P1.46

NCEP SREF Forecasts of Three Hurricanes during the 2004 Tropical Season

By
Richard[1] *H. Grumm*
National Weather Service
State College Pennsylvania
and
Jun Du
National Centers for Environmental Predictions
Camp Spring, Maryland

1. Introduction

The tropical cyclone season of 2004 was one of the most active seasons in recent years with 15 named storms, 9 hurricanes, and 6 intense hurricanes (Franklin 2005). An average year, based on the 1950-1990 climatology has 9.3 named storms, 5.8 hurricanes, and 2.3 intense hurricanes (see Table 2 in Landsea et al. 1998). In addition to the number of named storms and hurricanes in 2004, the track of the tropical storms led to the land fall of 4 hurricanes in the state of Florida including hurricanes Charlie, Frances, Ivan, and Jeanne. Four or more hurricanes making landfall in a single state in a single season is historically very rare. This phenomenon was last observed in 1886 when four hurricanes struck Texas (Landsea et al 2004). The extremely active season of 1995 (Landsea et al 1998) had 19 named storms, 11 hurricanes, and 5 intense storms. During the season of 1995, 4 tropical storms affected Florida including hurricane Opal in October 1995 (Landsea et al 1998). Each of the four hurricanes which impacted Florida during the 2004 hurricane season moved northward, affecting other areas of the eastern United States.

O'Brien et al. (1996) showed that the probability of 2 or more hurricanes striking the United States in a single season is 21% and 46% during an El Niño and La Niña year, respectively. Bove et al. (1998) performed an updated climatology from 1900-1997 and found that probability of 2 or more hurricanes striking the United States was 28%, 47%, and 66% in an El Niño, La Niña, and ENSO neutral year, respectively. The number of storms and the number of storms to strike the United States in 2004 was unusually high providing an opportunity to evaluate forecasts of several land falling storms.

Larson et al. (2005) showed the impact of tropical storms on the overall rainfall in the United States. Tropical storms make the largest contribution to rainfall during the month of September where some coastal areas receive approximately 15% of the total rainfall from these systems. In some years, tropical storms may account for over 90% of the precipitation in many coastal regions from Texas to Maine (see Fig. 3 Larson et al. 2005). The important contributions that tropical systems make to the overall precipitation, combined

[1]Corresponding author address: Richard H. Grumm, NOAA/NWS, 227 W. Beaver Avenue, State College, PA 16801

with the locally heavy rainfall these systems produce make forecasting rainfall with these systems a critical forecast problem. The four storms of 2004 season provide a means to assess the value of ensemble forecast products in forecasting the rainfall associated with tropical storms.

The use of short-range ensembles in the forecast process was demonstrated by Stensrud et al. (1999). This was a demonstration of an early version of what evolved into the National Centers for Environmental Predictions (NCEP) Short-Range Ensemble Forecast (SREF) system. In the original study, there were 10 ensemble members with 80 km horizontal resolution. Key findings showed that the coarser ensemble system was comparable in skill to the finer resolution deterministic model. They also found no direct correlation between the spread of the ensemble members and the skill of the ensemble mean forecast.

Mullen et al. (1999) showed that impact of cumulus parameterization schemes on ensemble quantitative precipitation forecasts (QPF). They found that the QPF was extremely sensitive to the physical parameterization scheme in each member. This can have an impact on the overall model performance due to the impact on the larger scale features. In a more recent study Zhang et al. (2003), examined the effects of convection and convective parameterizations showing how they can greatly affect a models forecast of larger scale fields. They found that beyond 24-36 hours significant convection can alter the large scale conditions and greatly impact the developing surface cyclone. In tropical cyclones, convective processes dominate the precipitation and the impact of the convective parameterization scheme can have a significant impact on the forecast of the cyclone track and the precipitation.

The hurricanes of 2004 offer an opportunity to evaluate the performance of ensemble forecast techniques with respect to heavy rainfall during extratropical transition (ET). The heavy rain associated with these systems during ET is a critical forecast issue (Jones et al 2003). The issues associated with the heavy rains during the ET of hurricane Floyd have been shown by Atallah and Bosart (2003). Floyd produced heavy rains in the Mid-Atlantic region, despite its rapid acceleration during ET.

The paper will document the landfall forecasts of three of the tropical storms to affect the Mid-Atlantic region during the tropical storm season of 2004. The three storms selected offer an opportunity to evaluate the operational use of the National Centers for Environmental Predictions (NCEP) Short-Range Ensemble Forecast (SREF) system. The emphasis is on how the SREF performed as the storms took on more extratropical characteristics. Hurricane Charlie was poorly forecast by the SREF system in the Mid-Atlantic region, therefore, examining the SREF data may provide insights on whether the SREF data would have been of value in improving upon these forecasts. Hurricanes Frances and Ivan were chosen due to the amount of rainfall and severe weather each storm produced. These storms offer the opportunity to evaluate critical parameter forecasts, such as model convective available potential energy (CAPE) and probability forecasts of rainfall amounts.

