THE USE OF ENSEMBLE AND ANOMALY DATA TO ANTICIPATE EXTREME FLOOD EVENTS IN THE NORTHEASTERN UNITED STATES

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Abstract

Widespread extreme flood events in the northeastern U.S. during the past 20 years have caused millions of dollars in damage and resulted in numerous casualties. Most recently, the flood events of October 2005, May 2006 and June 2006 were characterized by 200 to 350 mm of rain in parts of New York and New England, producing record river levels in some cases. While the potential for heavy rain and flooding was well anticipated by meteorologists across the region during these recent events, the magnitude and impact were greatly underestimated.

Analysis of past flooding events showed two dominant patterns supportive of widespread extreme flood events in the northeastern United States. One pattern has been defined as the Atlantic Flow pattern, characterized by strong high pressure over eastern Canada and low pressure tracking east and offshore the East Coast of the U.S., producing strong, deep southeast flow off the Atlantic Ocean. The second pattern has been defined as the Gulf/Tropical Origins pattern, characterized by a very slow moving trough over the eastern U.S. with successive upper impulses originating from the Gulf of Mexico and subtropics, enhancing deep southerly flow and moisture advection for two or more days.

In this study, ensemble guidance, such as plume diagrams and probability plots, provided clues that there was an increased likelihood of more significant rainfall and flooding 24 to 48 hours before flooding was observed. Effective use of ensemble guidance can increase lead times and forecast confidence of high impact precipitation events. Ensemble guidance can also add value to forecast and warning products, providing users with more specific information and additional lead time to make critical decisions.

1. Introduction

Flooding disasters are high impact events that not only result in millions of dollars of damages each year, but cause more loss of life than most other weather-related hazards (National Weather Service 2008). Several record-setting widespread flooding events have occurred in the northeastern U.S. recently, affecting large population centers in New York and New England. The events of October 2005, May 2006, and June 2006 were compared to other extreme events, namely June 1982, May 1984, April 1987, October 1996, November 1996, and October 1998, in an effort to define atmospheric patterns supportive of widespread, high impact flood events. Analysis of these events resulted in recognition of signals from a variety of sources of guidance to better predict the magnitude of flooding and maximize the warning lead times.

Flood events are typically well-anticipated, sometimes days in advance. However, accurate prediction of the magnitude of flooding has proven to be more challenging. During the events of October 2005, May 2006, and June 2006, flooding rains of 4 to 10 inches (100 to 250 mm) were predicted over a significant portion of the northeastern U.S. However, in the May and June 2006 events, based on National Weather Service (NWS) Stage 4 Rainfall Analyses (Lin and Mitchell 2005) nearly twice the predicted rainfall fell, with maxima of roughly 8 to 15 inches respectively for each event (200 to locally around 350 mm) (Fig. 1). These events highlight the crucial need to better predict the magnitude of these events with greater lead times, so all users can better prepare and allocate resources for improved response of these flooding disasters.

It will be shown that utilizing information from medium-range ensemble forecasts (MREF) (Tracton and Kalnay 1993), now known as the Global Ensemble Forecast System (GEFS), short-range ensemble forecasts (SREF) (Tracton et al. 1998), and anomalies can increase the accuracy and confidence of forecasting the magnitude of extreme flood events in the northeastern U.S. At the very least, analyzing ensemble means and spreads can identify situations when deterministic operational guidance from the North American Mesoscale Model (NAM) and Global Forecast System (GFS) (Kanamitsu et al. 1991) represent outliers, compared to the other members of the ensemble systems. This can lead to increasingly accurate forecasts, since forecasters could improve upon operational deterministic guidance, when necessary.

Toth et al. (2001) showed the value of climatic data and ensemble spread to distinguish between forecasts of small and large uncertainty. Their results showed that when ensemble member forecasts converged, they tended to be more accurate, indicating lower uncertainty. As the spread between members decreases, the anomalies produced by the ensemble mean are likely to be large when a significant event is predicted by the Ensemble Prediction System (EPS).

Analyzing the synoptic-scale features and anomaly data resulted in the identification of two types of patterns associated with widespread extreme flood events in the northeastern U.S: the Atlantic Flow pattern and the Gulf/Tropical Origins pattern. Standardized anomalies (Grumm and Hart 2001a; Grumm and Hart 2001b) from observational data of mean sea level pressure (MSLP), 850 hPa winds, 500 hPa heights, and precipitable water (PWAT) were used to identify common features associated with the two patterns.

It will be shown that forecast anomalies of MSLP, 850 hPa winds, 500 hPa heights and PWAT from GEFS and SREF will aid forecasters in predicting the magnitude of flooding events. Derived products from the GEFS and SREF such as Quantitative Precipitation Forecast (QPF) probabilities and plume diagrams are also valuable sources of guidance in predicting widespread major flooding events.

It should be noted that this study does not include flooding that results from tropical storms and hurricanes. However, the remnants of tropical disturbances can contribute to the magnitude of an event, such as in October 1996 and October 2005. This study also focuses only on the warm season, defined as the period from April through October, when a snow pack typically does not contribute to flooding events. The purpose is to show the value of using ensemble spreads and anomalies to provide information highlighting the potential for a significant precipitation event. These data, when used with QPF probabilities, can tie the pattern to confidence in the probability of a

Fig. 1(a).

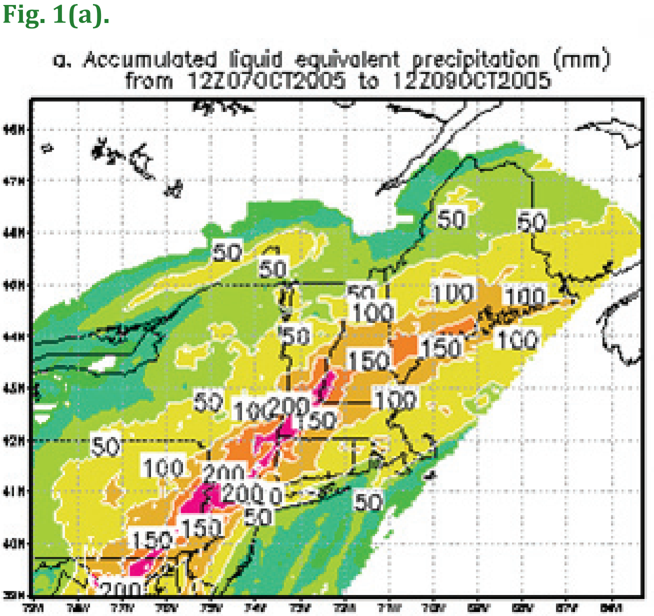


Fig. 1(b).

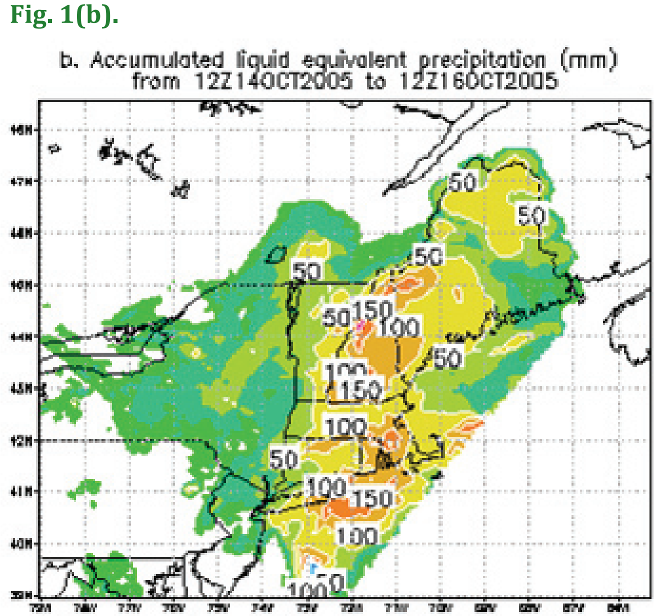


Fig. 1(c).

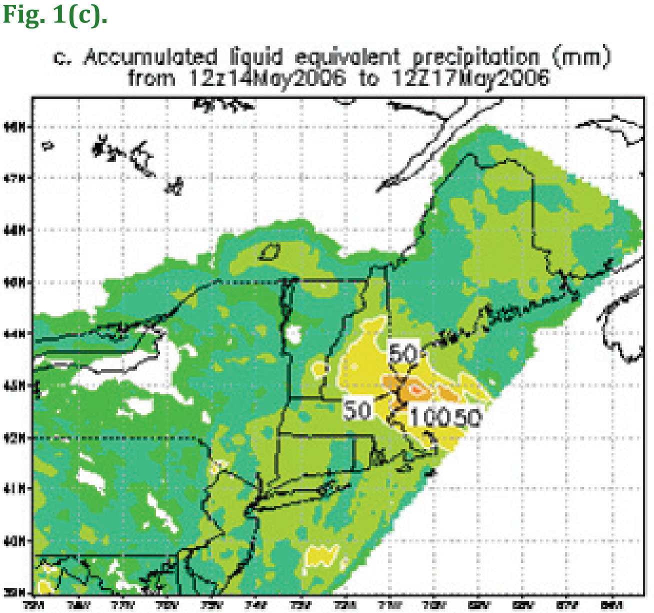


Fig. 1(d).

