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New England Record Maker Rain Event of 29-30 March 2010

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ABSTRACT

A significant East Coast Storm affected New England on 29-30 March 2010. The storm brought heavy rainfall and record flooding to portions of southeastern New England. Providence, RI set a daily rainfall record of 135.1 mm (5.32 inches) on 30 March 2010 and had a two-day total rainfall of 223.3 mm (8.79 inches) setting a new record. Many sites in southern New England set daily and monthly rainfall records. The heavy rain event was relatively well predicted by the National Centers for Environmental Predictions (NCEP) Ensemble forecast systems (EFS).

The forecasts of this event depicted a pattern conducive for heavy rainfall. Standardized anomalies aided in identifying the potential impact of this event. Initially, the NCEP models and ensemble forecast systems predicted a surge of high precipitable water with strong southerly winds over southern New England. As the event unfolded, a second surge of rainfall was predicted with strong easterly winds over the same region as a surface cyclone developed and moved up the coast. This created a unique situation where a Maddox-type synoptic heavy rain pattern evolved into a frontal type event. The two periods of heavy rainfall produced the record two-day totals and contributed to the flood problems.

Both forecast and analyzed anomalies associated with this historic storm will be presented. These data will show how the synoptic-scale anomalies were well correlated with the heavy rainfall. The anomalies facilitate putting this event into a historical perspective relative to previous events. This case demonstrates the utility of using anomalies to increase forecaster confidence and situational awareness. Improved anomaly-based situational awareness combined with probabilistic ensemble quantitative precipitation forecasts can facilitate forecasts of and decisions related to future significant events such as this.

1. Introduction

The third of three significant successive nor'easters to affect the northeastern United States struck on 29-30[1] March 2010. The combined effects of these storms, the first occurring on 13-14 March, another on 22-24 March 2010, produced many new monthly rainfall records in southern New England. Heavy rains from the second storm produced widespread flooding in southern New England and record flooding in Rhode Island and Massachusetts. It was reported

[1] The event date is based on the two days that most of the rain fell. Rain fall after 0000 UTC 31 March through 1200 UTC is credited as falling on the 30th in this instance.

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that Rhode Island experienced the worst flooding in over 200 years. Flooding in Rhode Island closed portions of I-95 and caused Amtrak[2] to cancel trains. Total rainfall from the Stage-IV dataset (Lin and Mitchell 2005; Seo 1998) showed around 128.0 mm (~5 inches) of rainfall in 48 hours from eastern Long Island into eastern Massachusetts (Fig. 1). Over 192 mm (7.56 inches) fell near Providence, RI.

Records for the event included 49.4 (1.95 inches) and 73.8 mm (2.91 inches) at Boston's Logan Airport on 29 and 30 March, respectively. The monthly total at Logan was 377.7 mm (14.87 inches) making March 2010 the wettest March on record and the second month on record, behind the 430.1 mm (17.09 inches) set in the famous "tropical August" of 1955[3]. Blue Hill set a record of 477.8 mm (18.81 inches) eclipsing the August 477.0 mm (18.78 in) set in 1955. At Providence 135.1 mm (5.32 inches) of rainfall was observed on 30 March which was the 5th largest daily rainfall record for the site. The two day total (30-31 March) was 223.3 mm (8.79 inches) breaking the previous all-time record of 199.1 mm (7.84 inches) set on 14-15 October 2005. Providence set a new all-time monthly record of 415.0 mm (16.34 inches) breaking the previous record of 390.7 mm (15.38 inches) set October 2005. Worcester had its second wettest March on record with 257.8 mm (10.15 inches) compared to 282.7 mm (11.13 in) set in March 1936. Worcester had 42.4 mm (1.67 inches) and 61.7 mm (2.43 inches) on the 29th and 30th respectively. Figure 2 shows the 24-hour rainfall for the days that encompassed the event.

Based on the work of Stuart and Grumm (2009), Grumm (2000), and Maddox et al. (1979), this event possessed classic characteristics of a heavy rainfall event. Early in the event the sharp north-south frontal system and moisture plume had a classic Maddox-synoptic event type look. The Maddox-Synoptic event is characterized by a sharp north-south frontal zone with

[2] Wall Street Journal article on the storm.
[3] From KBOX Record Event report of 31 March 2010.

a poleward surge of deep moisture in the warm air. This plume of deep moisture is often associated with strong low-level poleward flow. The plume of deep moisture or atmospheric river (AR: Neiman et al. 2008) along the coast during this event brought heavy rains to the region. The moisture surge was associated with above normal precipitable water (PW) and above normal v-wind anomalies indicating the potential for a meteorologically and climatologically significant event.

It will be shown that as the surface cyclone rolled up the frontal boundary, the event transitioned into a Maddox-frontal system (Maddox et al. 1979); characterized by a quasi east-west frontal boundary with strong easterly winds along and north of the boundary and abundant moisture south of the boundary. The heavy rainfall is often focused on the cool side of the boundary near the region of strong easterly winds; the larger events are often associated with a strong and anomalous low-level easterly jet (Stuart and Grumm 2009). This event had persistent and anomalous moisture and anomalous southerly and then easterly flow, the moisture and implied convergence are key ingredients (Doswell et al. 1996) for a significant heavy rainfall event.

From a prediction perspective, it will be shown that the NCEP models such as the North American Mesoscale Forecast System (NAM) and the Global Forecast System (GFS); and ensemble prediction systems, including the short-range ensemble forecast system (SREF: Tracton and Du 2001), and the global ensemble forecast system (GEFS), correctly predicted the pattern and anomalies. The value of ensembles and anomalies of key ingredients associated with heavy rainfall were demonstrated by Junker et al. (2009). Previous studies have illustrated the value of anomalies in identifying and predicting potentially significant heavy rainfall events

(Hart and Grumm 2001; Grumm and Hart 2001; Graham and Grumm 2010; Stuart and Grumm 2006; Junker et al. 2008).

This paper will document the historic rainfall and flooding event of 30-31 March 2010. The focus is on the pattern and anomalies associated with this meteorologically and climatologically significant event. Forecasts from the NCEP models and EFSs are presented to show the value of ensembles in the forecast process. It will be shown that 32 km SREF did well predicting the pattern and the probability of heavy rainfall.

2. Data collection and methodology

The 500 hPa heights, 850 hPa temperatures and winds, and other standard levels were derived from NCEP GFS, GEFS, and NCEP/NCAR (Kalnay et al. 1996) reanalysis data. The means and standard deviations used to compute the standardized anomalies were from the NCEP/NCER data as described by Hart and Grumm (2001). Anomalies were displayed using GrADS (Doty and Kinter 1995).

The standardized anomalies are computed as:

$$\boldsymbol{SD = (F - M)/\sigma} \qquad \textbf{(1)}$$

Where **F** is the value from the reanalysis data at each grid point, **M** is the mean for the specified date and time at each grid point and **σ** is the value of 1 standard deviation at each grid point. **M** and ***σ*** were computed using 21-day centered values for each variable from the NCEP/NCAR re-analysis data (Kalnay et al. 1996) as described by Hart and Grumm (2001). Model and ensemble data shown here were primarily limited to the GFS and GEFS. The NAM and SREF data were also available for use in this study. All references to anomalies herein refer to standardized anomalies. Furthermore, the terms normalized and standardized anomalies are interchangeable.

For brevity, times will be displayed in day and hour format such as 31/0000 UTC which signifies 31 March 2010 at 0000 UTC. Displays will focus on the observed pattern and forecast issues associated with the pattern.

Precipitation fields were derived from the Stage-IV dataset (Lin and Mitchell 2005; Nelson et al. 2010; Seo 1998). The 24-hour and event total values were derived using the 6-hourly fields and summing over the requisite time periods. These data are available in 1, 6 and 24 hour form. The 6-hourly data is not presented here though they were examined to time the periods of intense rainfall used in the following section. The rainfall amounts at specific locations and the records set during the event were retrieved from National Weather Service public information statements. These data were archived in near-real time.

3. Analysis

a. Synoptic scale pattern

The larger scale pattern is shown in Figs. 3-5. A short-wave length and high amplitude 500 hPa trough was moving over the eastern United States (Fig. 3) with -1 to -2 SD height anomalies. To the east of this upper-level system, a plume of high PW air (Fig. 4) was pulled into the region by 1200 UTC 30 March (Fig. 4d). The PW plume had a subtropical connection containing PW values over 32 mm as far north as New Jersey with 2 to 3SD above normal PW values in this plume or AR (Neiman et. al. 2008 & 2002; Ralph et al. 2006).

The 500 hPa trough cut-off over the northeastern United States around 30/0000 UTC (Fig. 3c) and then lifted slowly to the north and east through 31/1200 UTC (Figs. 3c-f). The initial 250 hPa jet along the coast was elongated from south to north (Figs. 5b-c) and implied a coupled jet entrance and exit regions over the southeastern United States (Figs. 5b-c). The two positive wind anomaly areas defined this area quite well. Over the northeastern United States, the upper-level jet weakened by 30/1200 UTC (Fig. 5d) as the system cut-off. A stronger 250 hPa jet with +3 to +4SD wind anomalies moved from Washington State to the western Great Lakes between 29/1200 UTC and 31/1200 UTC (Figs. 5b-f). This impressive feature flooded the United States with relatively warm Pacific air.

b. Regional pattern and anomalies

The regional depiction of mean sea-level pressure is presented by the NAM 00-hour analysis (Fig. 6). The NAM mean sea-level pressure (MSLP) field for the period of 29/0000 UTC through 31/0000 UTC show a weak cyclone in the Ohio Valley with an implied trailing front at 29/0000 UTC (Fig. 6a). The accompanying 850 hPa winds and u-wind and v-wind standardized anomalies are shown in Figs. 7 and 8, respectively. Though not shown, a surge of cold air pushed below normal 850 hPa temperatures into the Gulf States which were associated with the cyclogenesis to the south (Figs. 6e-d). The resulting cyclone rolled up the coast on the 30th (Figs 6e-h) reaching Long Island, New York at 31/0000 UTC (Fig. 6i).

The initial heavy rainfall on March 29th was associated with the approaching cyclone and the enhanced southerly flow. The 850 hPa wind and v-wind standardized anomalies showed +3 to +4 SD and at times +4 to +5 SD v-wind standardized anomalies from Maryland into southern New England (Figs. 7a-d). The largest v-wind anomalies affected southern New England around 29/1200 UTC (Fig. 7c). During the initial stage of the event 850 hPa u-winds were weak (Figs. 8a-d). The first phase of the rainfall was dominated by this surge of strong southerly flow and the high PW air (Figs. 9a-e) along this zone. This was a textbook example of the Maddox-Synoptic type precipitation event. Lacking a strong frontal zone in a thermal context, the system had a strong moisture zone (Figs. 9a-e) oriented from south to north during the first period of heavy rain. A strong low-level jet was embedded within this moisture zone (Fig. 7). The PW anomalies in this moisture zone were on the order of 2-3SDs above normal during this phase of the event.