2. Method

All SREF data were obtained from the NCEP archives. The data were available as imagery and GRIB format. For display purposes, a mix of data is shown. Many images are from the NCEP image archive. Other images were reproduced in post analysis mode. The latter allowed for customizing of thresholds and variables shown.

Images showing climatic anomalies were reproduced after the event. All anomalies are shown based on the NCEP/NCAR reanalysis data (Kalnay et al 1996). Anomalies are shown as departures from normal in standard deviations (SDs). The mean and standard deviations were computed as described in Hart and Grumm (2001). In general terms, large positive and negative anomalies often help define weather events which depart significantly from normal. Large negative anomalies in U winds components and mean sea-level pressure (MSLP) fields are often associated with major snow storms along the East Coast (Grumm and Hart 2001).

In this study use of anomalies is applied to the ensemble mean forecast of fields such as MSLP and U and V wind components. The U and V wind components are used to show the easterly and southerly jets associated with the tropical storms. A large negative U wind anomaly is associated with an above normal easterly jet and may help define areas susceptible to heavy rainfall. Large positive V-wind anomalies are often associated with severe weather and heavy rain. All anomaly fields and other graphical displays of SREF data were accomplished using GrADS.

Severe weather reports were obtained from the Storm Prediction Center.

3. Results

i) Hurricane Charlie

The first storm was Hurricane Charlie which struck the west coast of Florida on 13 August 2004. This storm made a last minute change in direction making landfall south of the original forecast area. Making landfall near Captiva Island along the Gulf Coast of Florida (Franklin 2004) spared the city of Tampa from experiencing the full force of the storm. The storm entered the western Atlantic near Daytona, Florida and made landfall again in South Carolina on the 14^{th}. The storm weakened over southeastern North Carolina and moved out over the western Atlantic and became an extratropical storm on the 15^{th}. This storm did considerable damage to Florida but spared the Mid-Atlantic and New England regions.

Forecasts as early as 12 August indicated the potential for high winds and heavy rains in the Mid-Atlantic region on the 14^{th} and 15^{th} of August (Grenci 2004). These heavy rain forecasts, which were not observed, were a "*bust*" associated with Charlie in the Mid-Atlantic region as document by Grenci (2004). These poor forecasts reflected problems in properly forecasting the track of the storm. This section will focus on the track and rainfall forecasts associated with hurricane Charlie.

The forecast tracks of hurricane Charlie from SREFs initialized at 0900 UTC 12 and 13 August 2004 are shown in Figure 1. Forecasts from the 12th suggested that the storm could make landfall from near Tampa on the West Coast of Florida to the Florida panhandle. There appeared to be a clustering toward these two solutions. The storm was then forecast to move up the East Coast tracking several hundred kilometers west of the coast line.

Forecasts initialized at 0900 UTC 13 August clustered toward a West Coast Florida landfall then a track up the East Coast, slightly farther east than the previous forecasts. This track favored the potential for heavy rainfall from the Gulf Coast up the Atlantic coast. This two tracks favored heavy rainfall along and west of the cyclone track as indicated in the forecasts of 25 mm or greater rainfall shown in Figure 2. These quantitative precipitation forecasts (QPFs) suggest heavy rain as far north as New York State. These forecasts also show some disagreement in the timing of the heavy rainfall.

As the SREFs, in later runs, converged on a faster northward speed and a more easterly track of the surface cyclone, the resulting QPF diminished and shifted eastward as shown in Figure 3. The threat of heavy rain for Virginia and Pennsylvania was no longer a significant forecast consideration. Most of the Mid-Atlantic and the northeastern United States received little significant rainfall from hurricane Charlie.

ii) Hurricane Frances

Hurricane Frances made landfall on the east coast of Florida just after midnight on 5 September 2004 near Stuart, Florida (Franklin 2005). As it moved west-northwestward it crossed into the Gulf of Mexico making landfall as a tropical storm along the Florida panhandle. The storm took on extratropical characteristics over West Virginia.

Frances produced severe weather including 46 tornadoes in the southeastern United States on the 7th and the storm was associated with over 100 tornadoes along its path (Franklin 2005). The storm produced heavy rains from the Gulf Coast northward into Pennsylvania, Ohio, and western New York on the 8-9th of September. Unlike the forecasts associated with hurricane Charlie, in this event, the SREF produce useful guidance in relation to areas where heavy rains would and did fall.