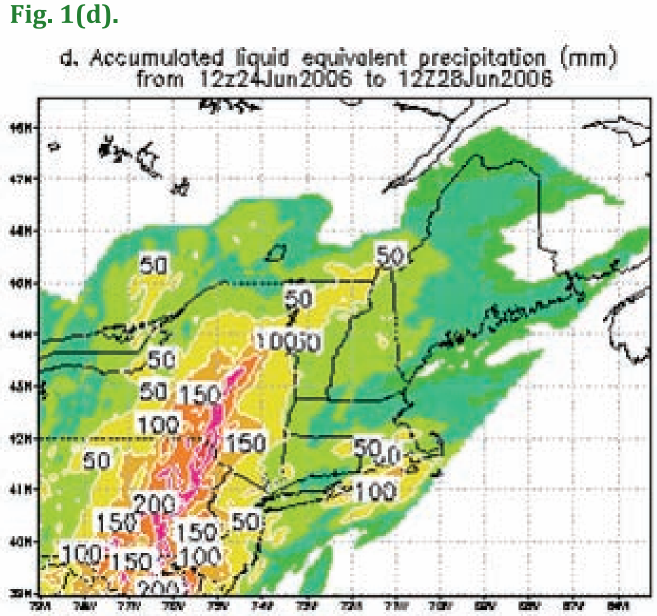


Fig. 1. Observed National Weather Service Stage 4 rainfall accumulation (mm) for a) 7- 9 October 2005, b) 14-16 October 2005, c) 14-17 May 2006 and d) 24-28 June 2006.

significant precipitation event. The events presented here do not include weakly forced localized events which are more difficult to predict and may not be resolvable by the current EPS.

2. Data and Methodology

All climatological means and standard deviations were computed from the Global Reanalysis (GR) data (Kalnay et al. 1996) using the methods described by Grumm and Hart (2001a) and Grumm and Hart (2001b). The 21-day centered climatological values were computed over the 30 year period from 1 January 1970-31 December 1999 in 6-hour increments. For a full description of the data methodology and variables used, see Grumm and Hart (2001b). PWAT was computed in a similar manner as described in Hart and Grumm (2001).

To compute the standardized anomalies during an event, the North American Regional Reanalysis data (NARR) (Mesinger et al. 2006), or the appropriate model data were used. These data were compared to the GR data using the following methods

$$SA = (F - \mu)/\sigma \quad (1)$$

where SA is the standardized anomaly, F is the forecast or observed value from the NARR or the appropriate model and μ and σ are the 21-day centered mean and standard deviation for the data and time. For example, computing the standardized anomalies for 0000 UTC 20 October, the raw NARR fields (F) were compared to GR mean (μ) and standard deviations (σ) valid at 0000 UTC on 20 October. It is understood that these later data are 21-day centered values computed from the GR data.

a. Gridded climatic datasets

As originally noted in Grumm and Hart (2001b), all departures from normal used in this analysis are shown as a standard deviation (SD) from normal. These departures are referred to as "standardized anomalies" (Grumm and Hart 2001b). Throughout this paper, the term anomalous refers to fields that depart by more than 2.5 SD from the 30-yr means. This value was arrived at based on the confidence limits determined using the Chebyshev theorem (Blaisdell 1993) as an upper limit and those of the normal distribution as a lower limit (see Table 1 from Grumm and Hart 2001b). In an absolute sense, a departure of 2.5 SD from normal implies that the anomalous field occurs between 5% and 16% of the time at any given location (Grumm and Hart 2001b). Based on the results of Grumm and Hart (2001b), the actual confidence limits are probably closer to those of the normal distribution. The analysis of events contained in this study was limited geographically to the northeastern U. S.

Anomalies were computed using SREF and MREF during the May 2006 and June 2006 flooding events. Prior to 2006 the SREF consisted of 10 Eta and five Regional Spectral Model (RSM) members. In 2006, six WRF members were added bringing the total number of SREF members to 21. The MREFs were an ensemble of 15 GFS members until 2006, when it increased to 21 members, and is now referred to as the GEFS. It should be emphasized that the SREF is composed of members of different models, while the GEFS is composed of members of the same model. This is one reason for the difference in the ensemble means and spreads between the two ensemble systems. Additionally, the SREF and MREF mean analysis and forecast fields tend to dampen out some of the extreme anomaly values compared to single deterministic models due to averaging and grid resolution issues. The EPS data also allows for the computation of probabilities of critical thresholds that cannot be obtained from a single deterministic model.

b. Diagnostic gridded datasets

Model diagnostic grids used in image production were retrieved in near real-time from NCEP in GRIB format. These data were archived for later use in the case studies to depict the analysis anomaly fields. The gridded forecast data used for comparing operational weather prediction data to the climatology were obtained from the NCEP stepped-terrain Eta, the Weather Research and Forecast System – Nonhydrostatic Mesoscale Model (WRF-NMM) (Janjic et al. 2001), the RSM from the GFS, MREF and SREF guidance. The May and June 2006 events were identified to show how these data could be used operationally to add value to real forecast problems. All the graphics for the May and June 2006 events were depicted at the times of the peak anomaly values to illustrate the range of extreme values, including the mean values.

The utility of these pattern recognition techniques and use of new forms of guidance was tested in real-time while forecasting the April 2007 storm. Forms of ensemble guidance that will be presented include probabilities and spreads for 2.00 in. (50 mm) of rainfall, plume diagrams depicting accumulated precipitation and three-hourly precipitation rate from individual ensemble members. The plume diagrams are shown in 3 hour increments from initialization to the 84 hour forecast period on the SREF, and are shown in 6 hour increments out to 8 days on the GEFS. Forecast results from the April 2007 storm will also be presented.

It should be emphasized that forecasters use ensemble output with caution, since there is very limited formal research on verification and calibration of ensemble output. However, the ensemble guidance during the May and June 2006 flood events was subjectively very accurate and showed skill, outlining areas under the threat for rainfall of the magnitude that could produce flooding. Ensemble output has also been shown subjectively to show skill in other extreme precipitation events such as in the Valentine's Day 2007 (Grumm and Stuart 2007), and Tax/Patriots Day April 2007 (Stuart et al. 2007) storms.

c. Case study selection

The selection of historic case studies was confined to events that affected the northeastern U. S. over the period from 1979 through 2007. *Storm Data* (NOAA 1959–2003) and local climatological data were used to identify widespread extreme heavy rainfall and flooding events. For each case, the reanalysis data were compared to the 30-yr period of record (POR) to determine if the event represented a substantial departure from normal (>2.5 SD, as stated earlier).

Flooding events that occurred in June 1982, May 1984, April 1987, October 1996, November 1996, October 1998 and October 2005 were analyzed to identify those that had a substantial impact on populated areas in the northeastern U.S. This analysis was performed to determine if the magnitude of the May and June 2006 flood events could have been better forecasted through use of anomaly data. Anomaly and ensemble interpretation of these flooding events provide the forecaster with a quantitative measure of the range of atmospheric variability, and often contributes to the level of forecaster confidence in the likelihood and areal extent of flooding rains. Wind anomalies in the *U* (positive values from the west and negative values from the east) and *V* (positive values from the south and negative values from the north) directions at 850 hPa, height anomalies at 500 hPa, MSLP anomalies, and PWAT anomalies were analyzed for the June 1982, May 1984, April 1987, October 1996, November 1996, October 1998 and October 2005 flood events to illustrate the typical synoptic patterns and anomalies associated with these events.

3. Patterns for Heavy Rain in the Northeastern U.S.

In a similar study, Grumm and Holmes (2007) categorized heavy precipitation events in the mid-Atlantic region and provided details on the characteristics and patterns associated with synoptic, synoptic tropical, and synoptic frontal patterns of heavy rain. Based on

Date	Maximum Rainfall in inches (mm)	Region affected	Event Type
June 1982	6-12 (150-300)	Southern/Eastern New England	Atlantic Flow
May 1984	4-8 (100-200)	New England	Gulf/Tropical Origins
April 1987	6-12 (150-300)	Eastern NY and Southern New England	Gulf/Tropical Origins, transition to Atlantic Flow
October 1996	4-10 (100-250)	Eastern New England	Atlantic Flow
November 1996	4-8 (100-200)	Northern New England	Gulf/Tropical Origins
October 1998	4-8 (100-200)	Eastern/Northern New England	Gulf/Tropical Origins, transition to Atlantic Flow
October 2005	5-11 (125-275)	Southern/Eastern NY and New England	Gulf/Tropical Origins, transition to Atlantic Flow
May 2006	8-15 (200-375)	Eastern/Northern New England	Atlantic Flow
June 2006	8-15 (200-375)	Maryland, Eastern PA/NY	Gulf/Tropical Origins
April 2007	4-8 (100-200)	Eastern PA, NJ and southern NY	Rare hybrid Gulf/Tropical Origins and Atlantic Flow

Table 1. Dates of rainfall events analyzed, maximum rainfall amounts, region affected and event type.

an analysis of the events (Table 1), two larger-scale synoptic patterns, the Atlantic Flow pattern and the Gulf/Tropical Origins pattern, were further identified in Stuart et al. (2007) that included the subset listed in Grumm and Holmes (2007). The two larger-scale patterns support extreme precipitation and flooding in the entire northeastern U.S., including the mid-Atlantic and New England.

It should be noted that in both patterns, a mean upper trough axis just west of the Appalachian Mountains existed, with either a cut-off 500 hPa low or developing 500 hPa low within the upper trough. It was determined that the 500 hPa height anomaly was not a clear signal for the potential for extreme rainfall, since the strength of the 500 hPa low did not always correlate to the moisture or wind fields that supported the extreme rainfall. However, the evolution and movement of the upper trough axis, and any 500 hPa low pressure centers have a significant impact on the duration of the moisture and wind conditions supportive of extreme rainfall over the region.

a. Characteristics of Atlantic flow events

In the Atlantic Flow pattern, anomalously strong surface high pressure is centered over southeastern Canada. As low pressure tracks east and out of the Tennessee and Ohio Valleys, the surface high pressure remains anchored over southeastern Canada, increasing the pressure gradient, and the southeast wind flow from the surface through 850 hPa. The strong southeasterly flow increases moisture advection and transport off the Atlantic Ocean, and increases forcing through speed convergence and frontogenesis. The anomalous moisture and winds are evident in the PWAT and 850 hPa U wind anomalies.