The development of the strong 850 hPa easterly jet (Figs. 8f-8i) ahead of the advancing cyclone (Figs 6f-i) focused the heavy rainfall on the 30th over New Jersey, Long Island and southern New England (Fig. 2d). Interestingly the period of heavy rainfall on the 30th was associated with the strong southeasterly jet and -3 to -5 SD u-wind anomalies into southern and eastern New England. The largest 850 hPa u-wind anomalies affected southern New England at 30/1800 UTC (Fig. 8h). The NAM PW and PW anomalies (Figs. 9f-i) become more southwest to northeasterly ahead of the cyclone. This configuration is similar to the Maddox-frontal event type. This second surge of high PW, with 2-3SD anomalies on 30 March suggested "*a double whammy over Long Island and southern New England where the north-south PW maximum (Fig. 9c) and southerly winds (Fig.7c) transitioned into a more east-west boundary (Fig. 9h) with anomalous easterly winds (Fig. 8h)*".

c. Forecasts-GEFS

There was relatively small spread between individual ensemble members leading up to this event, therefore the ensemble mean is used to illustrate how well-predicted the key synoptic features were during this event. This somewhat deterministic presentation of the data facilitates depicting more forecast cycles but limits optimum use of the EFS data in showing the probabilities of occurrence. The relatively large standardized anomalies provide a signal that suggests a convergence of solutions.

The large scale PW plume and attendant AR from 9 GEFS forecasts valid at 1200 UTC on 29 March is shown in Fig. 10. The key point is that the GEFS correctly predicted the AR to surge up the coast. Subsequent forecasts show the inflection of the AR through time (Fig. 10). Relative to the NAM PW analyses, these data suggest that the GEFS correctly predicted the large scale pattern. The smaller PW anomalies relative to the NAM may imply some uncertainty issues, that is, the spread amongst the members slightly reduced the signal in the PW standardized anomalies, especially at longer forecast ranges (Fig. 10a verse Fig. 10i). Though not shown, the GEFS also forecast the strong southerly winds within the moisture plume.

The GEFS 850 hPa winds are shown at 30/1200 UTC (Fig. 11) as the event was transitioning from a north-south to more east-west oriented event. Due to large spread in the GEFS, the longer range forecasts (Figs. 11a-c) did not depict the strong wind anomalies. As the forecasts converged and the spread decreased, the GEFS showed larger total wind anomalies and a significant south-south east jet into New England (Figs. 11e-i). Probabilities of exceeding specific anomaly thresholds would likely provide useful information during events such as this one.

The ensemble mean QPF for the event valid at 31/1200 UTC is shown in Fig. 12. These data show the impact of the first surge of rain with the Maddox-Synoptic event with an elongated North-South axis of heavy rainfall. Clearly, these coarse data underestimated the potential maximum rainfall and they produced too much rainfall too far to the west. They correctly showed the potential for a heavy rainfall and outlined the general threat region quite well.

Figure 13 depicts a more effective use of the EFS data for the operational forecaster as it shows the probability of 4 inches (~100 mm) or more QPF and each ensemble member's 4 inch contour (~100mm). The shorter range forecast converged on the potential for a wider area of 4 inches or more of QPF. Prior to that, forecasts from both 26 and 27 March (not shown) indicated some potential for over 4 inches (~100 mm) of QPF in the same general time window. Due to the location of where each GEFS member predicted the heaviest precipitation the probability of 4 inches of rainfall was relatively low. The spaghetti plots of each member 4 inches (~100 mm) contour (Fig. 13b) suggests that 100 mm or more QPF was a potential outcome. The uncertainty and thus lowered probabilities were a reflection of increased spatial variability of the individual ensemble members. Though not shown, there may have been temporal issues related to the timing of heaviest precipitation from individual ensemble members in the area.

d. SREF forecasts

Based on a comparison of the GEFS forecasts in Figs. 12 & 13; and the observed rainfall in Fig. 1 relative to the SREF data in Fig. 14, it would appear that the SREF forecasts were comparable in skill to those produced by the GEFS. With finer grid spacing it predicted locally higher QPF amounts relative to the GEFS. The SREF QPF probabilities valid for the period ending at 31/0000 UTC are shown in Fig. 14. These data show that the forecast heavy rainfall (Fig.14a) was focused over New Hampshire and Maine and that during the past 24, 30, and 36 hours, heavy rainfall was supposed to affect southern New England and Long Island. The ensemble mean 4 inch (~100 mm) contour is shown in Fig. 14d. The area encompassed by the 4 inch contour was quite extensive.

Other SREF cycles showed comparable skill with the QPF threat area and are not shown. This is due to the SREF's ability to correctly predict the overall pattern. The pattern is illustrated in Fig. 15 using the exceedance probabilities of key parameters associated with heavy rainfall including the probability of the 850 hPa u-winds to be 2.5SDs below normal (Fig. 15a), the probability of the 850 hPa total winds to be 2.5SDs above normal (Fig. 15b), the probability of the PW values to exceed 2SDs above normal along with the 6.25 and 25mm mean contours (Fig. 15c), and the probability of the mean sea-level pressure to be 1.5 SDs below normal. The threshold values selected are based on previous work on standardized anomalies related to heavy rainfall. Fig. 15 clearly shows a high probability of large anomalies in the key fields often associated with heavy rainfall. The high probability of -2.5SD 850 hPa wind anomalies illustrate this point.

4. Conclusions

A record breaking rain event affected Long Island, New Jersey and southern New England on 29-30 March 2010. The storm brought over 100 mm (4 inches) of rainfall to a large swath of the region and locally produced in excess of 200 mm (8 inches) of rainfall over Long Island, Rhode Island and Massachusetts. The rain led to widespread flooding in southeastern New England. Rhode Island experienced what was reported as the worst flooding in over 200 years. As shown here, the pattern and the QPF were relatively well predicted by the NCEP EFS and provided good clues to the potential for this record event.

In the eastern United States, cold season heavy rain events typically transition from easterly flow (frontal) to southerly flow (Synoptic) events. The event of 13-16 April 2007 was a classic example of this frontal to synoptic event type of evolution (Stuart and Grumm 2009). The event of 29-30 March 2010 fit the archetype of the two primary rainfall events observed over the eastern United States. The heavy rain ending at 30/1200 UTC (Fig. 2) produced 50-75 mm (Figs. 2b-2c) of rainfall and was associated with the strong southerly flow (Fig. 7) and surge of high PW air in this moisture zone (Fig. 9). This produced locally 50-75 mm of rainfall over eastern Long Island and Rhode Island. The transition from a *Maddox-Synoptic to Maddox-*

frontal type system produced the second round of heavy rainfall on 30 March (Fig. 2d). The developing strong easterly low-level jet and strong u-wind anomalies and resulting 850 hPa strong moisture flux (Fig. 16f) indicated the potential for heavy rainfall.

The evolution of the moisture field with an inflection in the high PW plume or AR as the low-level easterly jet pulled the moisture westward, pivoting it over eastern Long Island and southeastern New England. This strong low-level jet was associated with a strong 250 hPa jet (Fig. 5) and a coupled jet (Uccellini and Kocin 1987) as depicted in Figures 5b & 5c. At 850 hPa, this strong low-level jet and AR produced +5 to +6 σ moisture flux anomalies (Fig. 16). Moisture flux anomalies of +3 to +5 σ were over southern New England at 29/1200 UTC (Fig. 16a) and +3 to +4 σ moisture flux anomalies were present again during the frontal phase at 30/1800 UTC (Fig. 16f). This second surge of moisture and anomalous moisture flux produced the record rainfall on the 30th (Figure 2) valid at 1200 UTC 31 March 2010. This "*double whammy*" led to the historic flooding in Rhode Island.

The NCEP GEFS and SREF guidance presented here suggests that both systems did relatively well in predicting the pattern conducive to heavy rainfall. Nine different GEFS forecast cycles (Fig. 12) showed significant QPF amounts over the correct region. Only 2 probabilistic forecasts were presented, one of which showed a 30 to 50 percent chance of over 4 inches (~100 mm) of rainfall. It is unknown how rare a 4 inch (100 mm) rainfall is in the NCEP GEFS. During this event, both NCEP EFSs predicted strong southerly flow with an AR moving into the region and the subsequent development of an easterly low-level jet north of the cyclone which developed along the north-south frontal zone.

The probabilistic QPF's in Figures 13 and 14 along with the predicted pattern may have provided confidence in a potentially significant high impact weather event (HIWE). Figure 14 has the added benefit of visualizing the probability of discrete precipitation amounts of discrete periods of time. This may aid in identifying periods of heavy rainfall which may be critical in decision making activities related to the impacts of the rainfall.

Figures 14-15 showed the probabilities of exceedance of key parameters associated with heavy rainfall. The selected fields and thresholds were based on studies by Grumm and Hart (2001) and Stuart and Grumm (2006 and 2009). *These data illustrate the potential to show the threat and provide confidence of the potential for a HIWE based on key probabilities*.