The heavy rain and severe weather aspects of this storm are shown here. These are best conveyed by CAPE, low-level winds, and QPFs. Figure 4 shows the SREF 24-hour forecast of 50 mm of rainfall or more for the 24 hour periods ending at 2100 UTC on 8 September and 1200 UTC on 9 September 2004. There was a high probability forecast of heavy rains in the mountains of North and South Carolina. The consensus forecast showed a 2.5 inch contour in this region. A surge of heavy rain was forecast to move up the western side of the Appalachian Mountains. The by 1200 UTC 09 September, at least 30% of the SREF members forecast 2.00 inches of rain in portions of Pennsylvania and Ohio (Fig. 4b). The consensus forecast showed a 1.5 inch contour over Ohio and Pennsylvania. Though not shown accumulated rainfall for 36 and 48 hour periods showed higher probabilities of 2.00 inches of rain, and higher consensus forecasts of total accumulations.

Figure 5 shows the 850 hPa winds valid at 1800 UTC 7 September and 0600 UTC 9 September 2004. The times of these images was selected to coincide with times of climatic anomalies associated with significant weather. For example, in Georgia and the Carolina's, the southerly 850 hPa jet on the east side of Frances was forecast to be on the order of 5 SDs above normal in the area of the observed severe weather and tornadoes. Experience has shown that strong positive V-wind anomalies appear to be a good indicator of potential severe weather. North of the storm, a strong easterly jet was present. This region is where the heavy rains were both forecast and observed. The U-wind anomalies were on the order of 4.5 SDs below normal implying a much above normal easterly jet (Fig. 5a upper panel) into the southern Appalachian Mountains.

Later in the event (Fig. 5b) strong southeasterly winds were forecast over Pennsylvania with strong northeasterly winds over Ohio, on the west side the remnant circulation associated with tropical storm Frances. The strong northeasterly jet brought the observed heavy rainfall to northwest Pennsylvania and Ohio. Heavy rains farther east were associated with the strong southeasterly jet.

Figure 6 shows the CAPE forecast valid at 2100 UTC 7 September. The lower panel shows the probability of CAPE exceeding 900 JKg^{-1}. Extremely high CAPE is not normally observed with tropical storms. The SREF forecasts showed a high probability of CAPE exceeding 900 JKg^{-1} along and to the west of the Appalachian Mountains. Another region of relatively high CAPE was forecast along the coastal areas and the adjacent western Atlantic Ocean. The spaghetti plots showed the variation in both regions but overall, all SREF members outlined two distinct areas of instability as indicated by CAPE forecasts.

The combination of instability (Fig. 6) and the strong 850 hPa winds (Fig. 5), which implies strong shear, likely led to the 54 reported tornadoes on the 7th of September 2004 (SPC-StormData) of which 51 were observed in North and South Carolina. An additional 26 tornadoes were observed on the 8th from North Carolina to Maryland with most of the tornadoes occurring Virginia.

iii. Ivan

Hurricane Ivan was a particularly long-lived and long tracked storm. It reached hurricane strength on the 5th and after moving well to the west of Florida peninsula, it made a turn to the north and making landfall on the 16th at Gulf Shores, Alabama. This storm produced 29, 23, and 59 confirmed tornadoes on 15th, 16th and 17th of September respectively. In addition to the severe weather, the storm produced heavy rains over Pennsylvania on the 17th and 18th when it interacted with an east-west oriented frontal system in the Mid-Atlantic region. A few central Pennsylvania locations experienced record river stages on the 18th and 19th due to the rainfall. The focus on Ivan will be on QPF and severe weather forecasts associated with hurricane Ivan.

Figure 7 shows the 24-hour QPF for 50 mm or more rainfall from SREF initialized at 0900 and 2100 UTC 15 September 2004. These data are near the limbs of the 0900 UTC forecast cycle representing the rainfall ending 63-hours after ensemble system initialization time. They show the potential for heavy rains by 0000 UTC 18 September up the western slopes of the Appalachian Mountains. The period of heaviest rain was forecast to occur late on the 17th and early on the 18th as indicated by the 2100 UTC 15 September forecast valid for the 24-hour period ending at 1200 UTC 18 September 2004 (Fig. 7b). Observations (not shown) revealed heavy rains on the 17th and early on the 18th.

Overall, these forecasts (Fig. 7) showed the potential for heavy rains over Pennsylvania near an old frontal boundary (not shown). For the relatively long lead-times (63-hours) of the forecasts shown, the threat of heavy rains was clearly a forecast issue for the central Appalachians the 18th and the southern Appalachians on the 17th. Subsequent forecasts initialized at 0900 and 2100 UTC on 16 September 2004 (not shown) trended toward both a higher probability of heavy rains for the period ending at 1200 UTC 18 September and higher consensus total rainfall amounts.

