P9.7 The 2004 April Fool's New England Flooding Event: Analysis of Three Heavy Precipitation Episodes Associated with a Slow Moving Cutoff Cyclone.

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1. INTRODUCTION

Slow moving cutoff cyclones have been shown to be associated with heavy rainfall and deep convective outbreaks in the northeast United States (LaPenta et al. 1995; Novak et al. 2002; Najuch et al. 2004), accounting for as much as 30% of the annual rainfall in the region (Atallah et al. 2002). During the three day period from 0600 UTC 31 March – 0600 UTC 3 April 2004, a slow moving cutoff cyclone was responsible for as much as 19.4 cm (7.63 in) of rainfall in New England. Widespread urban and small stream flooding occurred in the wake of the rainfall, prompting the issuance of 21 Flood Warnings in 4 states (Fig. 1). Significant river flooding was also observed in New England. Of particular interest was that the heavy precipitation fell during three separate episodes. This paper will explore the relative roles of thermal and vorticity advection, orographic forcing, moisture availability, and stability in contributing to the heavy rains of each precipitation episode, and document the performance of numerical model guidance.

2. DATA SOURCES

Weather Surveillance Radar-1988 Doppler (WSR-88D; Klazura and Imy 1993) 2 km mosaic radar imagery and the 4 km Stage IV precipitation dataset (Seo 1998) were used to document the spatial and temporal evolution of the precipitation event. Rapid Update Cycle (RUC) model analyses were used to investigate the synoptic and mesoscale forcing environment. The RUC was run at a horizontal resolution of 20 km with 50 vertical levels at the time of this case (Benjamin et al. 2004). To investigate the performance of model guidance, forecast data from the

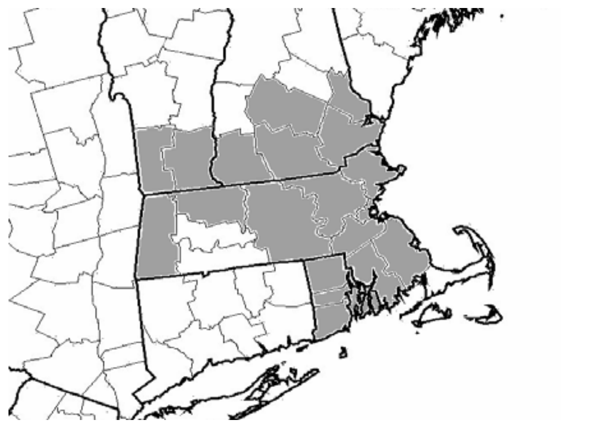

Fig. 1. Map of southern New England. Counties where Flood Warnings were issued during the 31 March 2004 – 3 April 2004 event are shaded.

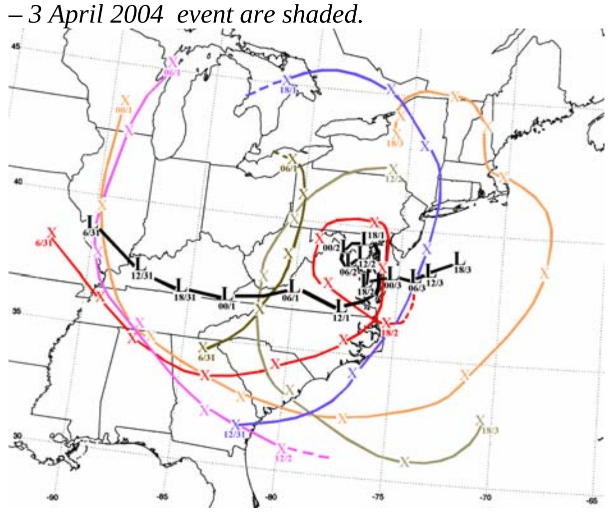

*Fig. 2. Track of 500-hPa cutoff low center and its associated transient 500 hPa short waves (defined in text) derived from RUC analyses during the 0600 UTC 31 March 2004 – 1800 UTC 3 April 2004 period. The position of the cutoff low center every 6 h is marked by a bold "**L**" and a time label ("time UTC/ day of month"). Positions of individual short waves are marked every 6 h by an "X", with starting and ending times labeled and respective tracks delineated in separate colors.*

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Eta model were used. The Eta was run at 12 km horizontal resolution with 60 vertical levels (Rogers et al. 2001). Archived 80 km and 40 km horizontal resolution display grids from the Eta model and 20 km grids from the RUC model were used.