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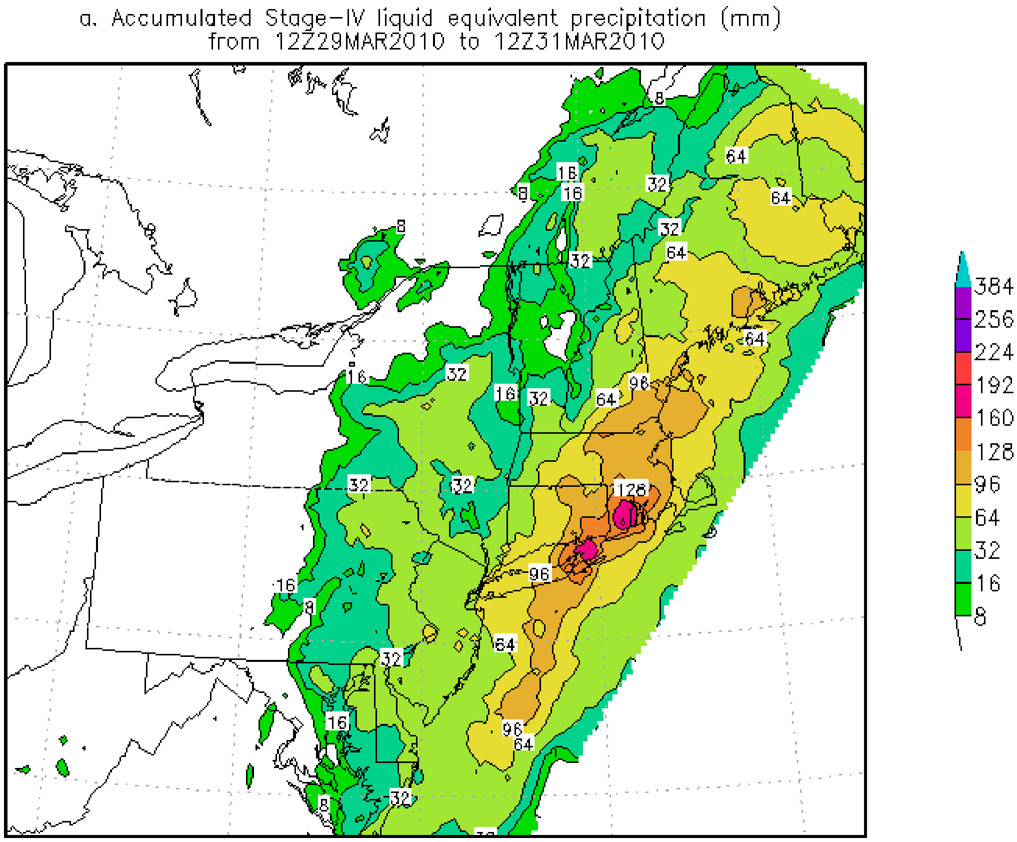

Figure 1. Total observed liquid precipitation (mm) from 1200 UTC 29 March through 1200 UTC 31 March 2010. From the 4km stage-IV data set.

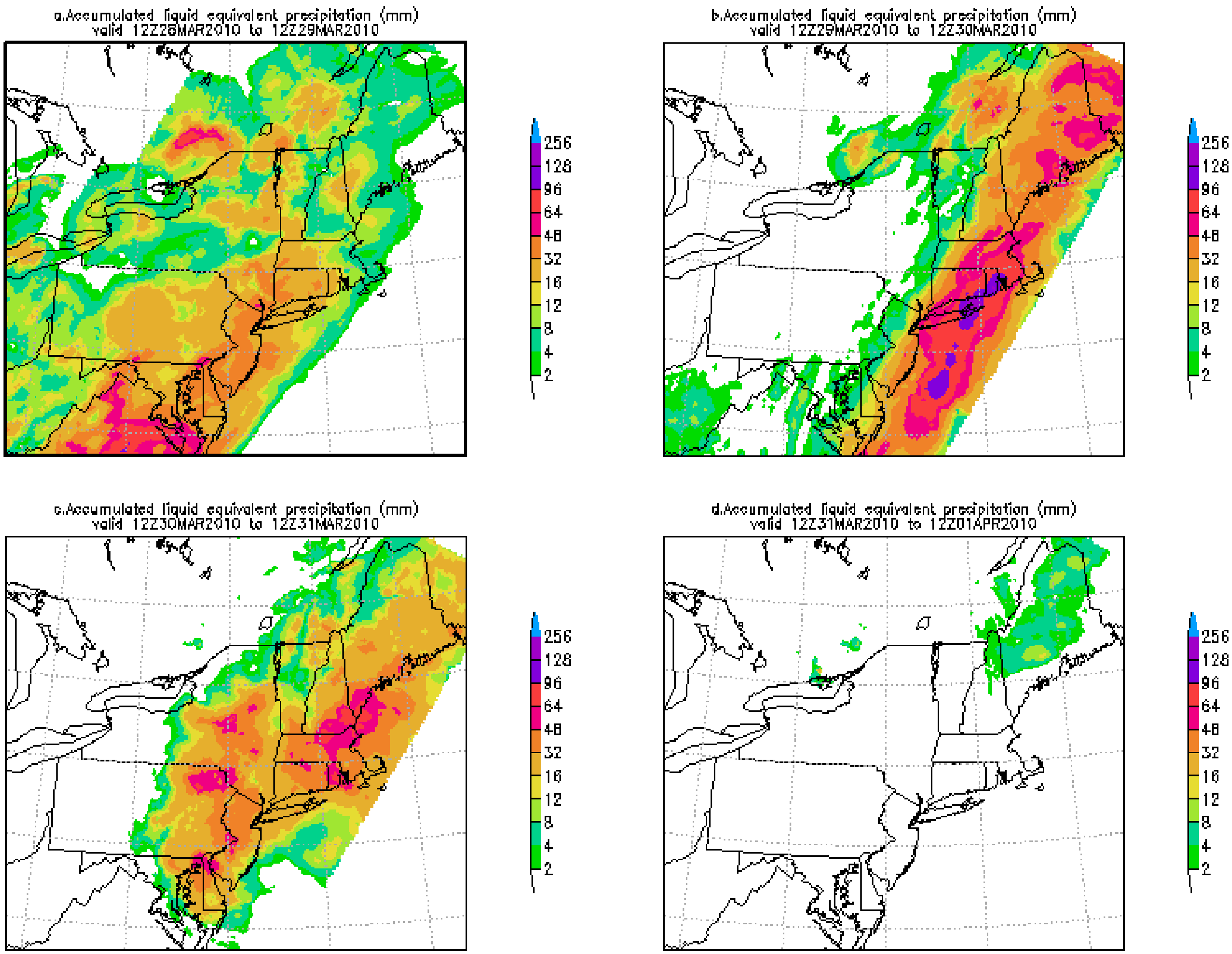

Figure 2. As in Fig. 1 except showing the 24-hour precipitation totals ending at a) 1200 UTC 29 March 2010 (upper left), b) 1200 UTC 30 March (upper right), c) 1200 UTC 31 March 2010 (lower left), and d) 01 April 2010 (lower right).

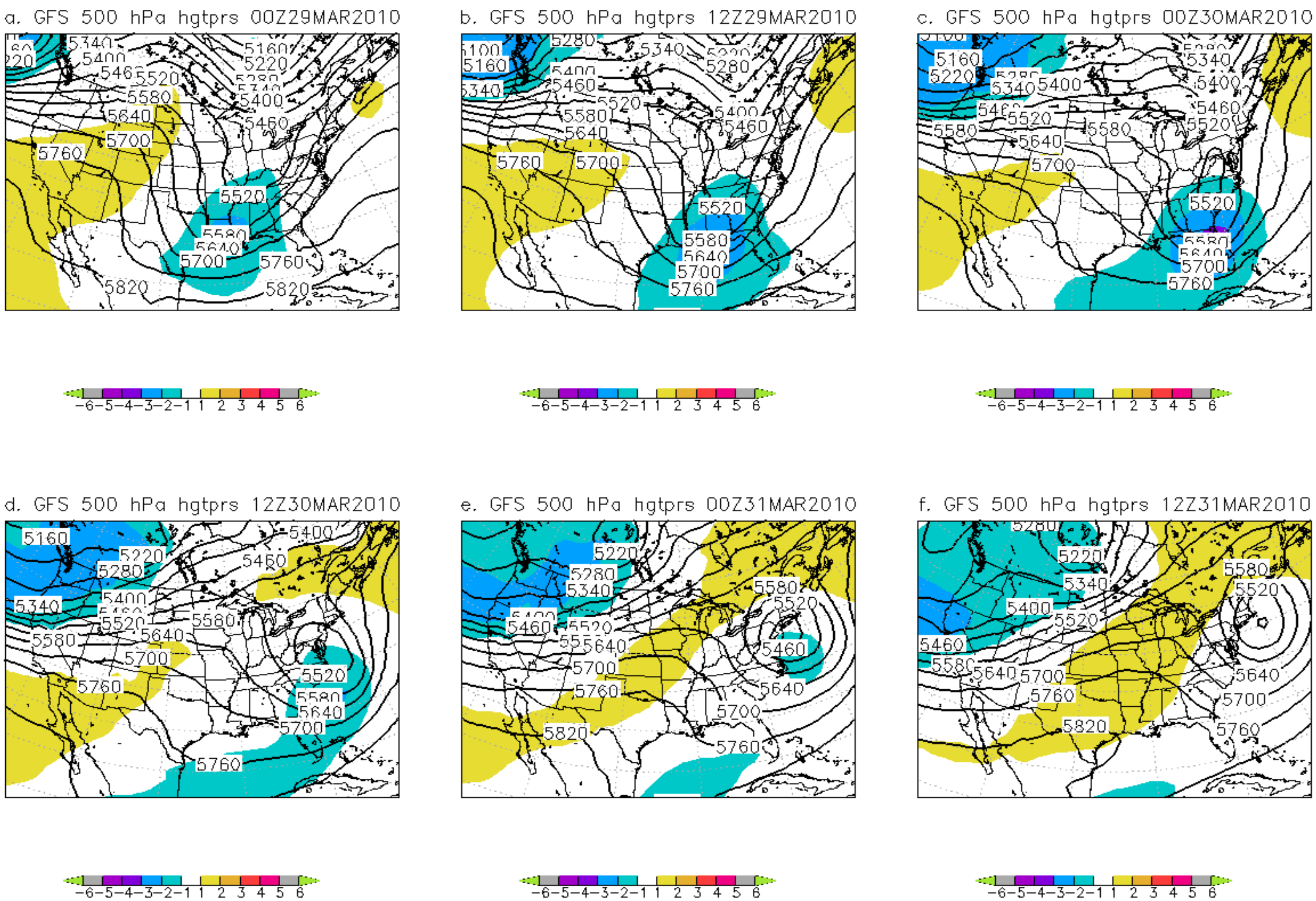

Figure 3. GFS 00-hour forecasts of 500 hPa heights (m) and 500 hPa height anomalies (standard deviations) valid at a) 0000 UTC 29 March, b) 1200 UTC 29 March, c) 0000 UTC 30 March, d) 1200 UTC 30 March, e) 0000 UTC 31 March 2010, f) 0000 UTC 31 March 2010.