In addition to the heavy rains, Ivan produced over 100 tornadoes. The SREF CAPE forecasts from 2100 UTC 15 September 2004 and 850 hPa winds forecasts are shown in Figures 8 & 9 respectively. These data show a high probability of CAPE exceeding 900 JKg^{-1} over Georgia and most of the southeast Atlantic coastal plain. The secondary area of high CAPE to the west shows the surge of moisture ahead of a frontal system that would interact with Ivan. The strong southerly low-level jet, as viewed by the 850 hPa winds, was in excess of 40KTS and near 50KTS over Georgia (Figure 9, lower panel). The V-winds were over 5 SD above normal implying a much above normal southerly jet. The combination these strong winds, implied shear, and the instability in the warm tropical air over Georgia were associated with the observed tornadoes. As the system moved northward on the 16th the tornadoes spread into South Carolina.

6. Conclusions

Four hurricanes made landfall along the southeastern coast of the United States. Three of the storms made landfall in Florida and a fourth, Ivan, made landfall in extreme eastern Alabama. All four storms brought heavy rains, winds, and tornados to the State of Florida. With the exception of hurricane Charlie, as these storms moved northward, they produced heavy rains and severe weather. The weather associated with these events made them ideal candidates with which to evaluate the efficacy of SREF products.

The first storm, hurricane Charlie was the smallest storm and the storm where the SREFs had the greatest difficulty. The landfall forecasts for this storm were initially too far west than observed, though the actual landfall location was within the envelope of solutions. Several SREF members forecast a more eastward track and some members showed the rapid acceleration that was actually observed. Overall there was considerable uncertainty with this storm. The SREF QPFs initially were too far west with the areas of heavy rains which may have led to overly optimistic forecasts for heavy rains and flooding as described by Grenci (2004). This storm had little significant impact on the Mid-Atlantic region though early human forecasts and many SREF forecasts did suggest the potential for heavy rains.

SREF forecast for hurricane Frances were in stark contrast to those associated with hurricane Charlie. The overall track of the surface cyclone, the areas under the threat for heavy rains, strong winds, and potential severe weather were relatively well forecast by the SREF several days in advance. The CAPE and anomalous low-level jet (850 hPa winds used as a proxy) outlined the high threat areas on the 7^{th} and 8^{th} where over 100 tornadoes were observed on those days. For tropical storms, with highly sheared environments, CAPE values of 500 and 900 JKg^{-1} appear to be sufficient to imply the potential for severe weather.

The SREF QPF forecasts associated with Frances showing the potential for over 2.0 inches of QPF were also well forecast. Though no member was capable of forecasting the 455 mm (18.07 inches: Franklin 2004) of rainfall observed at Linville Falls, North Carolina.

Hurricane Ivan shared many of the characteristics of hurricane Frances. The stronger frontal zone in the Mid-Atlantic region likely led to the increased rainfall in that region. Both storms had CAPE on the order of 500 to 1000 JKg^{-1} in regions east of the cyclone center, co-located with anomalously strong low-level winds. These regions experienced the severe weather and tornadoes. Both Frances and Ivan produced over 100 tornadoes as they transitioned from tropical to ET storms. Tornadoes in tropical storms appear to form in environments with relatively low CAPE compared to tornadoes in normal mid-latitude situations. However, the areas affected by the tornadoes are typically in areas of anomalously strong low-level winds and wind shear which contributes to the tornado threat. In these two events, the SREF clearly defined the areas of instability and areas of strong low-level winds.

The results shown here suggest that the NCEP SREF system has significant operational utility in forecasting the track of tropical storms as well as outlining areas susceptible to heavy rainfall and severe weather. Overall, the SREFs performed well in defining the threat area for heavy rains in Ivan and Frances as they interacted with a mid-latitude frontal system. This suggests some skill in the SREF system in dealing with the ET transition.

Some potential operationally-oriented SREF applications that could be useful during tropical storms that make landfall on the United States would include:

a) Defining areas susceptible to severe weather based on CAPE threshold forecasts and strong low-level winds such as 850hPa jets.

b) Track and timing information based on the track forecasts showed some problems like in Charlie, when forecasts cluster by model.

c) QPF forecasts of means and critical thresholds showed some skill during Frances and Ivan. However, they were of little value with hurricane Charlie.

Overall, SREFs did well with 2 of the 3 storms presented. The performance with Charlie was poor as they initially showed a more westward track that favored heavy rains and winds farther inland than observed. However, the SREF forecasts on landfall in Florida correctly forecast the landfall region though several members were initially far too north. This error decreased as the landfall time neared. The cause of the track error along the East Coast is a possible avenue of future research. The results here are promising and show that the SREFs provided extremely useful guidance and outlined the main threats and threat areas correctly in 2 out of 3 tropical storms.