The October 1996 Atlantic Flow event (Figs. 2a-d) shows a strong southeasterly flow from the surface through 850 hPa (Fig. 2a). The strong southeasterly flow coincides with the southern periphery of surface high anchored over southeastern Canada, (Fig. 2b) with the central pressure 1-2 SD above normal, and 850 hPa height anomalies also 1-2 SD above normal (Fig. 2d) contributing to an anomalously strong pressure gradient over New York and most of New England. An axis of high PWAT >2 SD above normal (Fig. 2c) was associated with the flow off the Atlantic Ocean. The strong flow provides moisture advection off the Atlantic Ocean, and implies forcing through speed convergence and frontogenesis.

The Atlantic Flow events are typically slow moving and thus long-duration events with 250 hPa *U-wind* anomalies (not shown) up to 3 SD below normal, indicating a system nearly cut off from the steering flow.

b. Gulf/Tropical origins events

In the Gulf/Tropical Origins pattern, a weak, high-amplitude 500 hPa trough axis is centered through the western Great Lakes, while smaller-scale upper impulses track north and northeast from the Gulf of Mexico or Gulf Stream. The mean 500 hPa trough axis is nearly stationary over the East Coast, resulting in a persistent low-level south to southwesterly flow originating from the Gulf of Mexico or the Gulf Stream. The nearly stationary nature of the upper trough is also evident in the below normal *U* wind anomalies at 250 hPa.

The June 2006 event was a typical Gulf/Tropical Origins event, with the small upper impulses along the eastern periphery of the 500 hPa trough strengthening the low-level forcing and consequently the southerly 850 hPa wind flow (Fig. 3a and 3b), suggesting an enhancement of moisture advection and speed convergence in their proximity. The northeastern U.S. is often in the right-entrance region of the 250 hPa jet in these types of events, indicated by 250 hPa *V* winds of 3 or more SD above normal (not shown). Sometimes two or more upper impulses track through the eastern U.S. in the span of several days to a week, producing the extreme rainfall. The anomalous winds and moisture are also evident in the PWAT (Fig. 3c) and 850 hPa *V* winds (Fig. 3b; 4 to 5 SD above normal) during the June 2006 Gulf/Tropical Origin event.

Fig. 2(a).

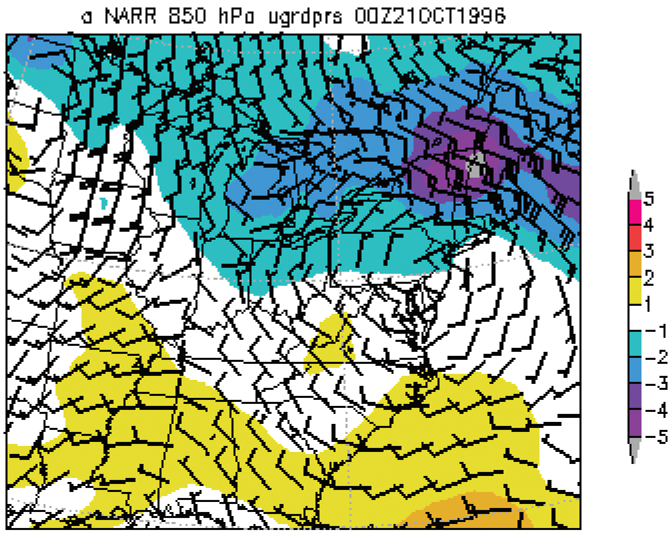
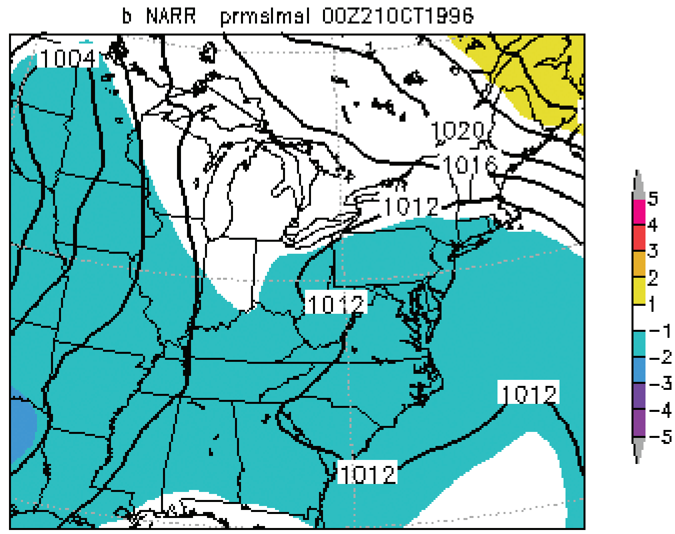


Fig. 2(b).



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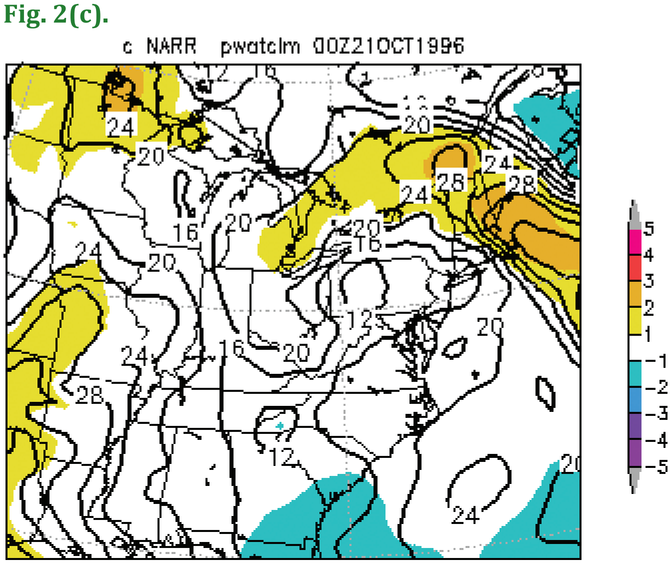

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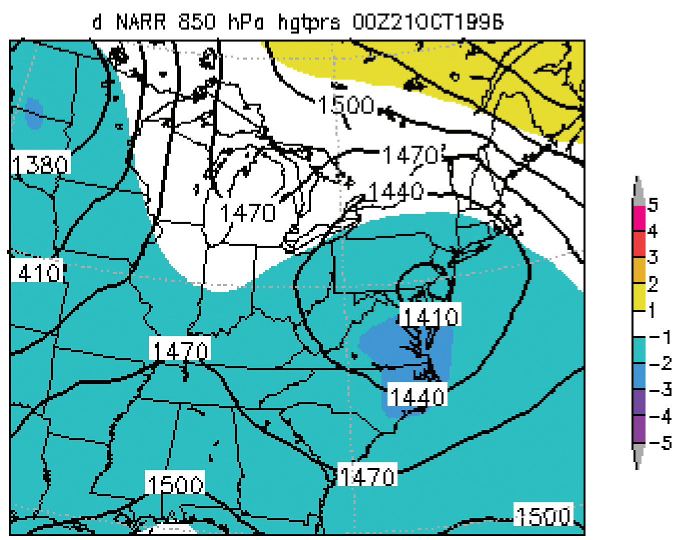
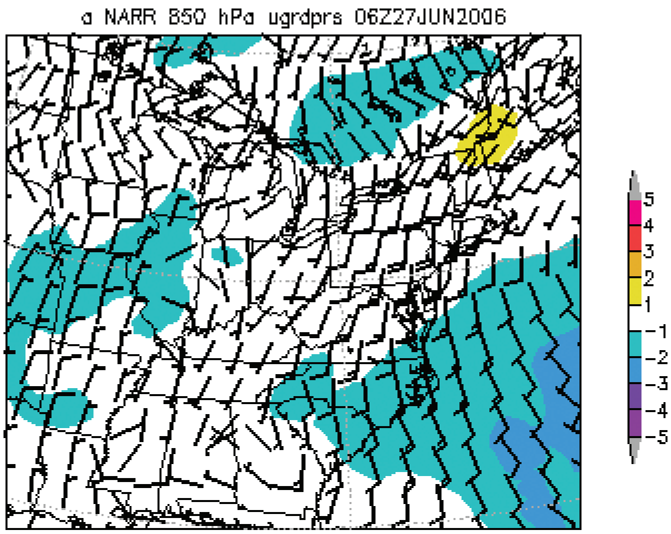


Fig. 2. NARR analysis valid at 0000 UTC 21 October 1996 a) 850 hPa wind barbs (kt) and U anomalies (color shaded), b) Mean sea level pressure (hPa) and anomalies (color shaded), c) Precipitable water (mm) and anomalies (color shaded) and d) 850 hPa heights (dm) and anomalies (color shaded).

Fig. 3(a).