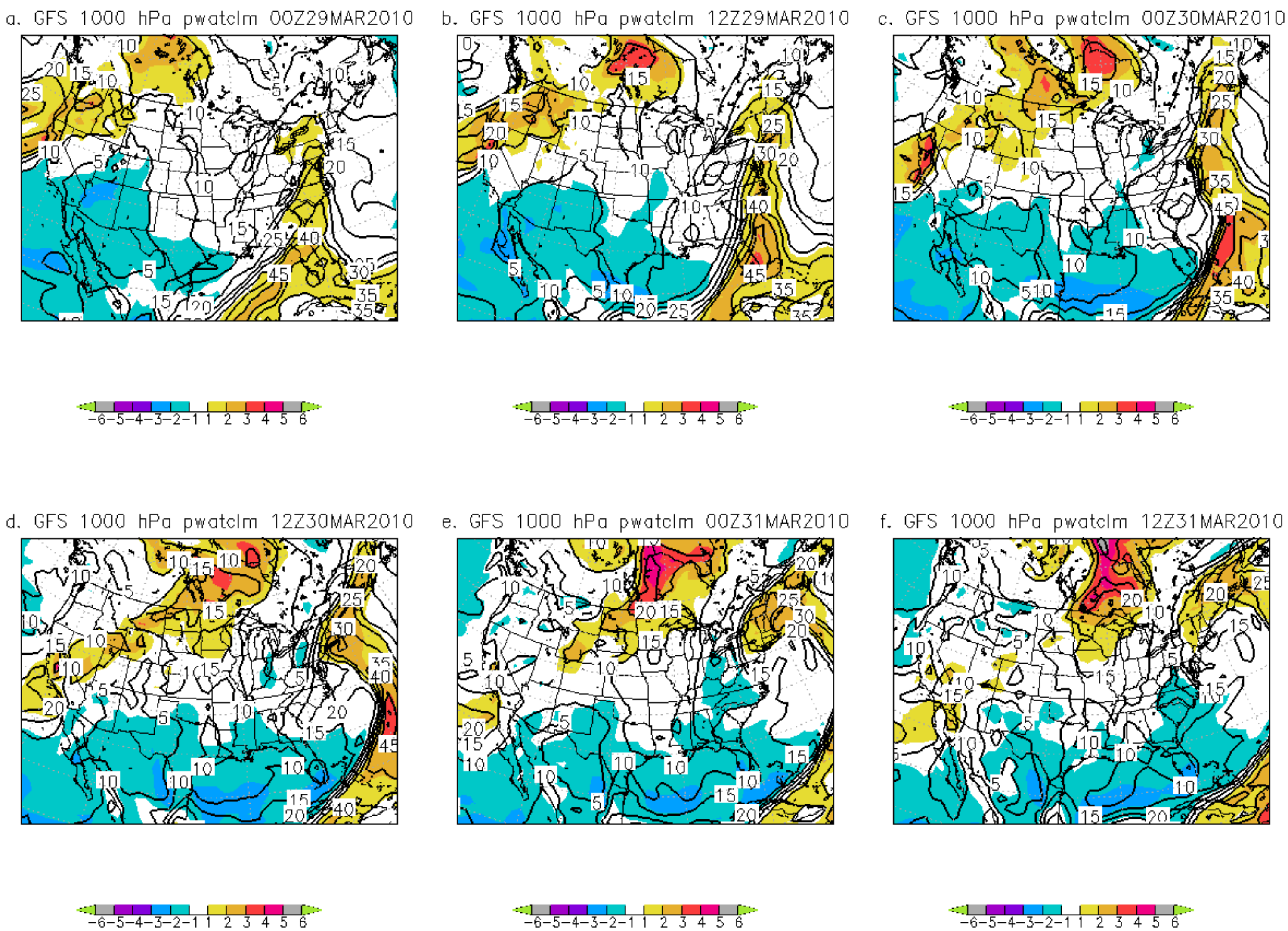

Figure 4. As in Fig. 3 except for precipitable water (mm) and precipitable water anomalies (standard deviations).

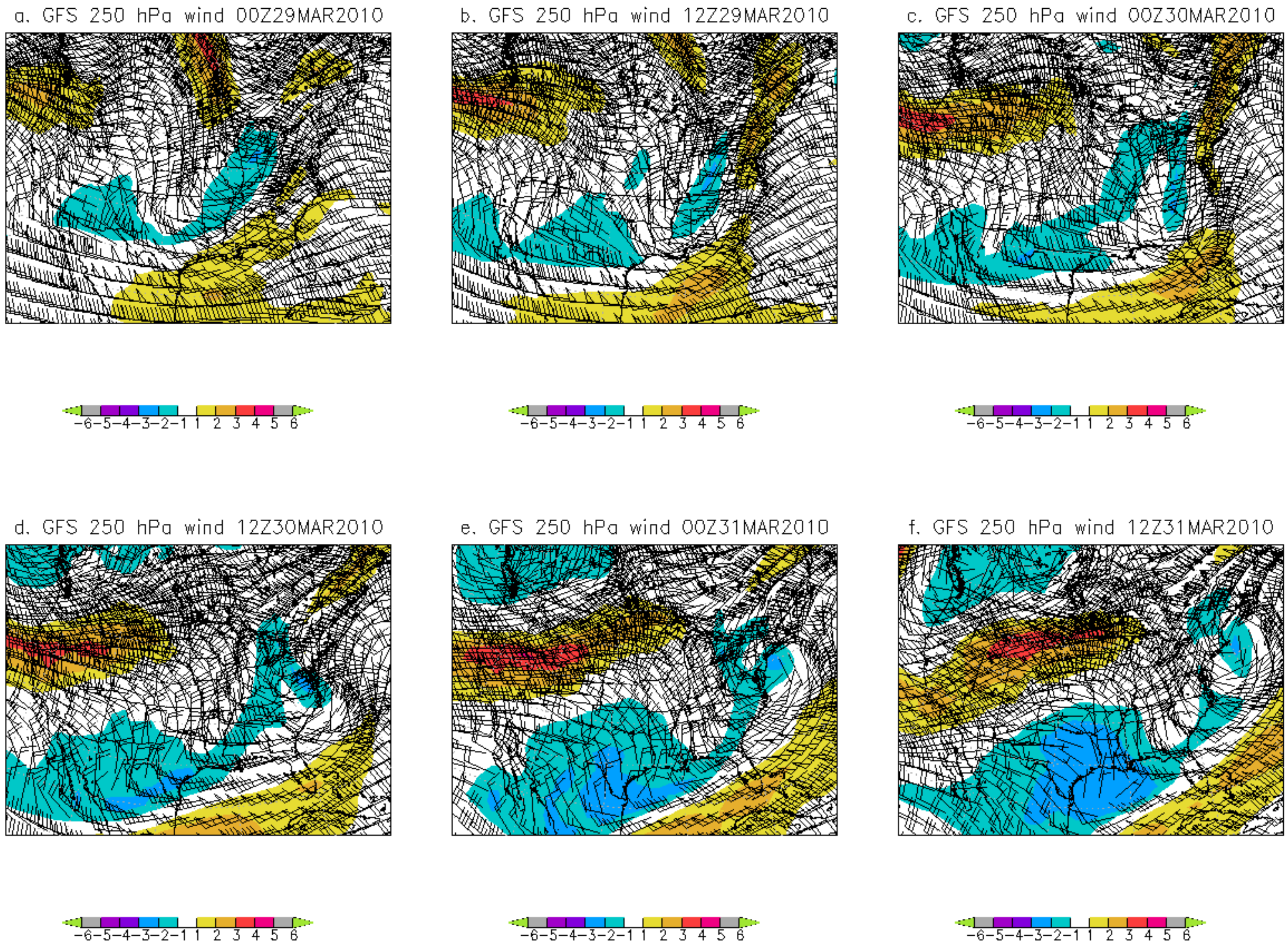

Figure 5. As in Fig. 3 except for 250 hPa winds (kts) and wind anomalies.

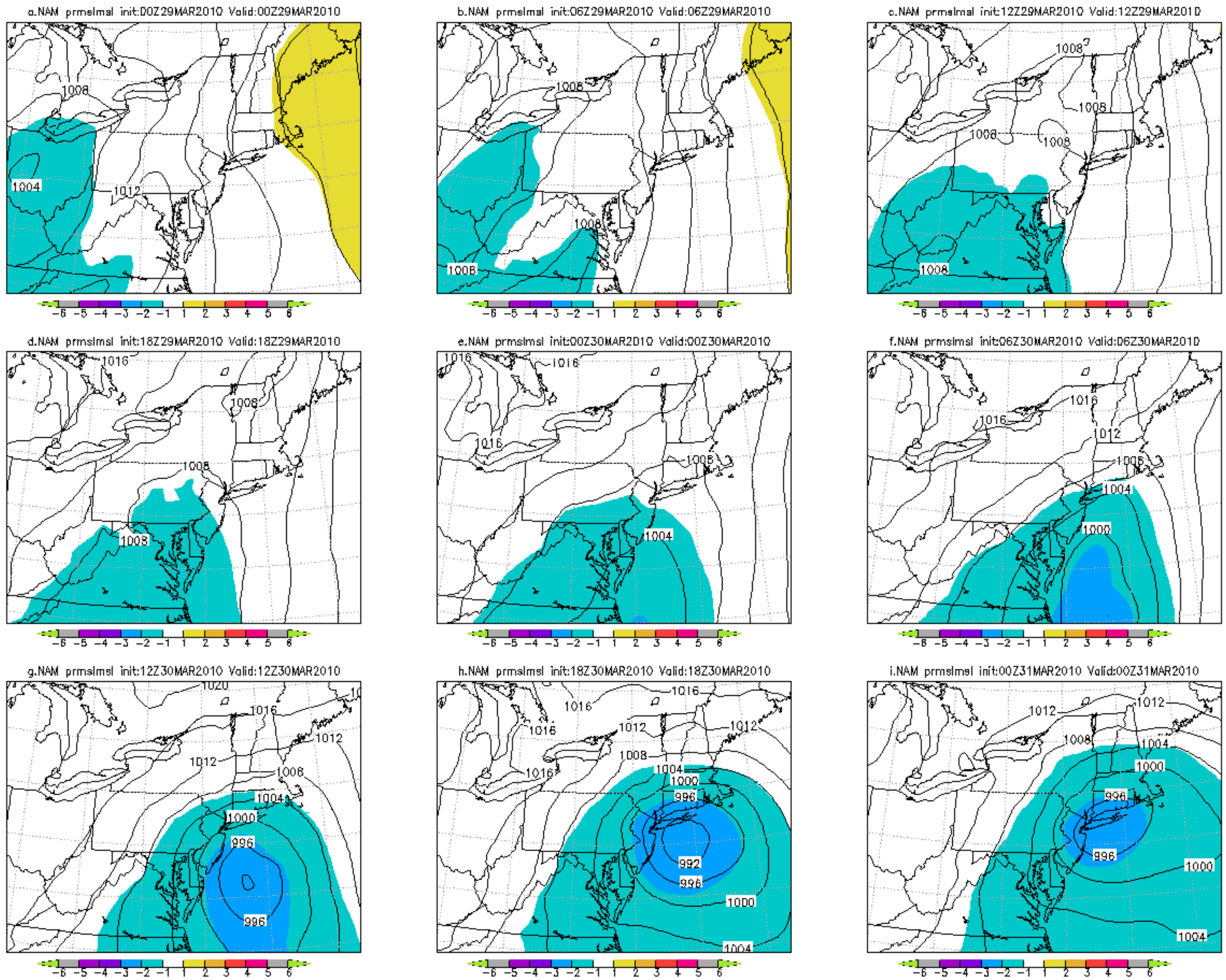

Figure 6. NAM 00-hour forecasts of mean sea-level pressure (hPa) and pressure anomalies valid at valid at a) 0000 UTC 29 March, b) 0600 UTC 30 March, c) 1200 UTC 30 March, d)1800 UTC 29 March, e) 0000 UTC 30 March, f) 0600 UTC 30 March, g) 1200 UTC 30 March, h) 1800 UTC 30 March and i) 0000 UTC 31 March 2010.