3. RESULTS

a. Event Analysis

The track of the 500-hPa cutoff low center and its associated transient 500-hPa short waves during the 0600 UTC 31 March 2004 – 1800 UTC 3 April 2004 period are shown in Fig. 2. The cutoff low center slowly moved east during 31 March 2004 and crossed the Appalachian Mountains on 1 April 2004. The cutoff then stalled over Virginia on 2 April 2004, before being "kicked" east by an approaching midlatitude trough (not shown) on 3 April 2004. Note that through the three-day progression of the cutoff, seven individual 500-hPa short waves [defined as coherent (traceable for at least 12 h) local 500-hPa vorticity maxima (greater than 4 x 10^{-5} s^{-1} over the background vorticity)] were tracked in the RUC analysis fields rotating around the 500-hPa cutoff low center. Two of these short waves were tied to the latter two episodes of precipitation affecting New England.

The total accumulated precipitation during the 0600 UTC 31 March 2004 – 0600 UTC 3 April 2004 period is shown in Fig. 3a. The cutoff cyclone was responsible for heavy precipitation across a large portion of the eastern United States, with the heaviest three-day total occurring over southern New England. A 500-hPa low center-relative storm total precipitation plot (not shown) shows that the heaviest precipitation occurred in the northeast quadrant of the cutoff cyclone. This is consistent with the unpublished work of Atallah et al. (2002).