7. References

Atallah E.H and L. F. Bosart. 2003: The Extratropical Transition and Precipitation Distribution of Hurricane Floyd (1999). *Mon. Wea. Rev.*, **131,** 1063–1081.

Bove, M.C., J.B. Elsner, C.W. Landsea, X. Niu, and J.O'Brien, 1998, Effect of El Nino on U.S. Landfalling Hurricanes, revisited. *Bull. Amer. Meteor. Soc*.,**79**,2477-2482.

Franklin, J.L, 2005: 2004 Atlantic hurricanes a season of devastation. *Weatherwise*, **58**,52-61.

Grenci, L, 2004: Another Charlie horse for weather forecasters. *Weatherwise*, **57**,50-57.

Grumm, R. H., and R. Hart, 2001: Standardized Anomalies Applied to Significant Cold Season Weather Events: Preliminary Findings**.** *Wea. Forecasting*, **16**, 736–754.

Hart, R. E., and R. H. Grumm, 2001: Using Normalized Climatological Anomalies to Rank Synoptic-Scale Events Objectively**.** *Mon. Wea. Rev.*, **129**, 2426–2442.

Jones, S.C, P.A. Haar, J. Abram, L.F. Bosart, P.J. Bowyer, J.E. Evans, D. E. Hanley, B.N. Hanstrum,R.E.Hart,F.Lalaurettee, M. R.Sinclair,R. K. Smith, C. Thorncroft, 2003 The Extratropical Transition of Tropical Cyclones: Forecast Challenges, Current Understanding, and Future Directions. *Weather and Fore.*,**18**,1052–1092.

Landsea, C. W., C. Anderson, N. Charles, G. Clark, J. Dunion, J. Fernandez-Partagas, P. Hungerford, C. Neumann, and M. Zimmer, 2004: The Atlantic hurricane database re-analysis project: Documentation for the 1851-1910 alterations and additions to the HURDAT database. Hurricanes and Typhoons: Past, Present and Future_, R. J. Murname and K.-B. Liu, Eds., Columbia University Press, 177-221.

-------,-,-, G.D Bell, W.M. Gray, and S.B. Goldenberg, 1998: The extremely active 1995 hurricane season: Environmental Conditions and verification of seasonal forecasts. *Mon. Wea. Rev.*,**126**,1174-1193.

Kalnay, E., and Coauthors, 1996: NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77,** 437–471.

Larson, J.,Y.Zhou, and R.W. Higgins,2005: Characteristics of landfalling tropical cyclones in the United States and Mexico: Climatology and interannual variability. *J.Climate*,**18**,1247-1262.

Mullen, S.L, J. Du and F Sanders, 1999: The Dependence of Ensemble Dispersion on Analysis–Forecast Systems: Implications to Short-Range Ensemble Forecasting of Precipitation. *Mon. Wea. Rev.*,**127**,1674–1686.

O'Brien, J. J, T. S. Richards, and A. C. Davis, 1996: The effect of El Niño on U.S. landfalling hurricanes. *Bull. Amer. Meteor. Soc.*, **77,** 773–774.

Stensrud, D.J., H.E. Brooks, J. Du, M.S. Tracton, and E.Rogers, 1999: Using Ensembles for Short-Range Forecasting. *Mon. Wea. Rev.*,**127,**433-446.

Zhang, F, C.Snyder, and R. Rotunno, 2003: Effects of moist convection on mesoscale predictability. JAS,**60**,1173-1184.