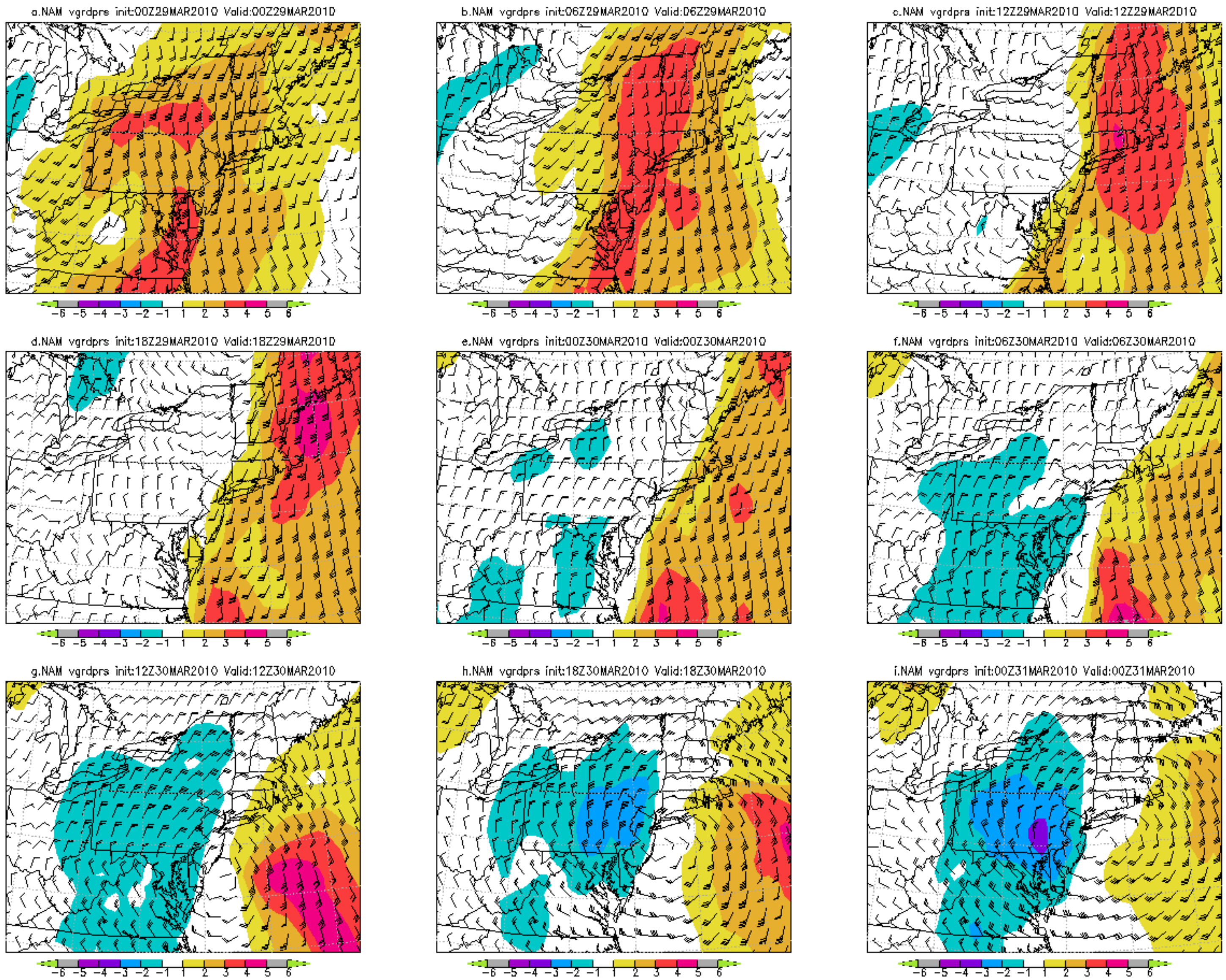

Figure 7. As in Figure 6 except NAM 850 hPa winds and v-wind anomalies.

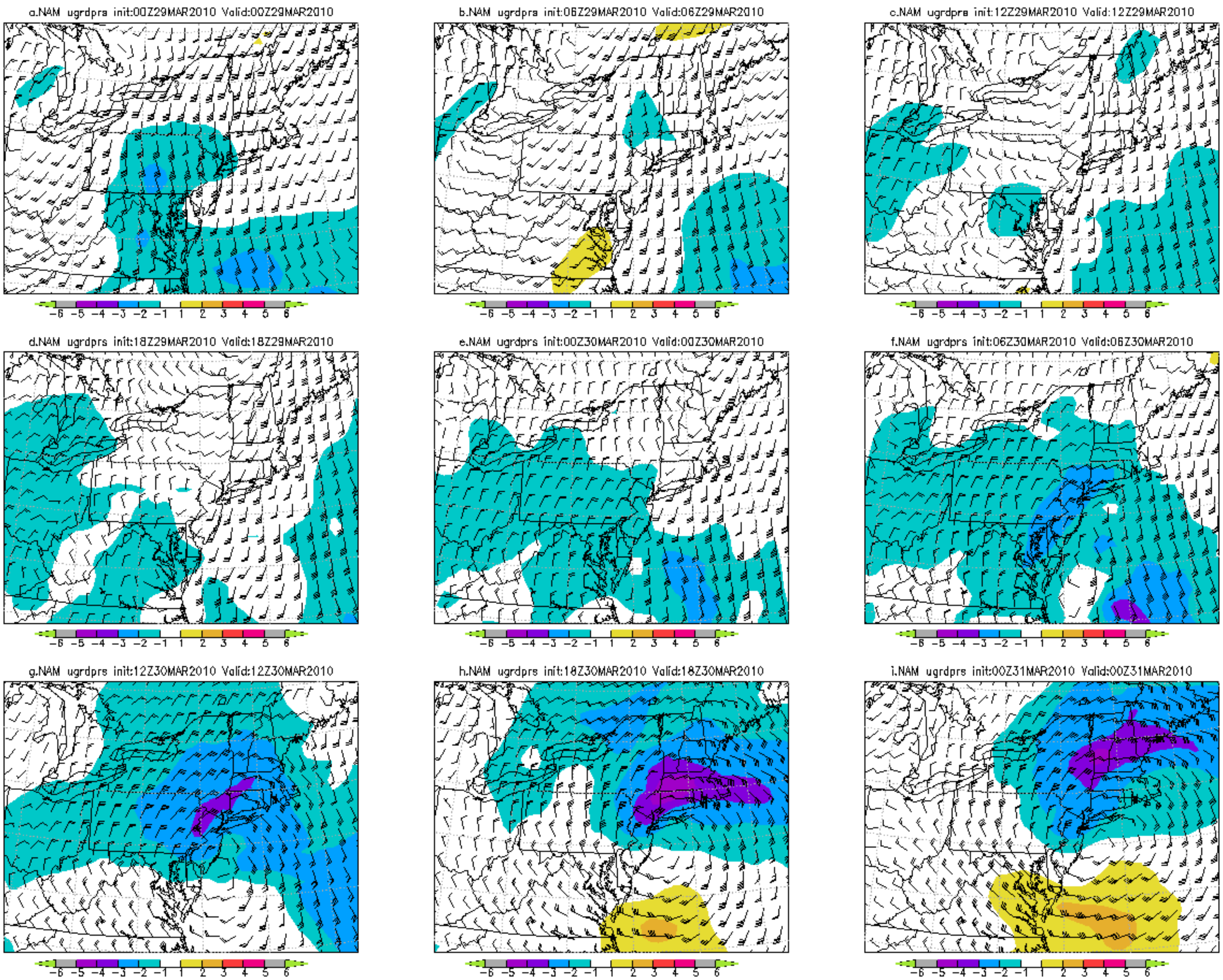

Figure 8. As in Fig. 7 except for 850 hPa winds and u-wind anomalies.