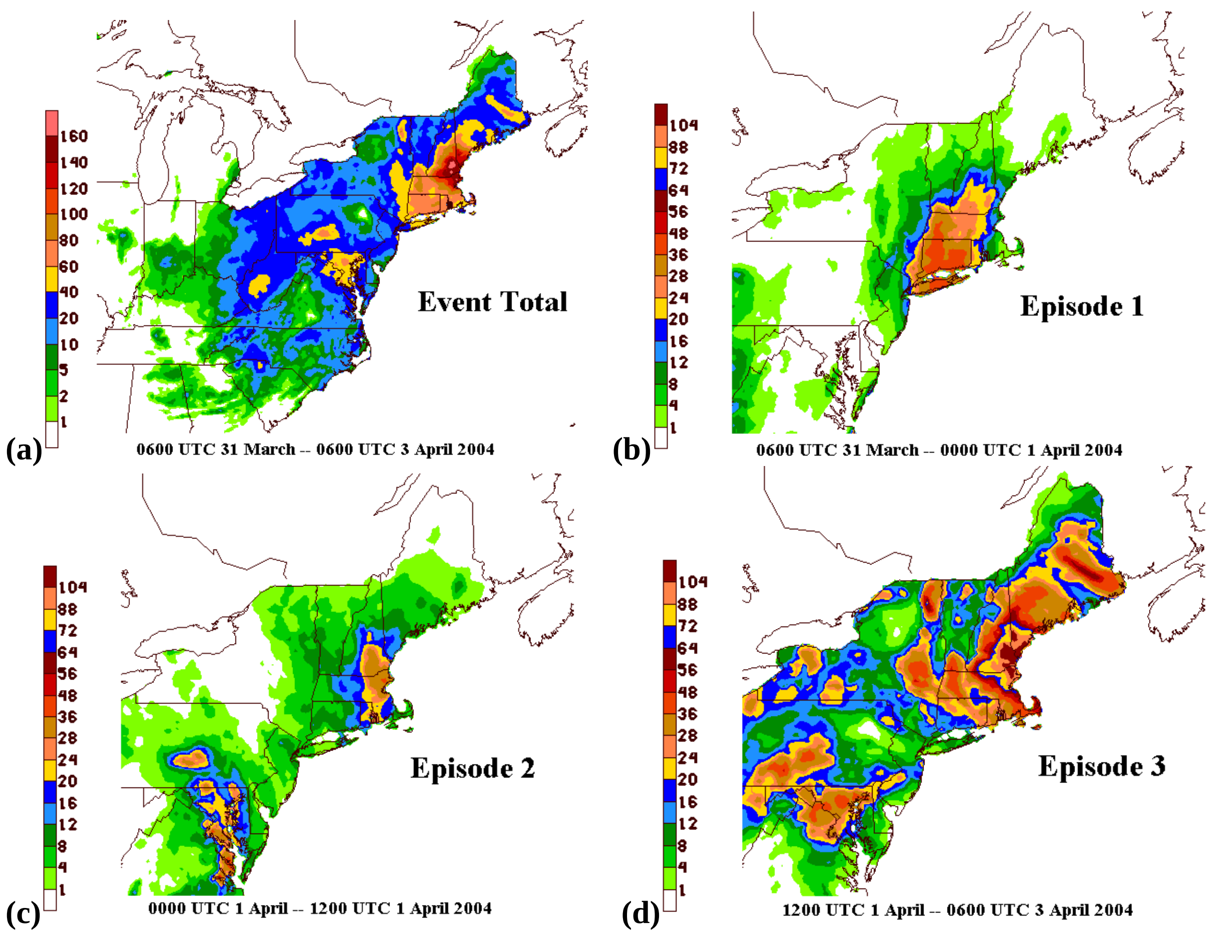

Fig. 3. (a) Stage IV accumulated precipitation (mm) during the 0600 UTC 31 March 2004 – 0600 UTC 3 April 2004 period. (b) As in (a), except during the 0600 UTC 31 March 2004 – 0000 UTC 1 April period (Episode 1). (c) As in (a), except during the 0000 UTC 1 April – 1200 UTC 1 April 2004 period (Episode 2). (d) As in (a), except during the 1200 UTC 1 April – 0600 UTC 3 April 2004 period (Episode 3).