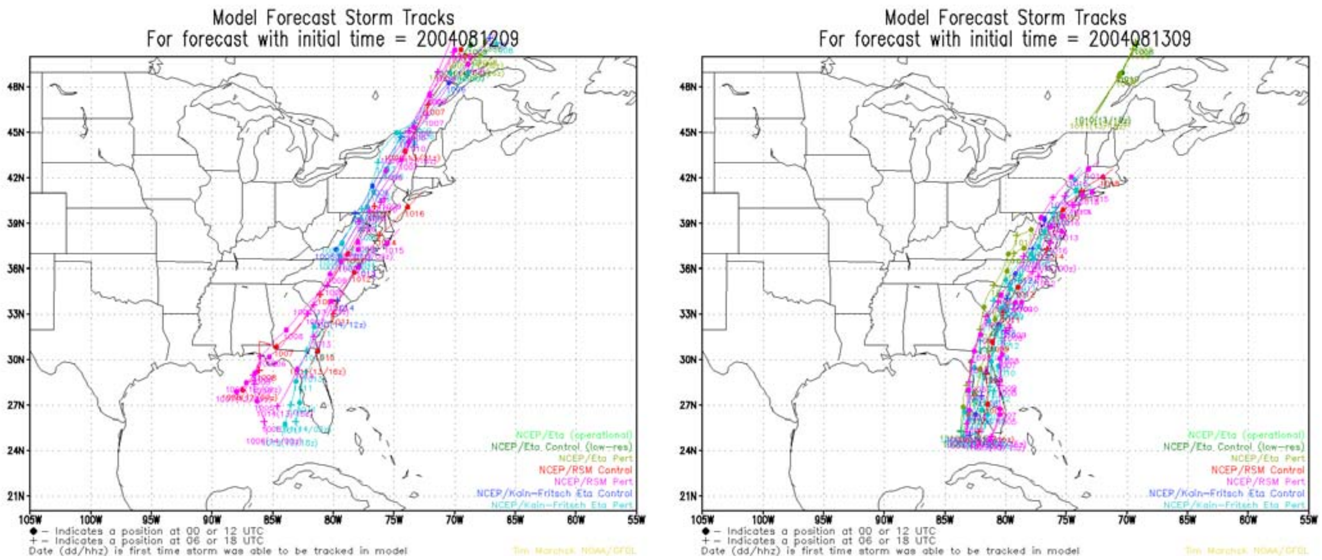

Figure 1 SREF forecast tracks of hurricane Charlie from forecasts initialized at 0900 UTC a) 12 August and b) 13 August 2004. Return to text.

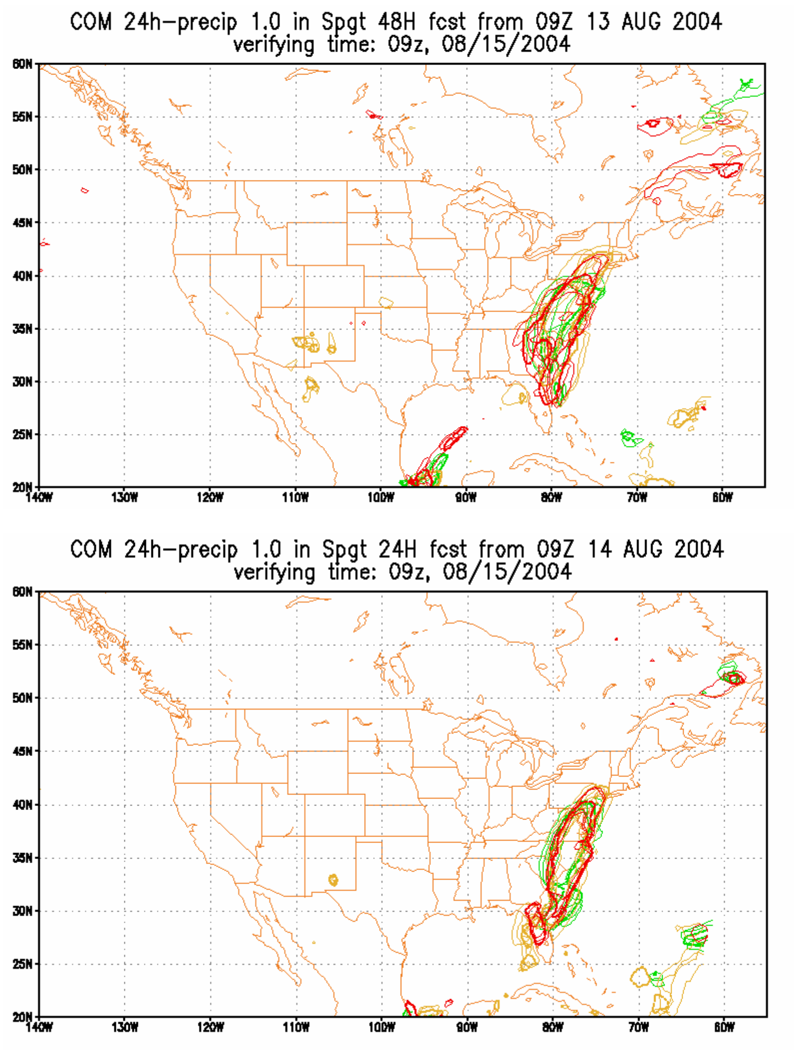

Figure 2 SREF of QPF showing the 1.0 inch or greater contour for the 24-hour period ending at 0900 UTC 15 August 2004. Return to text.