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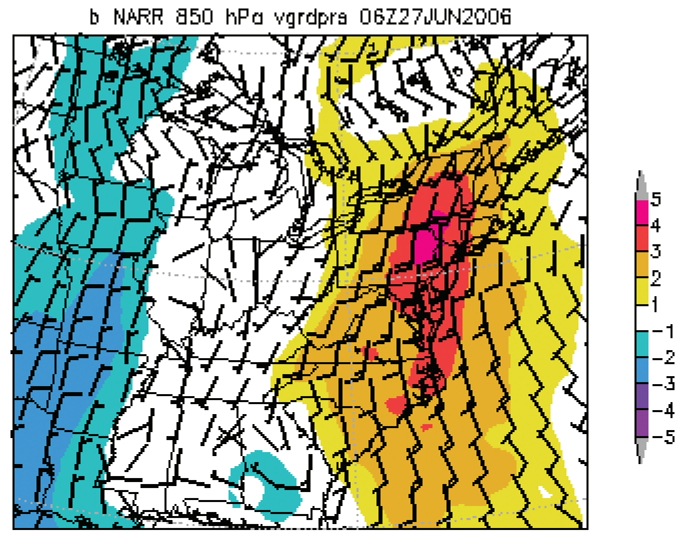

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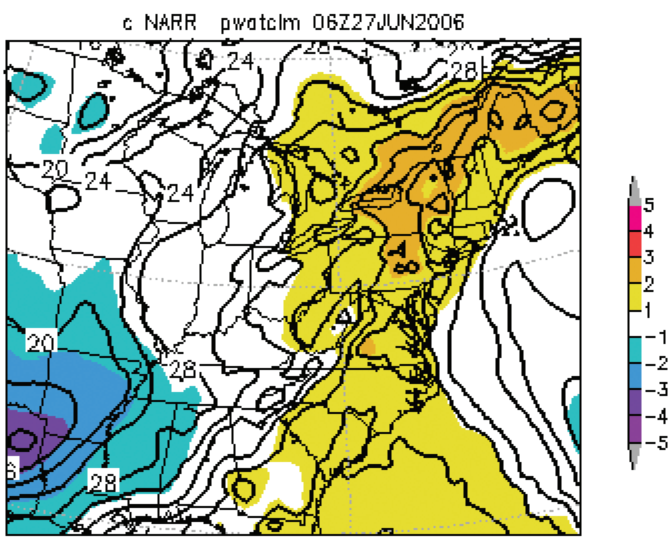

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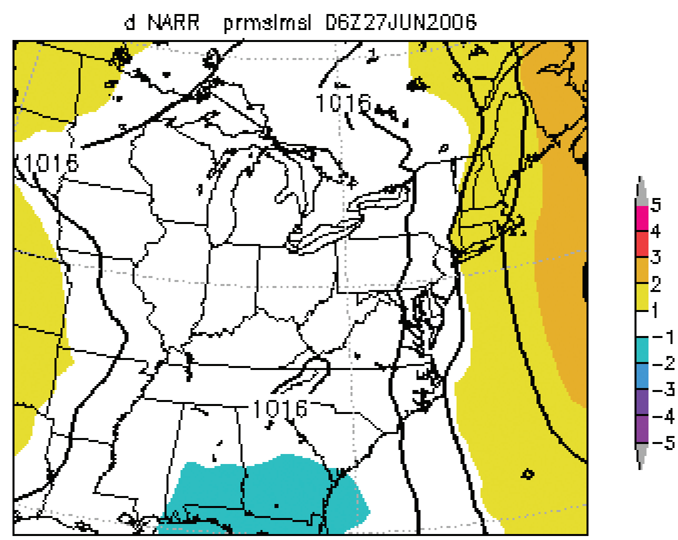


Fig. 3. NARR Analysis valid at 0600 UTC 27 June 2006 a) 850 hPa wind barbs (kt) and U anomalies (color shaded), b) 850 hPa wind barbs (kt) and V anomalies (color shaded) c) Precipitable water (mm), and anomalies (color shaded) and d) Mean Sea Level Pressure (hPa) and anomalies (color shaded).

4. Lessons from the May and June 2006 Events

a. May 2006 – Atlantic flow event

This event had similarities to the October 1996 event, with 850 hPa wind anomalies exceeding 3 SD from normal in the both the *U* and *V* directions (Figs. 4a-b). PWAT anomalies were 1.5 to 2 SD above normal (Fig. 4c) as a long band of enhanced moisture advected into the region. Strong surface high pressure was centered over southeastern Canada, and was nearly 2 SD above normal (Fig. 4d). The southeast wind flow off the Atlantic, forecasted to persist for 12 to 24 hours, suggested enhanced moisture advection and moisture convergence contributing to a widespread heavy rain event. The atmosphere was configured in a classic Atlantic Flow pattern for the northeastern U.S. 1 to 2 days prior to the onset of the event, suggesting the potential for a significant, widespread rainfall event.

Derived forecast guidance from the SREF and GEFS (not shown) was helpful in quantifying the areal and temporal extent of the potentially heavy rainfall. In particular, the probabilities for 2.00 in. (50 mm) of rain and plume diagrams helped quantify the most likely range of possible solutions. In this case, rainfall amounts that could produce flooding were likely. The SREF probabilities for ≥2.00 in. (50 mm) of rain in 36 hours were ≤50% over small areas of New England one

Fig. 4(a).

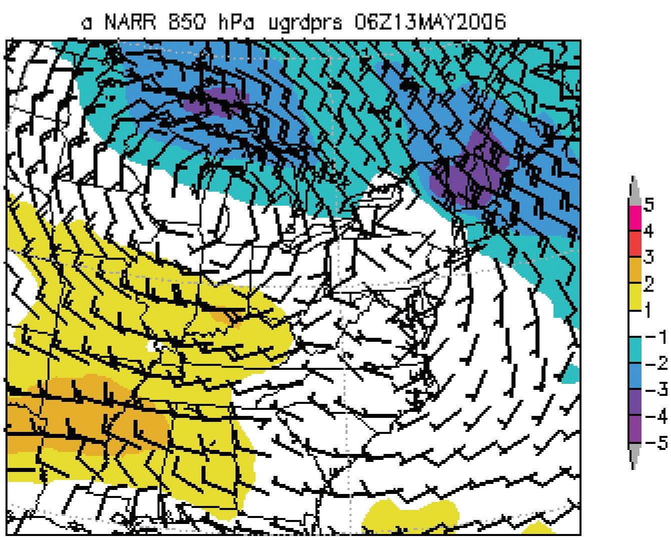


Fig. 4(b).

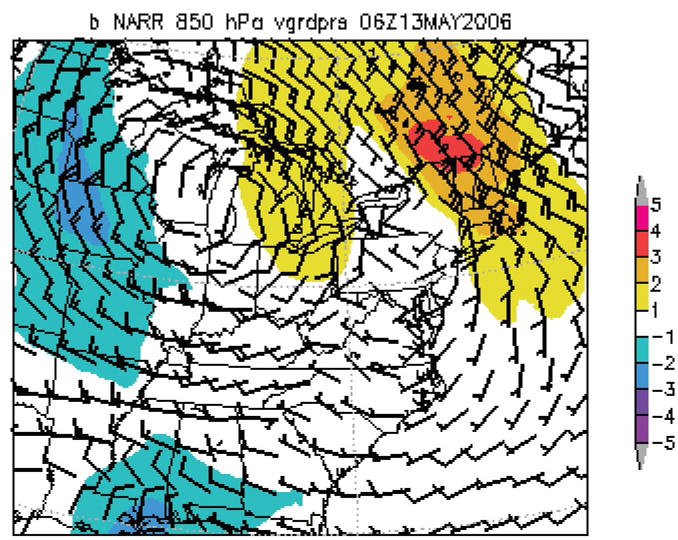


Fig. 4(c).

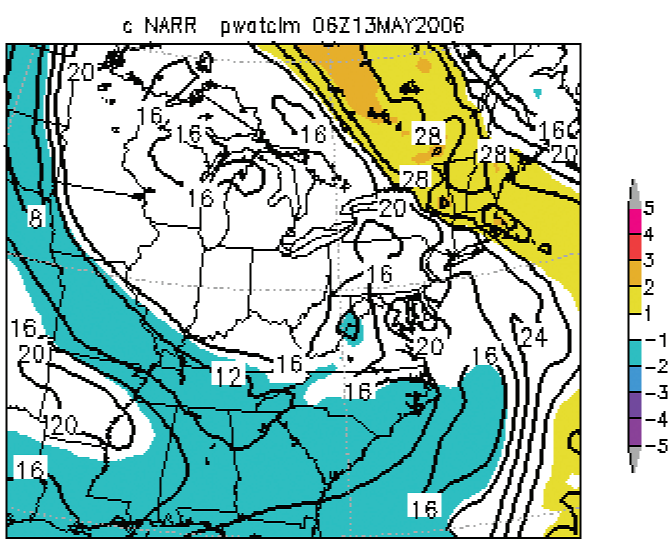


Fig. 4(d).

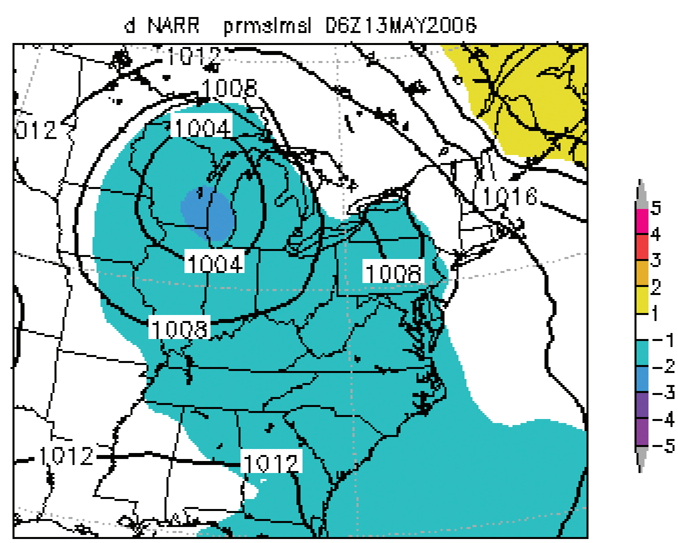


Fig. 4. NARR Analysis valid at 0600 UTC 13 May 2006 a) 850 hPa wind barbs (kt) and U anomalies (color shaded), b) 850 hPa wind barbs (kt) and V anomalies (color shaded), c) Precipitable water (mm) and anomalies (color shaded), and d) Mean Sea Level Pressure (hPa) and anomalies (color shaded).

to two days prior to the event (Fig. 5a). However, the spread (Fig. 5b) showed that nearly every ensemble member predicted ≥2.00 in. (50 mm) of rain in or near the northeastern U.S. with very little overlap, hence, the deceivingly small area of probable ≥2.00 in. (50 mm) of rain (Fig. 5a). Proper interpretation of the spread suggested a high probability of ≥2.00 in. (50 mm) in 36 hours around the northeastern U.S., considering NWP model and ensemble member perturbations and potential errors in placement of precipitation maxima.