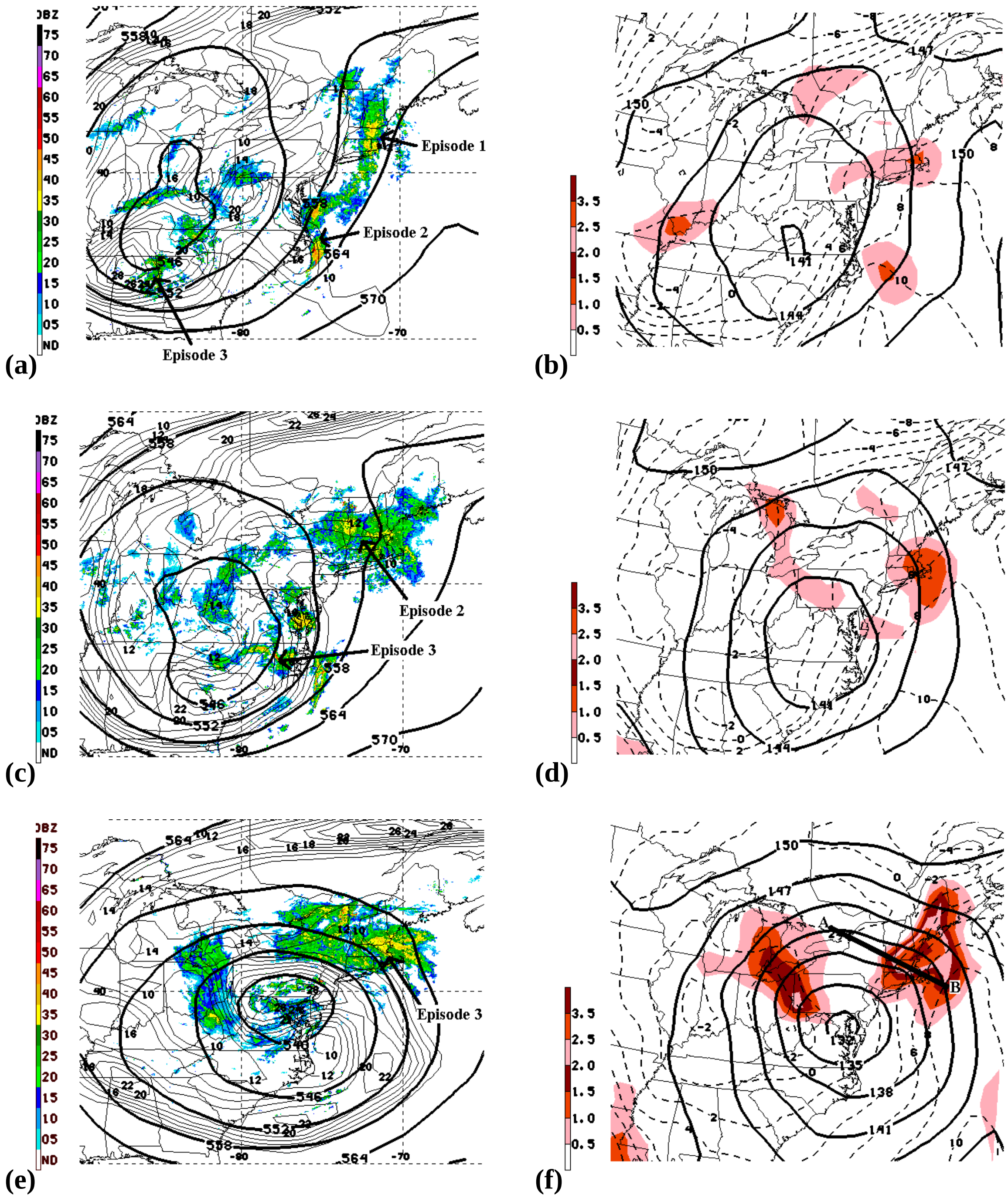

Fig. 4. (a) 1800 UTC 31 March 2004 RUC analysis 500-hPa geopotential height (thick solid) contoured every 60 m and absolute vorticity (thin solid) contoured every 2 x 10^{-5} s^{-1} where greater than 10 x 10^{-5} s^{-1} with WSR-88D mosaic radar imagery overlaid (shaded according to color scale in dBZ). (b) 1800 UTC 31 March 2004 RUC analysis 850-hPa geopotential height (thick solid) contoured every 30 m, temperature (dashed) contoured every 2 ºC, and thermal advection shaded according to scale in ºC day^{-1} where positive. (c) As in (a), except for 0300 UTC 1 April 2004. (d) As in (b), except for 0300 UTC 1 April 2004. (e) As in (a), except for 0000 UTC 2 April 2004. (f) As in (b), except for 0000 UTC 2 April 2004, with cross section orientation for Fig. 5 overlaid.

Temporal analysis of the Stage IV precipitation data revealed the heavy rains in New England occurred in three episodes. The first precipitation episode (Episode 1) occurred over an 18-h period from 0600 UTC 31 March – 0000 UTC April 1 2004 (estimated from the 6-h temporal resolution Stage IV precipitation data), and resulted in modest rainfall amounts of generally 20–30 mm (0.79–1.18 in; Fig 3b). A mosaic radar and RUC 500-hPa heights and vorticity analysis (Fig. 4a), shows that the precipitation occurred in the absence of any substantial 500-hPa vorticity advection (and implied upward increase of vorticity), but rather was embedded within an area of lower-tropospheric warm air advection ahead of the primary low center (Fig. 4b). Note that at this time the vorticity maximum responsible for Episode 2 is evident in eastern North Carolina, while the vorticity maximum responsible for Episode 3 is found in northern Alabama rounding the base of the 500-hPa cutoff (Fig. 4a).