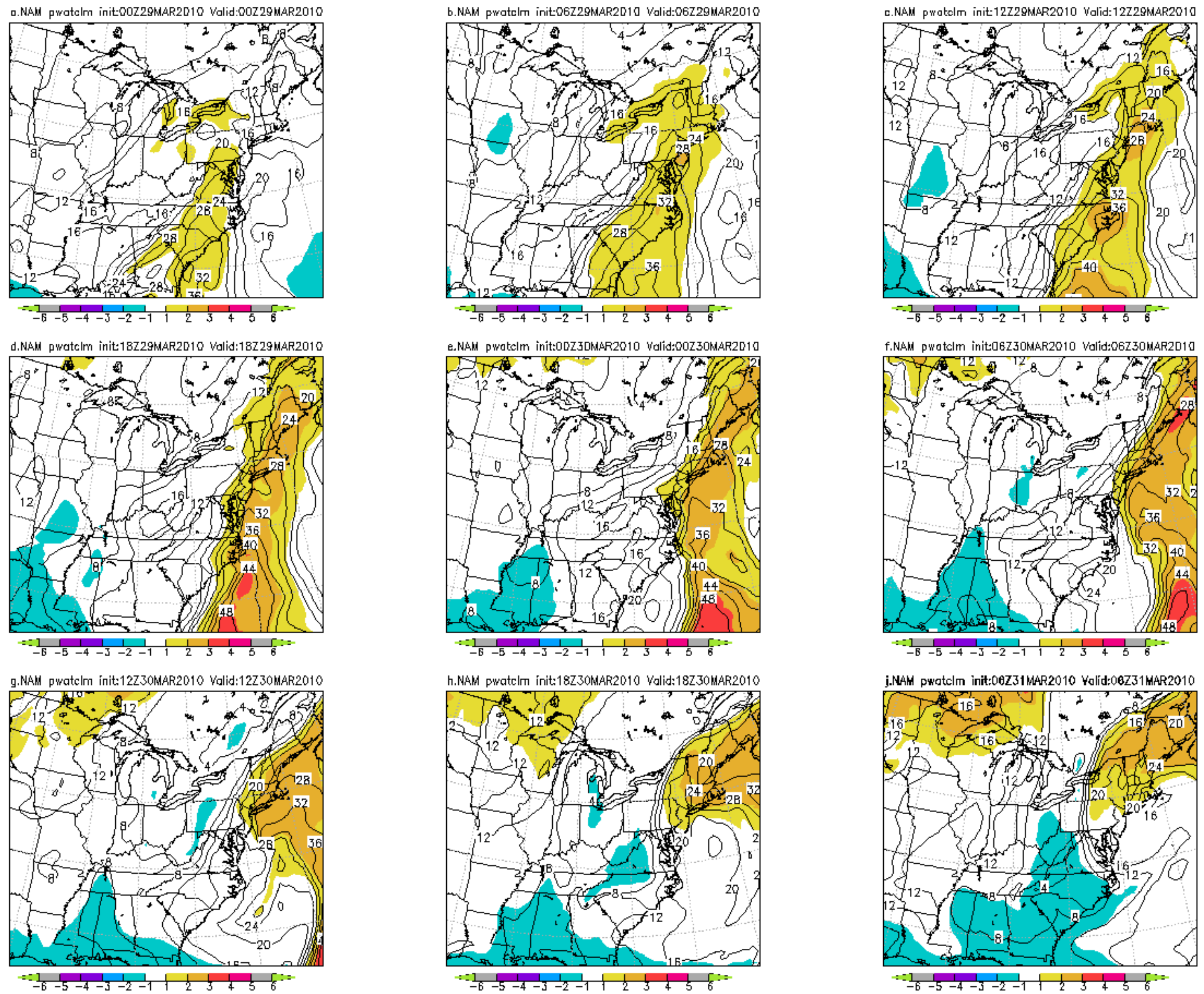

Figure 9. As in Fig. 8 except NAM PW forecasts for the times shown.

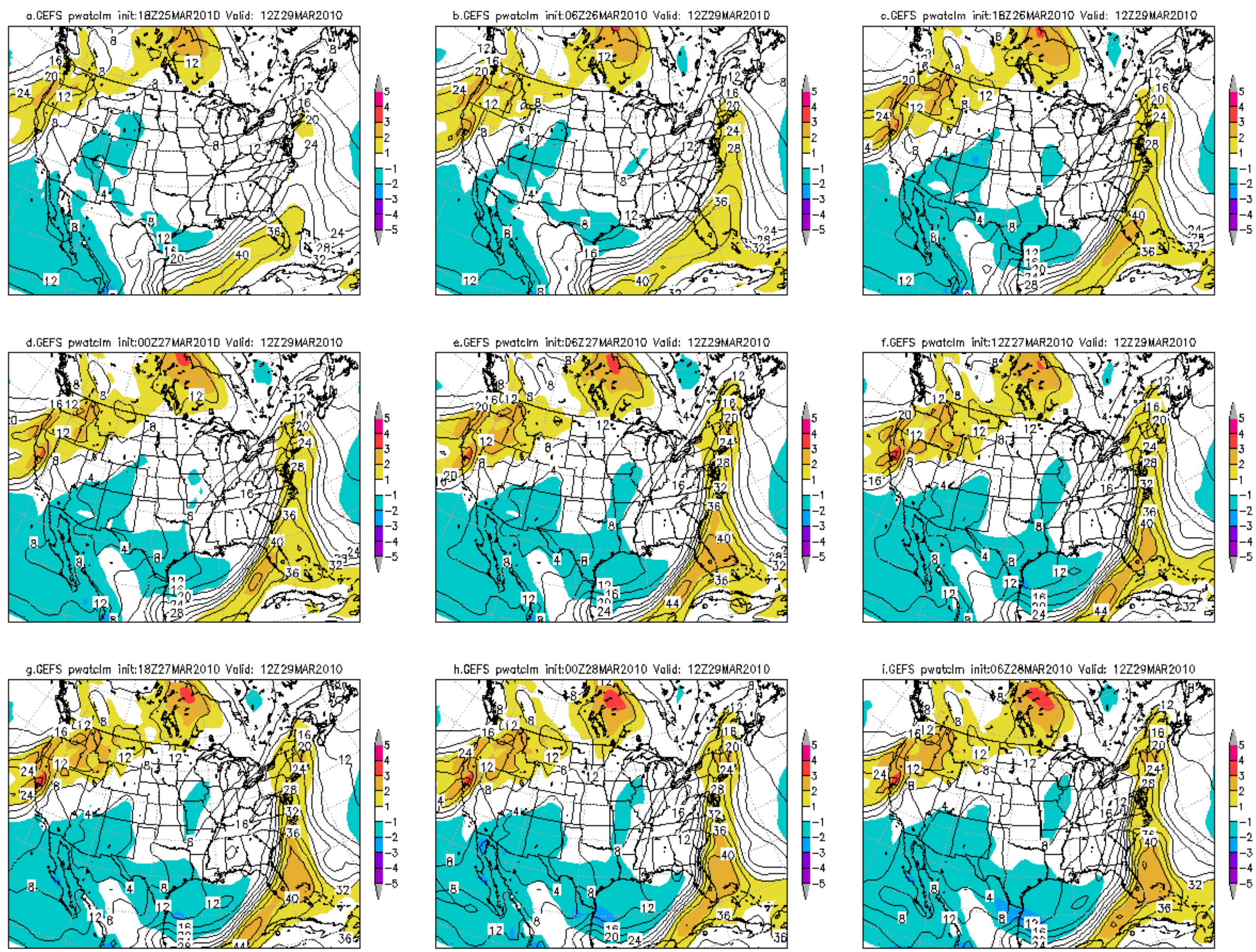

Figure 10. GEFS ensemble mean forecasts of PW and PW anomalies valid a 1200 UTC 29 March 2010 from forecasts initialized at a) 1800 UTC 25 March, b) 0600 UTC 26 March, c) 1800 UTC 26 March, d) 0000 UTC 27 March, e) 0600 UTC 27 March, f) 1200 UTC 27 March, g) 1800 UTC 27 March, h) 0000 UTC 28 March and i) 0600 UTC 28 March 2010.

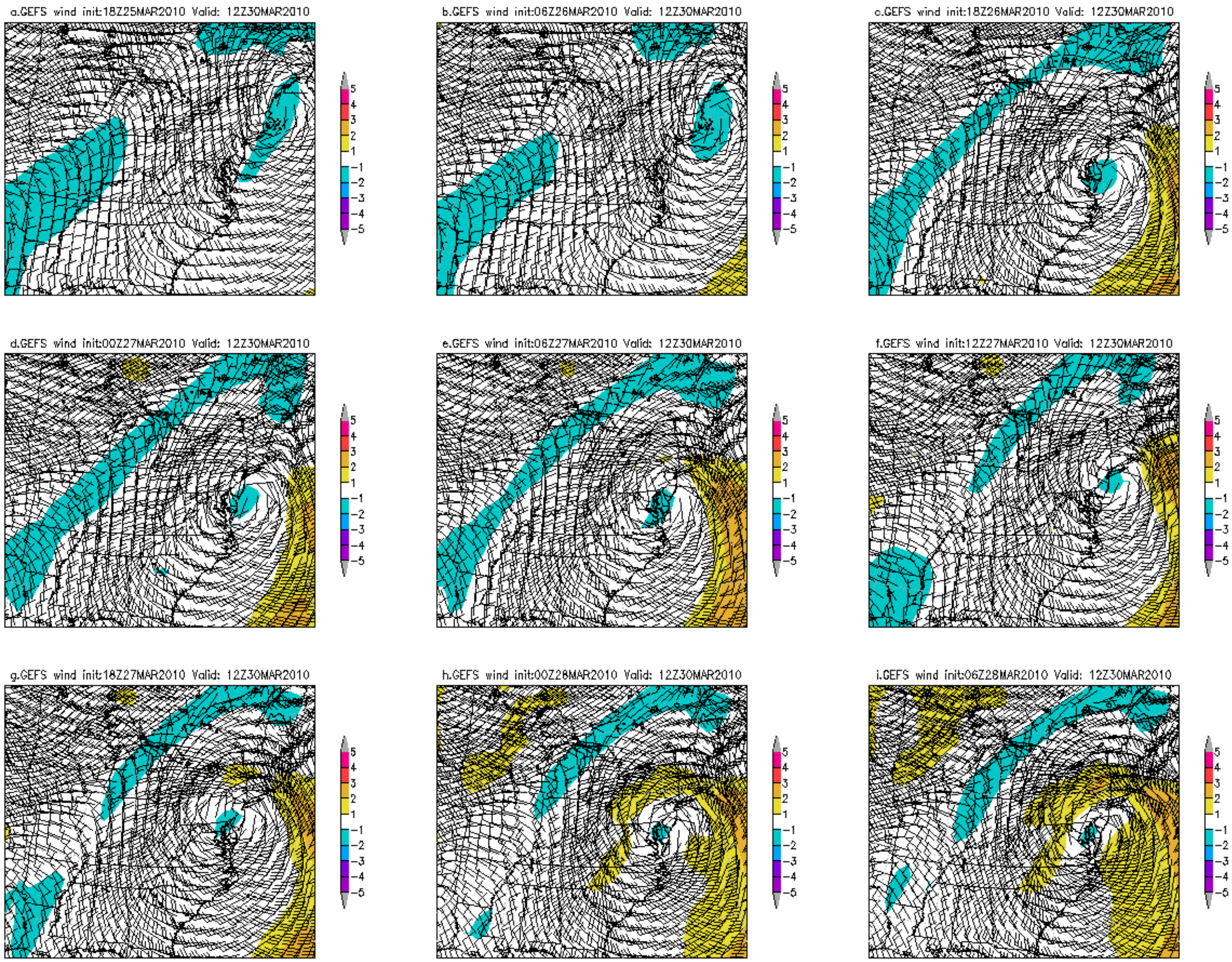

Figure 11. As in [Fig. 10] except for GEFS 850 hPa winds and total wind anomalies for the forecasts ending at 1200 UTC 30 March 2010.