Plume diagrams for Boston, MA were equally revealing, showing accumulated precipitation from each ensemble member (Fig. 6). Between 10 May and 12 May 2006, clustering of the ensemble members increased from 1.00 in to 3.50 in (25-85 mm) to 2.50 in to 4.70 in (65-120 mm) (Fig. 6). It should be noted that these precipitation amounts represent the average over the entire grid box surrounding the forecast site, in this case, Boston, MA. These precipitation forecasts must be interpreted with the understanding that mesoscale and convective scale processes (on the order of ≤5 km^2) are not resolved in the coarse resolution (5 km^2 to >80 km^2) of operational NWP models and ensemble members, so individual point value or rain gage rainfall amounts could be potentially greater than the wettest ensemble members if mesoscale and convective scale processes are expected.

b. June 2006 – Gulf/Tropical origins event

Several days prior to this event, deep south to southwest flow was situated over the eastern U.S. as a very slow-moving and high amplitude mean upper trough was centered over the Ohio and Tennessee Valleys. The strong low-level jet at 850 hPa tracked north out of the Gulf Coast region, transporting moisture, as evidenced by the axis of 2-3 SD above normal PWAT (Fig. 3). This low-level jet was 4-5 SD above normal (Fig. 3), which implies potentially enhanced low-level forcing through speed convergence in the low-level jet exit region.

Similar to the May 2006 case, ensemble probability and plume guidance signaled a potentially extreme precipitation event. However, the ensemble probabilities for 2.00 in (50 mm) of rain were calculated for an 84-hour time window, rather than the typical 24-36 hour time window, to encompass the entire event (not

Fig. 5(a).

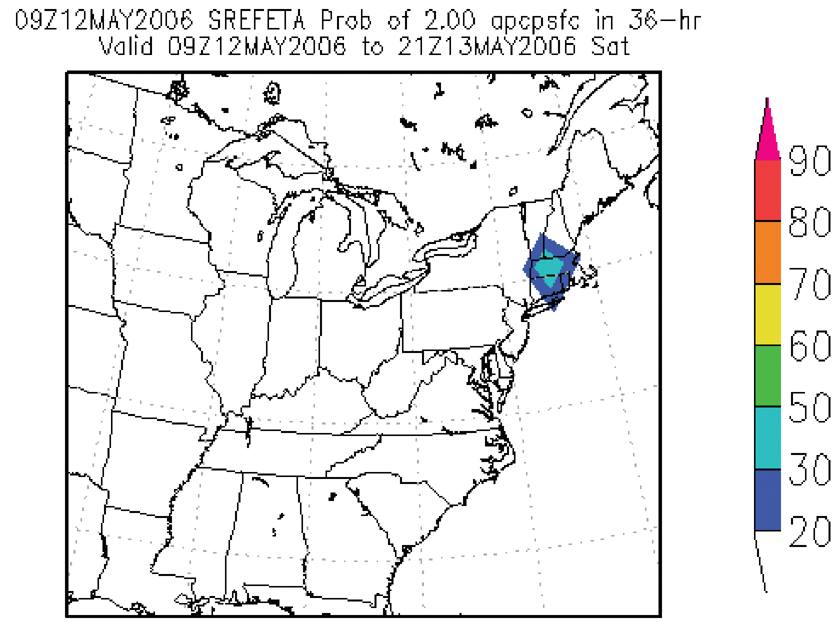


Fig. 5(b).

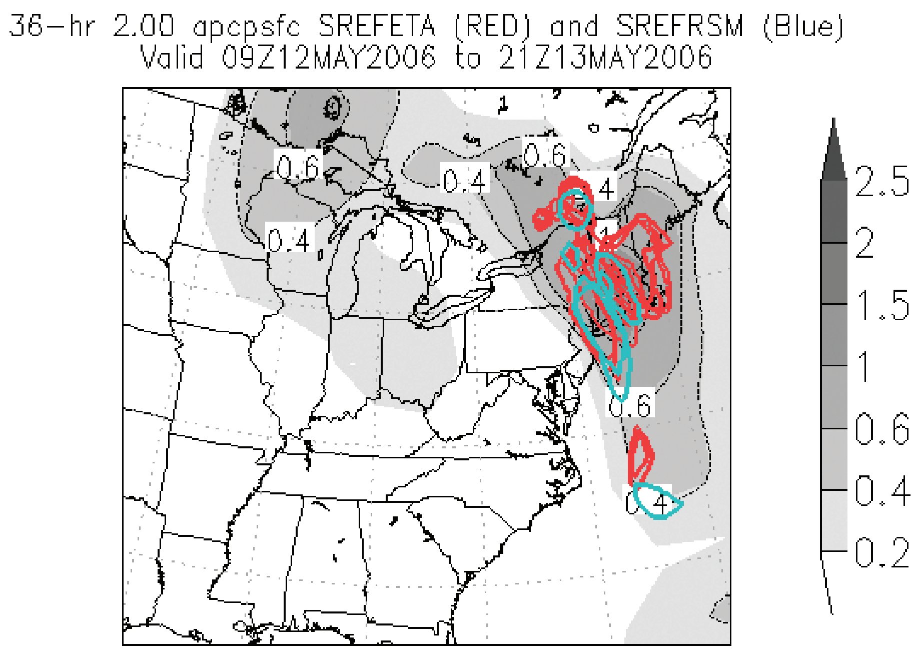


Fig. 5. 0900 UTC 12 May 2006 SREF a) probability for 2.00 in. (50 mm) of rain in 36 hours (shaded) for 0900 UTC 12 May through 2100 UTC 13 May 2006, and b) SREF spread of 2.00 in. (50 mm) rainfall between 0900 UTC 12 May and 2100 UTC 13 May 2006 and mean QPF (contours).

shown). There were widespread probabilities above 50% through the interior Mid-Atlantic States into central and western New York. This supported a very high confidence for widespread 2.00 in (50 mm) of rain during the forecast period, which suggested an increased probability for significant water level rises and potential flooding, independent of potential effects from much higher local rainfall where convective or mesoscale processes could dominate. This assertion also does not account for localized runoff patterns and antecedent soil moisture conditions, which also affect flooding.

5. Forecast Applications during the April 2007 Storm

Lessons learned from the 1982-2006 events were used during the forecast process prior to the April 2007 storm. This storm had characteristics of both Atlantic Flow and Gulf/Tropical Origins patterns, which could be considered a "combination" type event, similar to October 2005 and Ash Wednesday 1962. The patterns in the anomaly forecasts from the SREF and GEFS suggested a slow-moving, heavy precipitation event, similar to historical snowstorm patterns highlighted in Stuart and Grumm (2006). In fact, thermal profiles suggested snow as the predominant precipitation type in the higher terrain of New York, northeastern Pennsylvania and northern New England (not shown). However, in most of the northeastern U.S. outside of the mountains, the observed precipitation was mostly in the form of rain. Though not shown, earlier forecasts from the NCEP models and EPS indicated a higher potential for snow. These model forecasts were too cold and rain was the primary precipitation type across the region, including the coastal plain where the heaviest rain was observed.