Episode 2 occurred over a 12 h period from 0000 – 1200 UTC April 1 2004, and resulted in precipitation amounts of 15–25 mm (0.59–0.98 in; Fig. 3c). Episode 2 can be related to the passage of a 500-hPa short wave rotating around the eastern periphery of the 500-hPa cutoff. The 0300 UTC 1 April 2004 radar and 500-hPa height and vorticity analysis (Fig. 4c) shows cyclonic vorticity advection (and implied upward increase in vorticity advection) occurring over New England associated with this short wave. An area of 850-hPa warm air advection was also found in southern New England association with this short wave (Fig. 4d).

Episode 3 occurred over a 42-h period from 12 UTC 1 April – 06 UTC 3 April 2004 and accounted for most of the event total precipitation, with amounts greater than 100 mm (3.94 in) recorded in southeast New Hampshire (Fig. 3d). During this period the 500-hPa low center stalled over Virginia as a lobe of vorticity slowly swung northward (Figs. 2 and 4e). Two transient vorticity maxima were analyzed within this lobe of vorticity. Positive vorticity advection north of this vorticity lobe and strong 850-hPa warm air advection (Fig. 4f) were analyzed over New England. Note that the warm air advection is over double the magnitude as in the previous two precipitation episodes. The slow motion of the 500-hPa low allowed deep southeasterly flow to persist in the northeast quadrant of the cyclone over New England. This persistent southeast flow supported the training of precipitation through central New England, and accounted for the southeast-northwest orientation of the precipitation maxima in New England during this period (Fig. 3d). It is also during this period that the effects of the orography were most evident as deep southeasterly flow contributed to orographic precipitation enhancement (suppression) on the east (west) slopes of north-south oriented terrain features (Fig. 3d). A flow-parallel cross section through New England (Fig. 5; cross-section orientation shown in Fig. 4f) shows deep easterly flow, a frontal inversion at nearly the same height of the obstructing terrain (~1 km), and a conditionally neutral or weakly unstable layer extending from the top of the inversion to near 500-hPa. As Brady and Waldstreicher (2001) showed, such conditions are conducive to standing mountain waves in the northeast United States. Such mountain waves may account for the precipitation enhancement and suppression observed during this period..

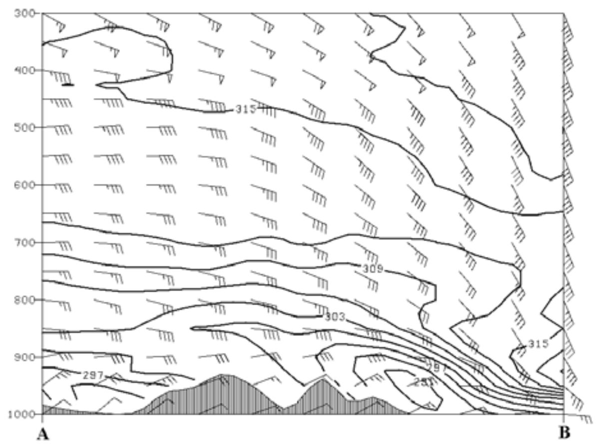

Fig. 5. 0000 UTC 2 April 2004 RUC analysis cross section (orientation shown in Fig. 4f) of saturation equivalent potential temperature (solid) and winds, with RUC topography (20 km resolution) along x-axis.

Analysis of soundings during the flooding event (not shown) show that all three precipitation episodes occurred in an environment exhibiting precipitable water values 150–200% above normal. Note that soundings from each precipitation episode did not exhibit any surface-based CAPE and minimal most unstable CAPE (as implied in Fig. 5). Consistent with this environment, there were few lightning strikes observed in New England during this event. However, the environment was conditionally neutral or weakly unstable above the lower tropospheric inversion (Fig. 5), supporting cores of strong elevated ascent and areas of heavy rainfall.

b. Model Guidance

Operational model guidance during the event alerted forecasters to the potential for heavy rainfall; however, the forecast timing, placement, and intensity of the latter two precipitation episodes were in error.