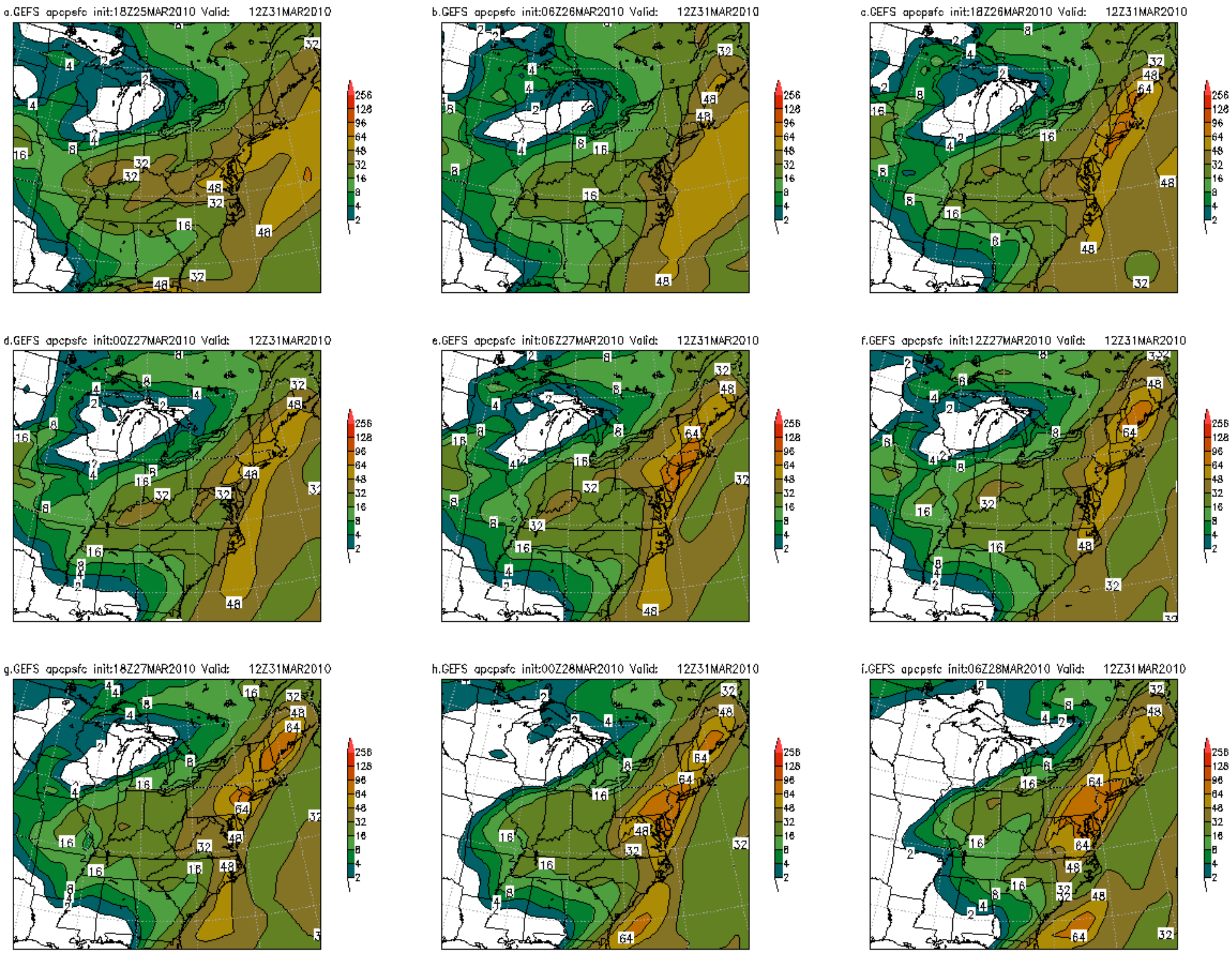

Figure 12. As in Fig. 10 except showing the mean total accumulated precipitation (mm) from the GEFS for the forecasts ending at 1200 UTC 31 March 2010.

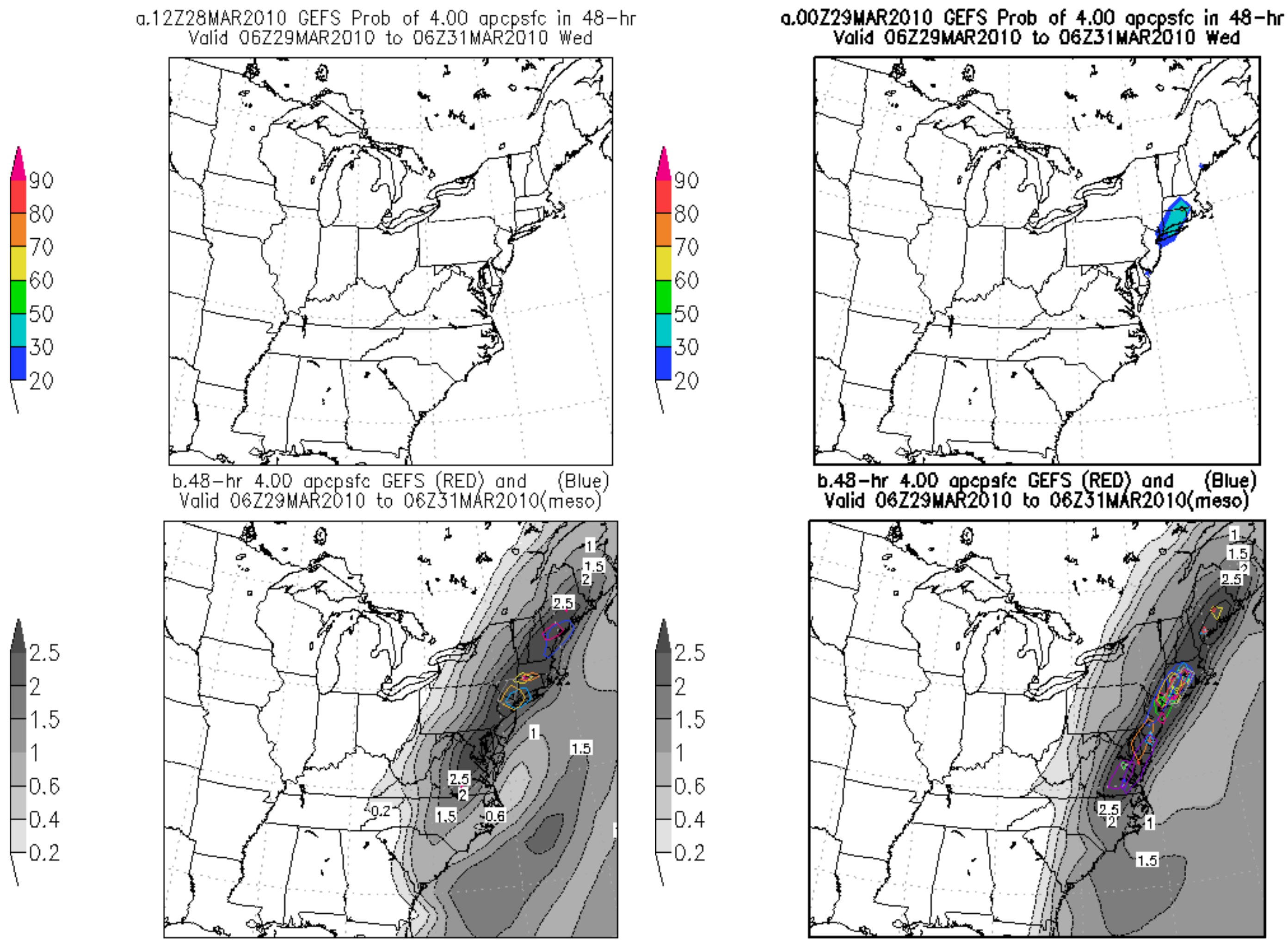

Figure 13. GEFS QPF from forecasts initialized at (a) 1200 UTC 28 March and (b) 0000 UTC 29 March 2010. Upper panels a) show the probability of 4.00 inches or more QPF in the 48 hour period ending at 0600 UTC 31 March. Lower panels (b) show the ensemble mean QPF and each member's 4.00 inch contour.