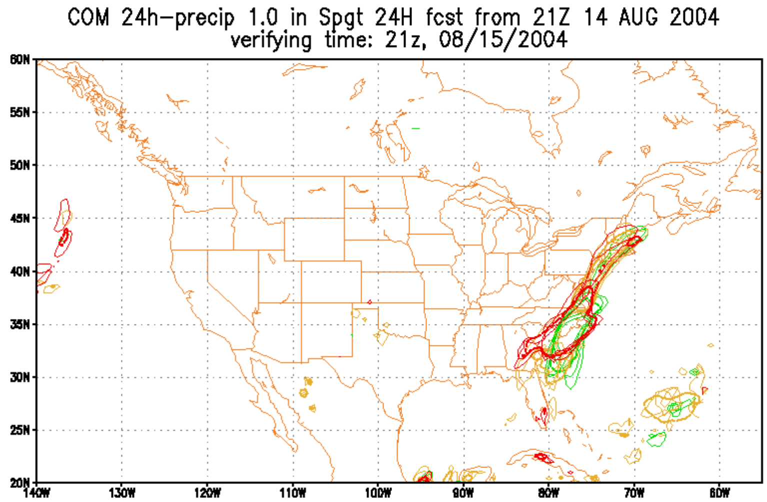

Figure 3 As in Figure 2 except from Forecasts initialized at 2100 UTC 14 August 2004. Return to text. Return to text.

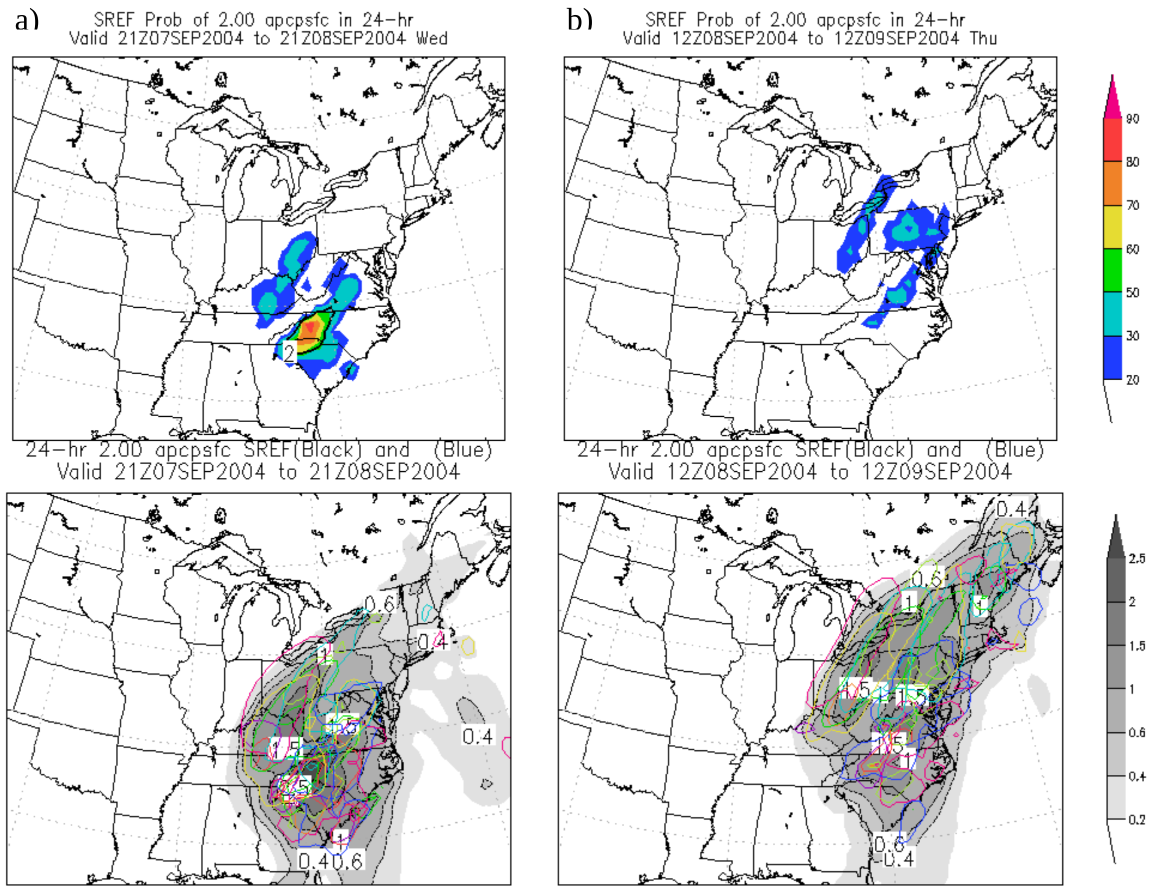

Figure 4 SREF initialized at 0900 UTC 07 September 2004 showing 24-hour accumulated rainfall for the periods ending at a) 2100 UTC 8 and b) 1200 UTC 09 September 2004. Upper panels show the probability of exceeding 2.00 inches (shaded) and the mean position of the 2.0 inch contour (black). Lower panel shows accumulated rainfall (shaded) and each SREF member's position (contours) of the 2.0 inch contour. Return to text.