In regards to Episode 2, the location of the 500-hPa vorticity maximum was misplaced by the Eta, even at 6-h and 12-h forecast projections. The Eta model 9-h forecast 500-hPa height and vorticity field valid 2100

UTC 31 March 2003 (Fig. 6a) shows south-southwest 500-hPa flow with a prominent vorticity maximum well southeast of the New Jersey coast. Accordingly, little precipitation was forecast in the vicinity of coastal New Jersey. However, the RUC 500-hPa height and vorticity analysis shows a shortwave embedded within the south-southwest flow south of New Jersey, ahead of which precipitation was occurring (Fig. 6b).

The largest model guidance errors were associated with the third precipitation episode, as the Eta model underestimated the rainfall, and suffered from significant phase errors. An example of these errors is shown by the Eta model 36-h forecast 6-h accumulated precipitation valid 0000 UTC 2 April (Fig. 7a). Although the shape and orientation of the forecast precipitation area was accurate, the precipitation maximum was nearly half that observed, and located more than 300 km southwest of the observed location (Fig. 7b). This phase and intensity error had substantial ramifications as the Eta model forecast suggested southeast New Hampshire would stay completely dry during this period (Fig. 7a), while in fact over 50 mm (1.97 in) of rainfall was observed (Fig. 7b).

Despite these phase errors, the Eta model was able to predict the orographic enhancement of precipitation observed during Episode 3. This is evident in Fig. 7a, as the east slopes of north-south oriented terrain features such as the Berkshires (western Massachusetts and southwest Vermont), and Catskills (southeastern New York) were coincident with forecast local precipitation maxima. The observed precipitation field (Fig. 7b) validates these features, although the observed precipitation maximum on the east slopes of the Adirondack mountains (northeast New York) was not forecast by the Eta model. It appears the phase error and subsequent northern extent of orographically enhanced precipitation was at least partially a result of the 500-hPa low center being forecast ~100 km too far south, as shown by a comparison of the position of the 540 dm contour in Figs. 7a and b.

4. SUMMARY

Three heavy precipitation episodes associated with a slow moving cutoff cyclone have been analyzed. Each episode occurred in the northeast quadrant of the cutoff cyclone associated with synoptic-scale forcing. The first precipitation episode was embedded within an area of 850-hPa warm air advection ahead of the primary 500-hPa cutoff low center. The second episode was related to the passage of a 500-hPa short wave rotating around the 500-hPa cutoff low center. The third and most intense precipitation episode occurred as the 500-hPa low center stalled over Virginia and an associated lobe of vorticity slowly swung northward. Anomalous moisture was available during this period, and conditionally neutral stability in the middle troposphere supported strong ascent, although limited lightning was observed. The effects of the orography were most evident during the third episode as deep southeasterly flow and a thermodynamic profile favoring standing mountain waves contributed to orographic precipitation enhancement (suppression) on the east (west) slopes of north-south oriented terrain features.

Operational model guidance during the event alerted forecasters to the potential for heavy rainfall; however, the forecast timing, placement, and intensity of the precipitation episodes had various degrees of error, even at forecast projections of less than a day. The largest errors were associated with the third precipitation episode, as the Eta model underestimated the rainfall, and suffered from significant phase errors. However the Eta model was able to predict orographic modulation of the preciptitation during the third episode.

This case highlights the multi-scale nature of cutoff cyclones, including features such as transient short waves and the modulating effects of orography, and highlights the challenge such features present to operational quantitative precipitation forecasts.