Several days before the onset of the April 2007 storm,

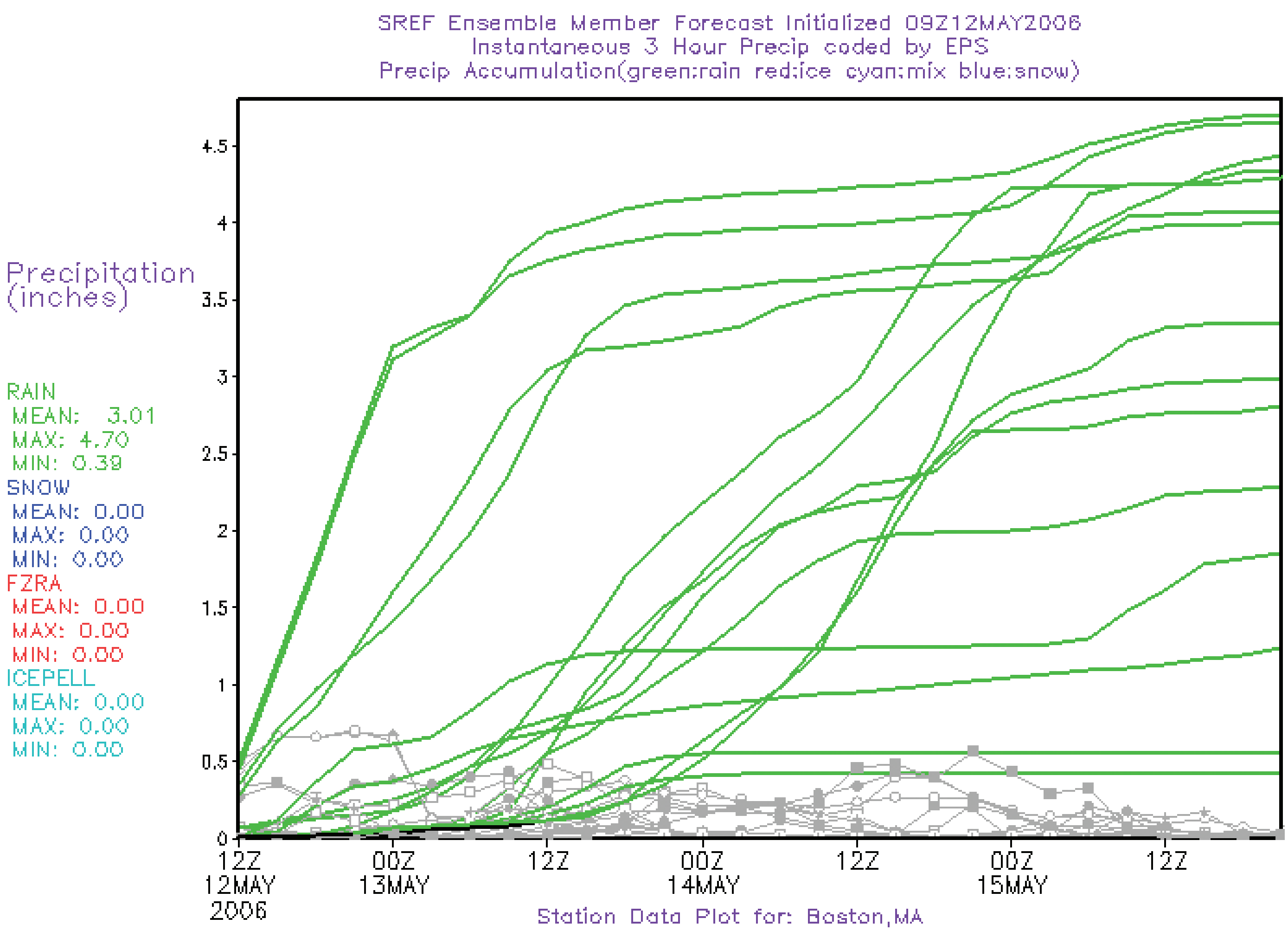


Fig. 6. Plume diagram from 09Z 12 May 2006 SREF for Boston, MA (rain, liquid equivalent snow, sleet and freezing rain depicted as green, dark blue, light blue and red, respectively). The gray filled squares and open circles represent instantaneous 3-hourly precipitation for each ensemble member.

ensemble guidance depicted 850 hPa wind anomalies exceeding -4 SD and 4 SD from normal in both the *U* and *V* directions, respectively (not shown). This signal was consistent in all successive runs of the SREF, GEFS and operational NWP model runs through the onset of the storm. In the extreme case of the 15-17 April 2007 storm, 850 hPa *U* and *V* winds in *both* 21 member ensembles exceeded -5 SD and 5 SD, respectively, a characteristic reserved for only the most extreme events which implied a convergence toward a high confidence solution.

When the April 2007 storm developed, it was highly anomalous, with the mean sea level pressure exceeding 5 SD below normal and 500 hPa heights exceeding 4 SD below normal (not shown). Observed winds at 850 hPa exceeded |5| SD in both the *U* and *V* directions, a characteristic observed only in the most unusually extreme storms (Fig. 7). Thus the area of southern New York and New Jersey had the threat of heavy rainfall north of the system with the large *U* wind anomalies. Once the low pressure center tracked north of the region, anomalous *V* winds and the associated surge of high PW air over the region contributed to additional heavy rain. Observed *U* winds at 250 hPa exceeded |3| SD from normal (not shown), confirming that the system was cut off from the jet stream, signaling a slow-moving storm. The 250 hPa *U* wind anomalies combined with the enhanced precipitation processes implied by the 850 hPa wind anomalies, increased the confidence that extreme precipitation amounts would be observed over the northeastern U.S.

There was a consensus from both the GEFS and SREF ensemble guidance for a widespread area of 2.00 in. (50 mm) or more of rainfall, based on probabilities 2 to 3 days in advance of the storm (Fig. 8). Note in Fig. 8a that the GEFS suggested a widespread area of >90% probability of 2.00 in. of rain, while the SREF suggested 50-60% probability of 2.00 in. of rain over a smaller area (Fig. 8b). The spread in the SREF was greater than in the GEFS (not shown) with less areal consistency in the depictions of 2.00 in. QPF in each individual member. As stated earlier, this may be due in part by the SREF being composed of members from different models with different physics, while the GEFS is composed of members of the same modeling system, with similar physics. However, the fact that all the SREF members were predicting 2.00 in. of rain (not shown) in the northeastern U.S. added to the confidence of 2.00 in. or more occurring.

Plume diagrams from Albany, NY (Fig. 9a) and Islip, NY (Fig. 9b) showed clustering in the 2.5 in.(75 mm) to 4.5 in. (125 mm) range for multiple runs, illustrating run-to-run consistency, another factor contributing to a high confidence for an extreme precipitation event. Clustering of plume diagrams shows the range of QPF values for the majority of ensemble members. The fact that there was such good agreement between two sets of 15+ member ensembles, as well as deterministic operational guidance from the NAM and GFS, added to the confidence for the expectation of an extreme precipitation event.

Armed with the forecast information and confidence, the meteorological community alerted the user

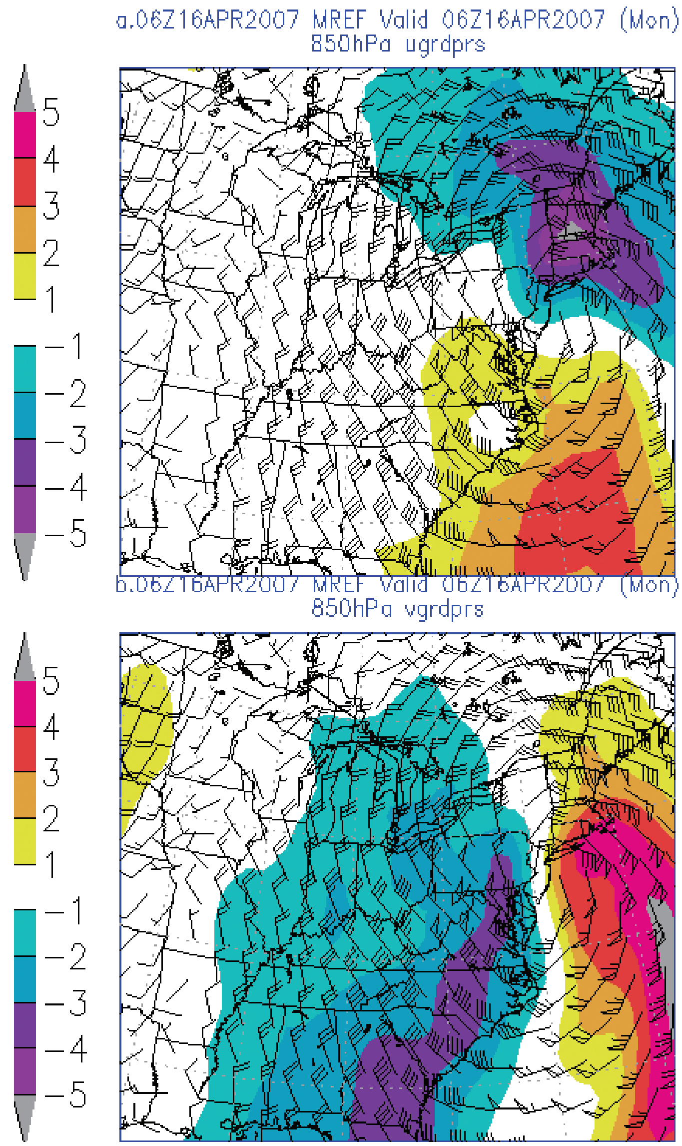


Fig. 7. Initial GEFS 0600 UTC 16 April 2007 wind barbs (kt) and 850 hPa anomalies (color shaded) for a) U-winds and b) V-winds. Note the nose of the U and V wind anomalies pointing into coastal regions of the northeastern U.S., implying the strongest speed convergence and moisture advection in that region.

Fig. 8(a).

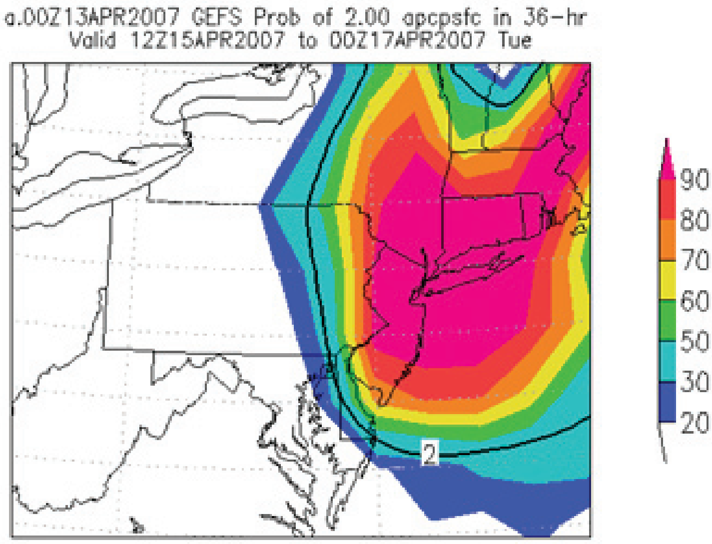


Fig. 8(b).

