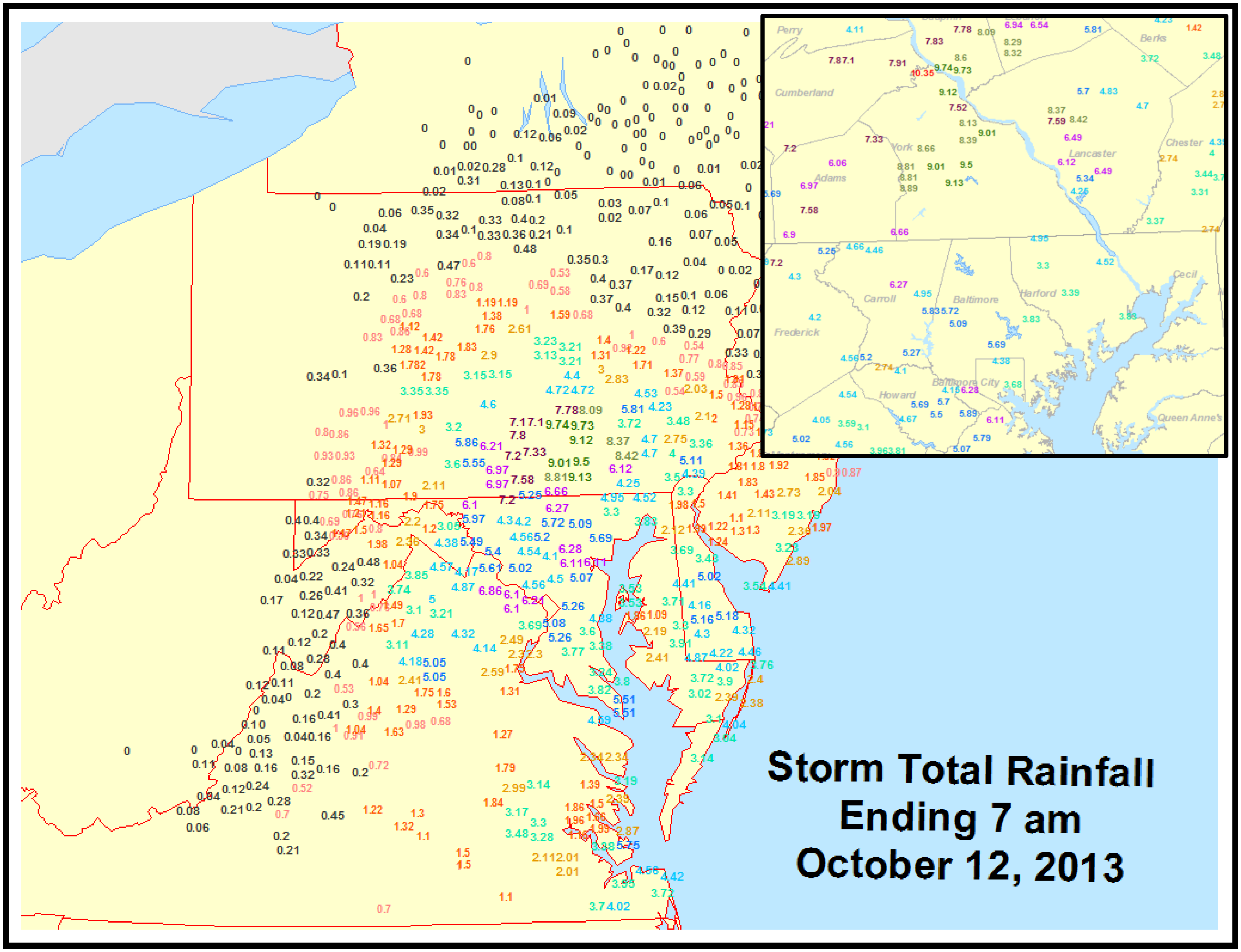

Figure 13. Point data of event-total rainfall (inches) color coded by amounts black is less than 0.50 inches, light red 0.50 to 1.0 inches, darker red is 1 to 3 inches, light green is 3-4 inches, light blues is 4-5 inches, dark blue is 5-6, light purple 6-7, deep red is 7-8, light green 8-9, 9-10 is dark green, The inset shows the higher rainfall amounts and deep red is over 10 inches (Harrisburg). Return to text.

NWS State College Case Examples

Station	LAT	LAT2	RAINFALL
CXY	40.22	-76.85	10.35
MDT	40.2	-76.77	9.74
YRKP1G	39.92	-76.75	9.5
THV	39.92	-76.88	9.01
PAAD02	39.92	-76.99	8.81
PADP14	40.23	-76.76	8.6
PADP18	40.26	-76.75	8.68
HARP1	40.25	-76.89	8.37
PAYR17	40	-76.75	8.39
PALB09	40.27	-76.57	8.29
HERP1	40.3	-76.67	8.09
PAYR20	40.05	-76.69	8.13
HRBP1	40.28	-76.87	7.83
PACD06	40.22	-77.01	7.91
CSLP1L	40.23	-77.19	7.8
PADP06	40.31	-76.76	7.78
YHNP1	40.12	-76.72	7.52
PALN07	40.06	-76.41	7.59
LNCP1	40.05	-76.28	7.21
PAAD03	40	-77.11	7.33
FAYP1	39.98	-77.42	7.2
CSLP1	40.23	-77.19	7.1
THUM2	39.65	-77.48	7.2
ORTP1	39.87	-77.36	6.97
KCIV2	38.98	-77.49	6.86
UNNP1	39.73	-77.02	6.66
TTSP1	39.89	-76.24	6.49
MILP1	39.99	-76.35	6.49
VAFX01	38.92	-77.38	6.48
CNPP1	40.03	-76.3	6.27
MDBL30	39.27	-76.77	6.28
MDCR07	39.58	-77.03	6.27
VAFX51	38.9	-77.28	6.21
BWI	39.18	-76.67	6.11
IAD	38.95	-77.45	6.1
BGLP1	39.93	-77.25	6.06
SAHP1	39.92	-76.38	6.12
WLLM2L	39.62	-77.85	6.1
USBP1	40.08	-77.72	5.86
MDHW03	39.2	-76.78	5.89

PALB10	40.3	-76.26	5.81
RSTM2	39.5	-76.84	5.83
DALD2	38.93	-77.12	5.84
MDAA04	39.13	-76.73	5.79
LNS	40.13	-76.3	5.7
MDHW18	39.24	-76.86	5.7
SMTP1	39.85	-77.5	5.69
MDHW16	39.23	-76.9	5.69
NUI	38.15	-76.43	5.51
MDHW11	39.2	-76.89	5.5
WVJF03	39.35	-77.86	5.49
LVRV2	39.27	-77.64	5.4
TRCP1	39.9	-76.24	5.34
REDD1	38.74	-75.42	5.18
EMMM2	39.68	-77.3	5.25
MDCR04	39.38	-76.92	5.27
MDPG20	38.85	-76.9	5.26
MDPG49	38.73	-77.03	5.26
BRGD1	38.72	-75.59	5.16
PACH11	39.91	-75.7	5.11
DAMM2	39.37	-77.15	5.2
MDPG08	38.8	-76.92	5.14
VIOD1	39.04	-75.57	5.02
WANP1	39.72	-77.61	5.02
HWDV2	38.45	-78.25	5.05
SHRM2	39.4	-77.72	5
MDBL26	39.46	-76.81	5.09
MDMG03	39.04	-77.21	4.98
MDMG65	39.14	-77.41	5.02

Table 2-alternate with station ID data and includes Wakefield (AKQ) data not in Table 2.