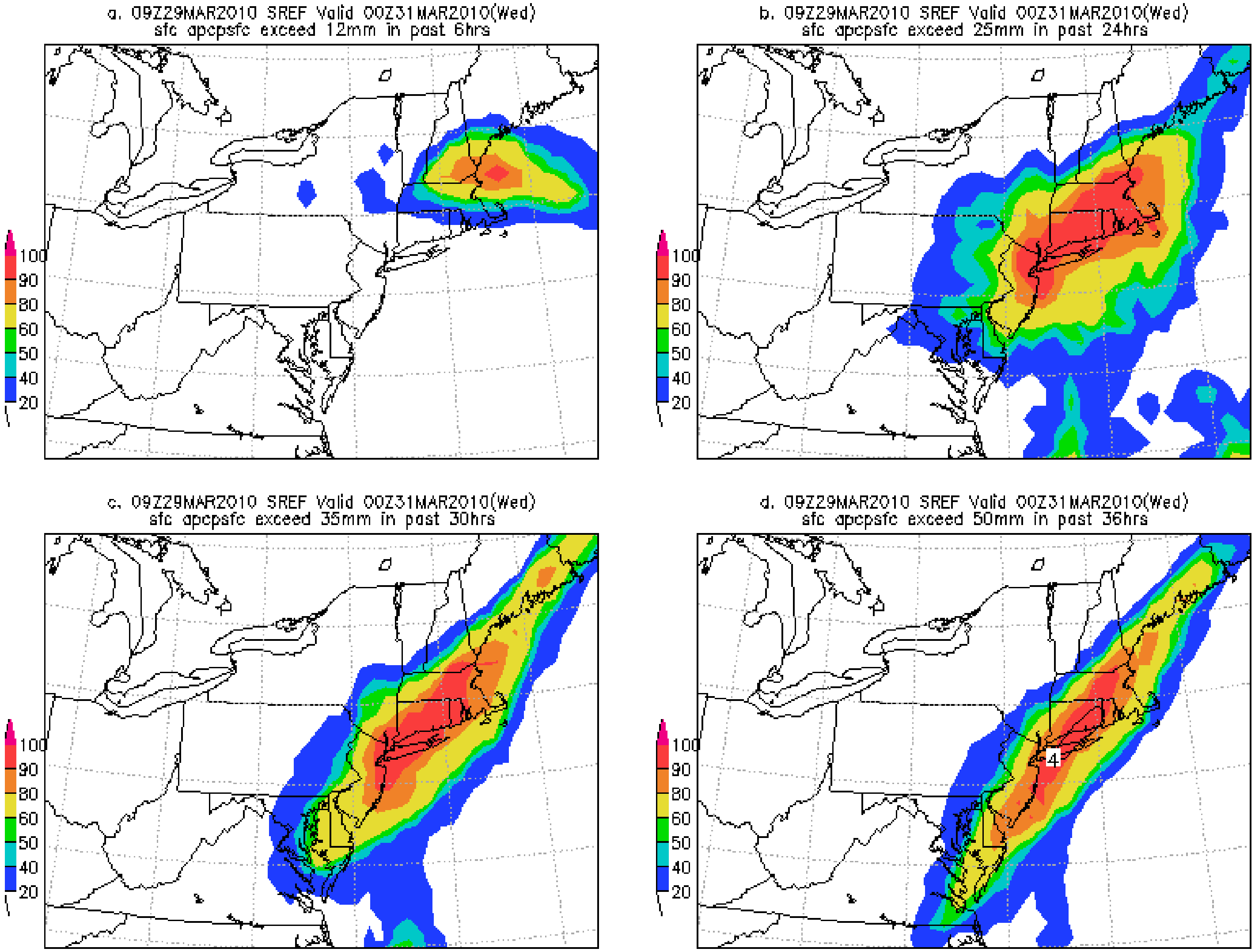

Figure 14. NCEP SREF initialized at 0900 UTC 29 March 2010 showing the probability of a) 12 mm of QPF in 6 hours, b) 25 mm in 24 hours, c) 35mm in 30 hours, d) 50mm in 36 hours for the period ending at 0000 UTC 31 March 2010. Shading shows probability and contours in 4 inch increments are drawn where applicable.

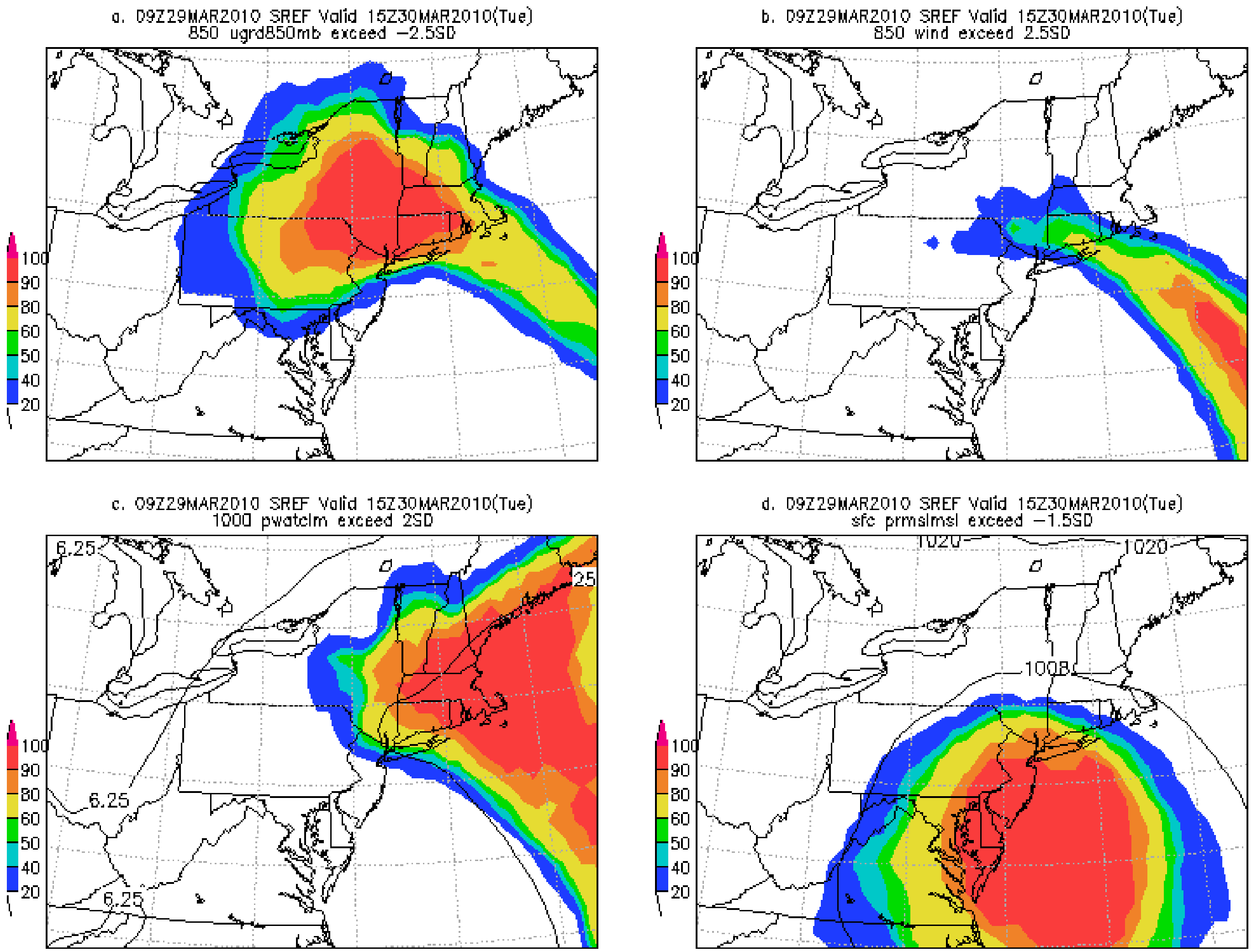

Figure 15. As in Fig. 14 except SREF probability forecasts valid at 1500 UTC 30 March 2010 showing a) the probability of 850 hPa u-winds of -2.5SD or lower anomalies, b) the probability of the 850 hPa wind being +2.5 SDs above normal, c) the probability of the precipitable water being +2SDs above normal along with the 6.25 and 25mm contours, and d) the probability of the mean sea level pressure anomalies -1.5SDs or lower and the 1008 hPa and 1020 contours.

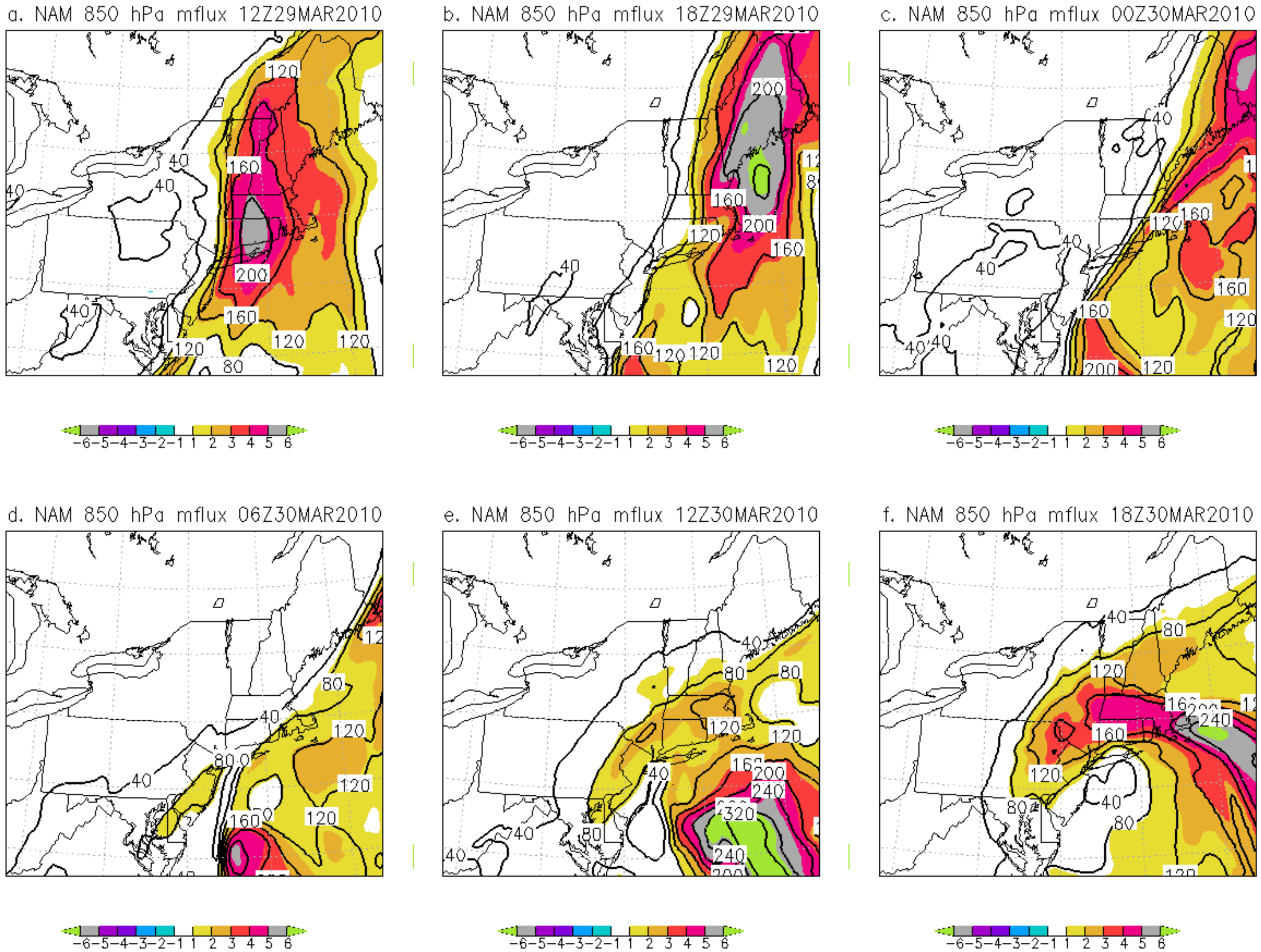

Figure 16. NCEP NAM 850 hPa moisture flux (gm*kg^{-1}s^{-1}) and moisture flux normalized anomalies from the 00-hour NAM valid at a) 1200 UTC 29 March 2010, b) 1800 UTC 29 March 2010, c) 0000 30 March 2010, d) 0600 UTC 30 March 2010, e) 1200 UTC 30 March 2010 and f) 1800 UTC 30 March 2010. Moisture flux contours are every 40 gm*kg^{-1}s^{-1}.