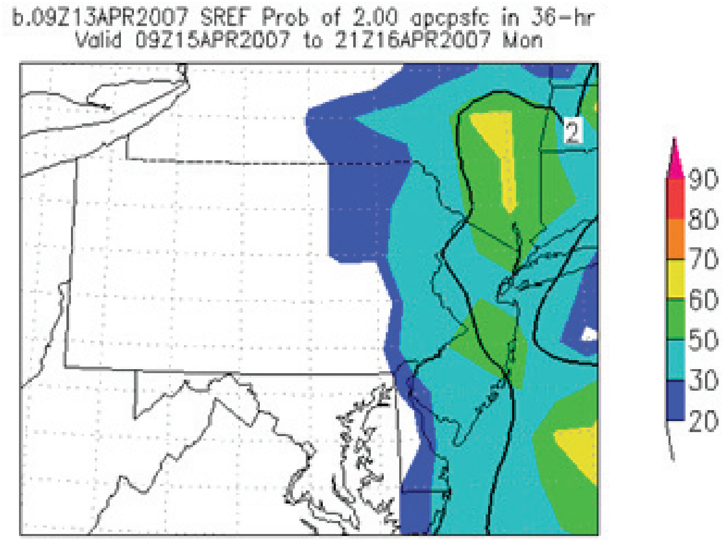


Fig. 8. Probabilities for 2.00 in. (50mm) of rain in 36 hours from a) the 0000 UTC 13 April 2007 GEFS, valid 1200 UTC 15 April 2007 through 0000UTC 17 April 2007, and b) the 0900 UTC 13 April 2007 SREF, valid 0900 UTC 15 April 2007 through 2100UTC 16 April.

community of the expectation of an extreme weather event several days in advance. A consistent message of increasing urgency was conveyed by the meteorological community as the onset of the storm approached, and confidence levels increased, describing the likelihood for heavy snow in higher elevations, strong winds, especially along the northeast U.S. coast, and potentially widespread flooding rains in lower elevations.

The storm affected the northeastern U.S. from late on 15 April through early 17 April, resulting in 1-2 feet (30-60 cm) of snow in the Adirondack Mountains of New York and the mountains of Vermont. Rainfall totaled 3.00 in. to 8.00 in (75 mm to 200 mm) across central and southern New York, New Jersey, and southern New England through the Delmarva Peninsula, with the maximum from northern New Jersey through the Delmarva (Fig. 10). This rainfall resulted in widespread flooding across the region. Winds gusted over 25 ms^{-1} along much of the coast of New England, with localized winds along the Maine coast exceeding 30 ms^{-1}. Similar wind gusts spread through the higher elevations of Vermont causing widespread wind damage. Along the coast there was significant coastal erosion (Storm Data 2007).

6. Conclusion

Prediction of heavy rainfall amounts prior to flooding events is a great forecasting challenge that has significant implications on how users prepare. Studies have shown (such as Schumacher and Johnson 2009) that NWP models often under-predict heavy rainfall, especially when convective process are present, due to relatively coarse horizontal grid resolutions. Widespread high impact flood events are relatively infrequent, and forecasters who depend on NWP model and EPS guidance can under-predict extreme rainfall events as well. Knowing the pattern and the anomalies associated with heavy rainfall events may aid in better predicting these events.

Based on the conceptual models of the Atlantic Flow and Gulf/Tropical Origins patterns in the anomaly data, and the real-time forecasting experience with the April 2007 storm, preferred forecast procedures for both types of events were identified. These procedures should be viewed as guidance, as any individual event has its own unique characteristics, but these procedures have resulted in the most success and may be an important component in optimizing the forecast information provided to users.

The first step in identifying extreme precipitation events 2 to 4 days in advance requires the ability to recognize the patterns in the SREF and GEFS winds, PWAT and MSLP fields. The use of anomalies may help forecasters recognize the signal for heavy rain more quickly than examining the raw data fields. A forecast of a high probability of heavy rainfall in 24 hours may seem more reasonable if the pattern

Fig. 9(a).

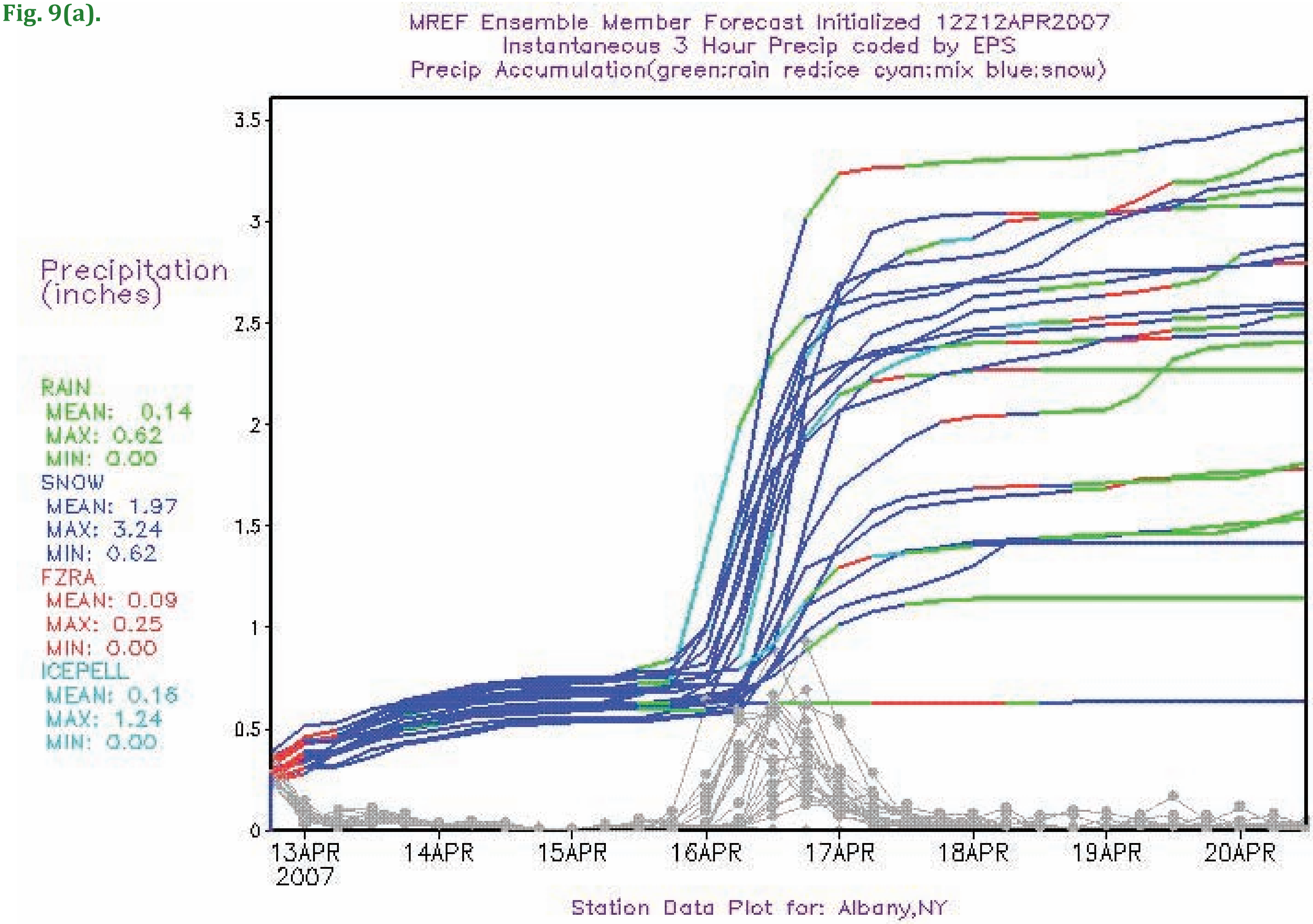


Fig. 9. Plume diagrams from the 1200 UTC 12 April 2007 GEFS for a) Albany, NY and b) Islip, NY. The gray filled squares and open circles represent instantaneous 3-hourly precipitation for each ensemble member.