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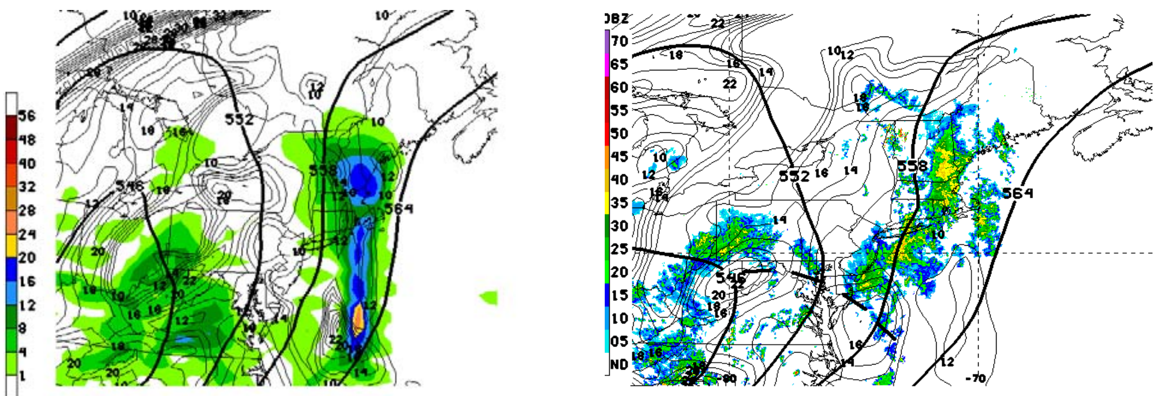
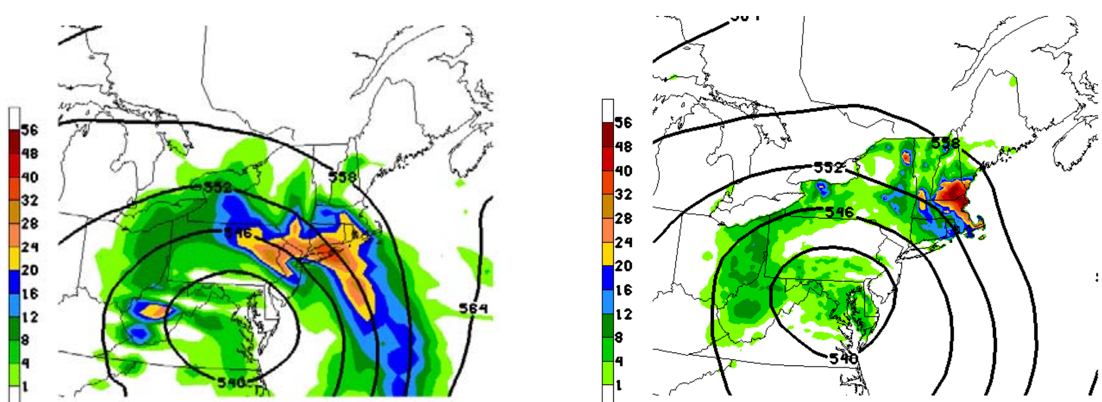


(a) **(b)**

Fig. 6. (a) Eta model 12-h forecast 6-h accumulated precipitation (mm; shaded)) valid 0000 1 April 2004, 500-hPa geopotential height (thick solid) contoured every 60 m,, and absolute vorticity (thin solid) contoured every 2 x 10^{-5} s^{-1} where greater than 10 x 10^{-5} s^{-1} valid 2100 UTC 31 March 2004. (b) 2100 UTC 31 March 2004 RUC analysis 500-hPa geopotential height (thick solid) contoured every 60 m, absolute vorticity (thin solid) contoured every 2 x 10^{-5} s^{-1} where greater than 10 x 10^{-5} s^{-1} shaded, with WSR-88D mosaic radar imagery overlaid, and short-wave trough position marked (dashed).



(a) **(b)**

Fig. 7. (a) Eta model 36-h forecast 6-h accumulated precipitation (mm; shaded) and 500 hPa geopotential height (thick solid, contoured every 60 m) valid 0000 UTC 2 April 2004. (b) Stage IV accumulated precipitation (mm; shaded) during the 1800 UTC 1 April – 0000 UTC 2 April 2004 period and 0000 UTC 2 April 2004 RUC analysis 500-hPa geopotential height (thick solid).