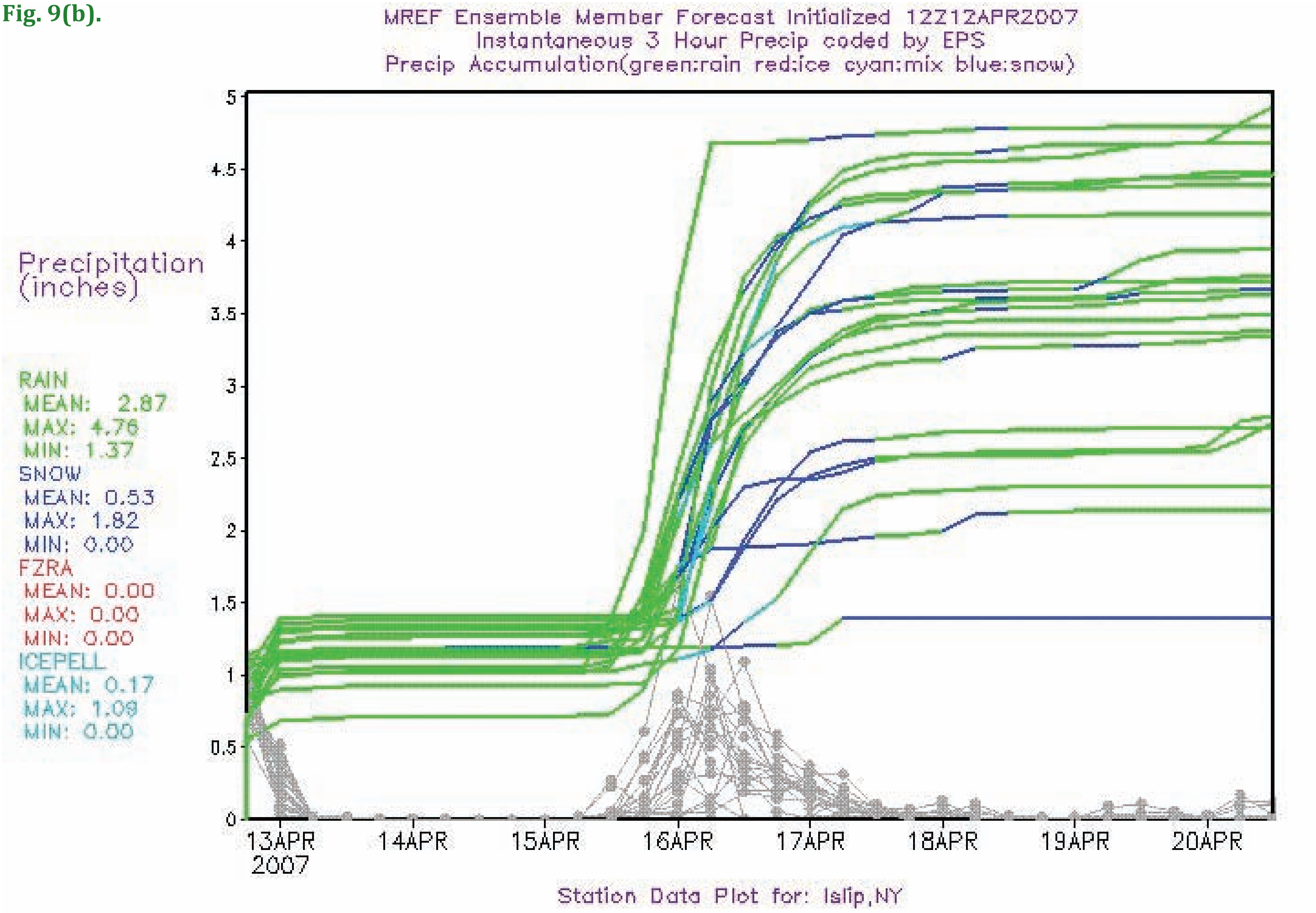
and anomalies support it. Additionally, the large anomalies require a convergence of forecasts and may indicate lower than normal uncertainty and thus a higher confidence event as shown by (Toth et al. 2001).

Depending on the forecast patterns and how they relate to similar event types from the past, lead times of 2 to 4 days are possible in identifying a broad area under the threat of extreme precipitation. The models and EPS often predict the pattern conducive for heavy rainfall, but often do not accurately predict the maximum rainfall amounts and locations, areal extent, and timing of the heaviest rainfall. The mesoscale nature of the heavy rainfall problem combined with limitations of NWP, including both initialization uncertainties and error growth within numerical models, continue to make QPF a difficult forecast problem. Thus, there is considerable uncertainty in predicted areas of heavy rainfall (Tan et al. 2004) relative to where the heavy rainfall is observed. Hence, confidence factors for different scenarios can be conducted through analysis of multiple sources of forecast guidance, including SREF and GEFS, and different types of derived forecast fields from ensemble means and spreads.

However, lack of a clear signal in the EPS data, due to large uncertainty and thus lower anomaly values, may significantly decrease lead times. The predictability of heavy rainfall events can vary from around <1 to 48 hours in low confidence scenarios, to 3-7 days when pattern recognition and guidance sources are consistent. Once the threat has been identified, more specific guidance from NWP models and ensembles should be consulted. Derived fields from the ensembles can be used to increase confidence in forecasting widespread extreme heavy rainfall events over a broad geographic region.

Plume diagrams and probabilities for 2.00 inches (50 mm) of rainfall helped to define a range of potential extreme rainfall amounts. Two sets of ensemble members depicting plume diagrams define an envelope of solutions bounded by the driest and wettest ensemble members. More heavy rain events will be studied to better quantify the relationship between QPF from plumes and observed rainfall. Similarly, >50 percent probabilities of ≥2 inches (50 mm) in the EPS output can signal the potential for widespread flooding rains over a region, depending on antecedent soil conditions and

Fig. 9(b).



the possibility of mesoscale atmospheric processes enhancing rainfall.

The flood threat may exist over a larger area than the probabilities suggest due to the spread within the 15+ member ensemble, since probabilities represent the areal consistency of the ensemble members. Only the overlap of the ensemble members is depicted as areas of probability for 2.00 in of rain (50 mm), with probabilities determined by the number of ensemble members depicting 2.00 in of rain (50 mm) for a given NWP model/ensemble grid area. Therefore, it is extremely important to consult the spreads, especially if most of the members are predicting 2.00 in or more (50 mm or more), with little to no overlap. The heaviest rain occurred within the area covered by the spreads in the May and June 2006 events, but statements on more specific placement of the maximum rainfall will require studying future events.

It should be noted, also, that there have been some early studies in calibration of ensemble output, including studies from the Storm Prediction Center (SPC) such as Bright et al. 2007, but some caution is still advised when using ensemble model output. Other than the initial work Bright and his colleagues have done at the SPC, there is a relative lack of formal verification and calibration studies of ensemble model output. However, multiple recent extreme precipitation events since 2006 have subjectively showed the accuracy and skill of the ensemble model output.

These techniques and tools help assess the magnitude of potential flood events and improve forecaster confidence in the prediction of magnitude and areal extent of extreme flood scenarios. This can result in more accurate information to users who can then improve decision making prior to and during flood events, ultimately reducing the societal impacts of one of the highest impact weather related disasters - extreme flood events.

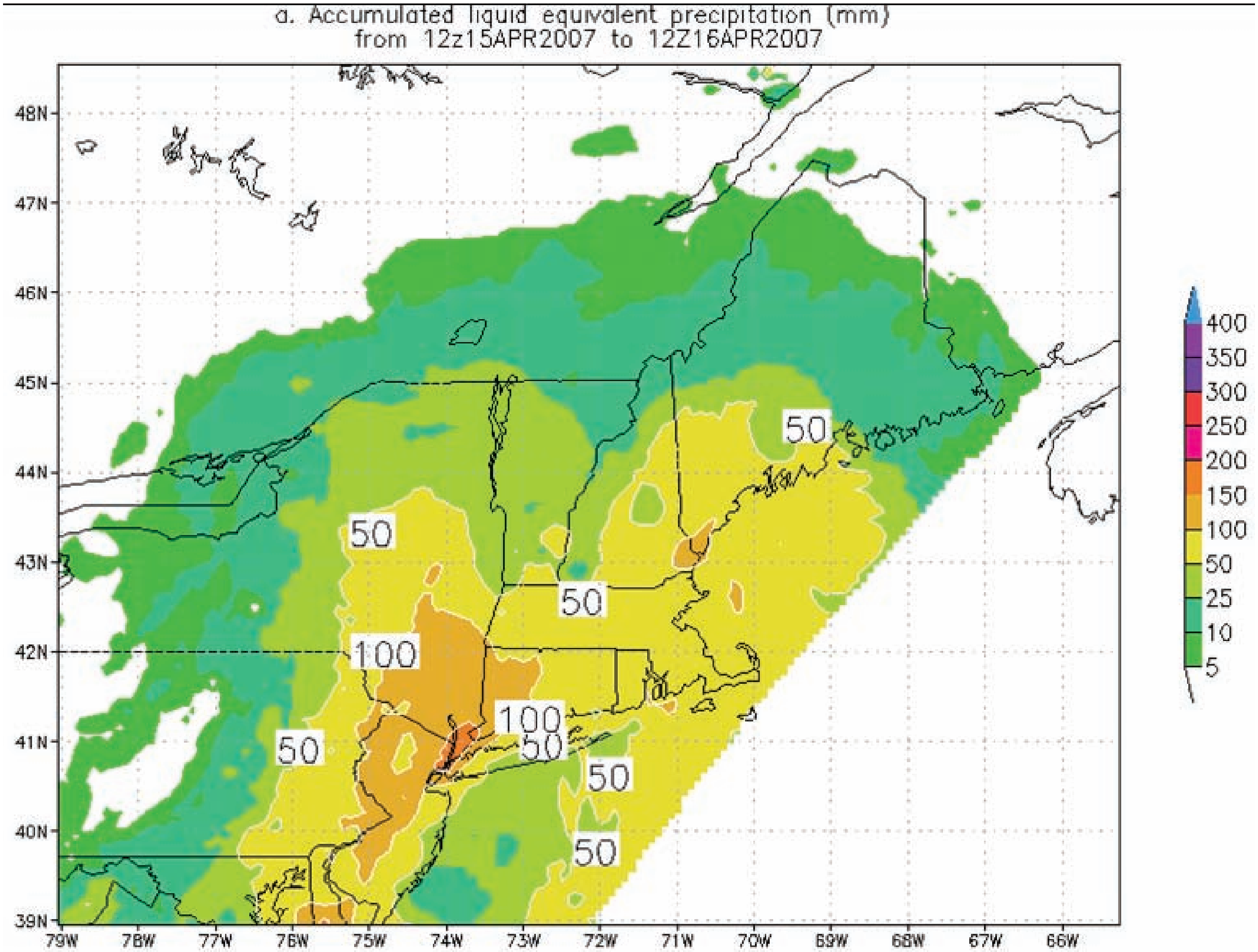


Fig. 10. Same as Fig. 1 except 15-16 April 2007.

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