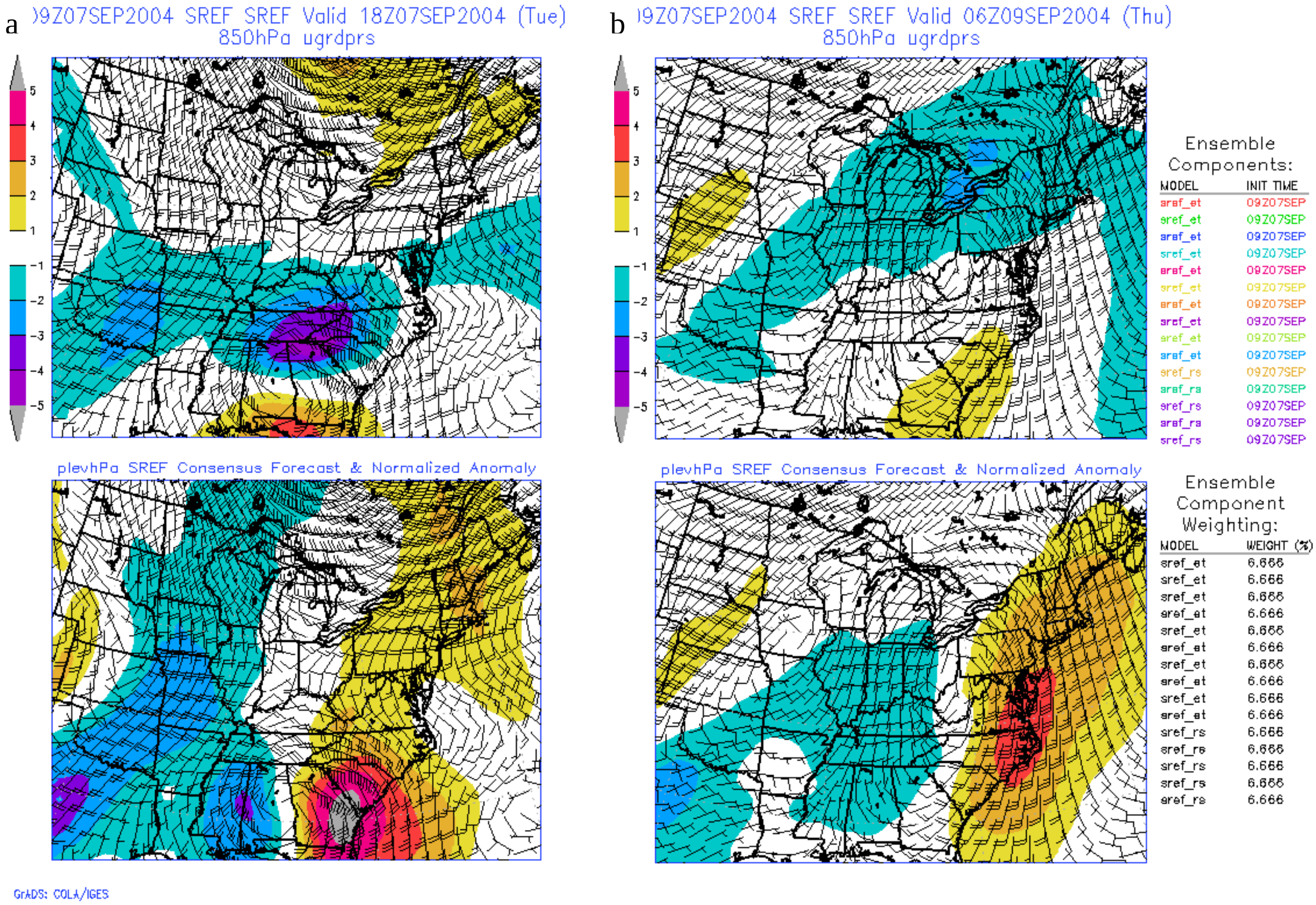

Figure 5 SREF 850 hPa ensemble mean winds (kts) from forecasts initialized at 0900 UTC 7 September 2004 showing U (upper panels) and V (lower panels) wind anomalies valid at a) 1800 UTC 07 September and b) 0600 UTC 09 September 2004. Wind barbs in knots. Anomalies (shaded) in standard deviations from normal as indicated by the color key to the left of the upper panels. Return to text.

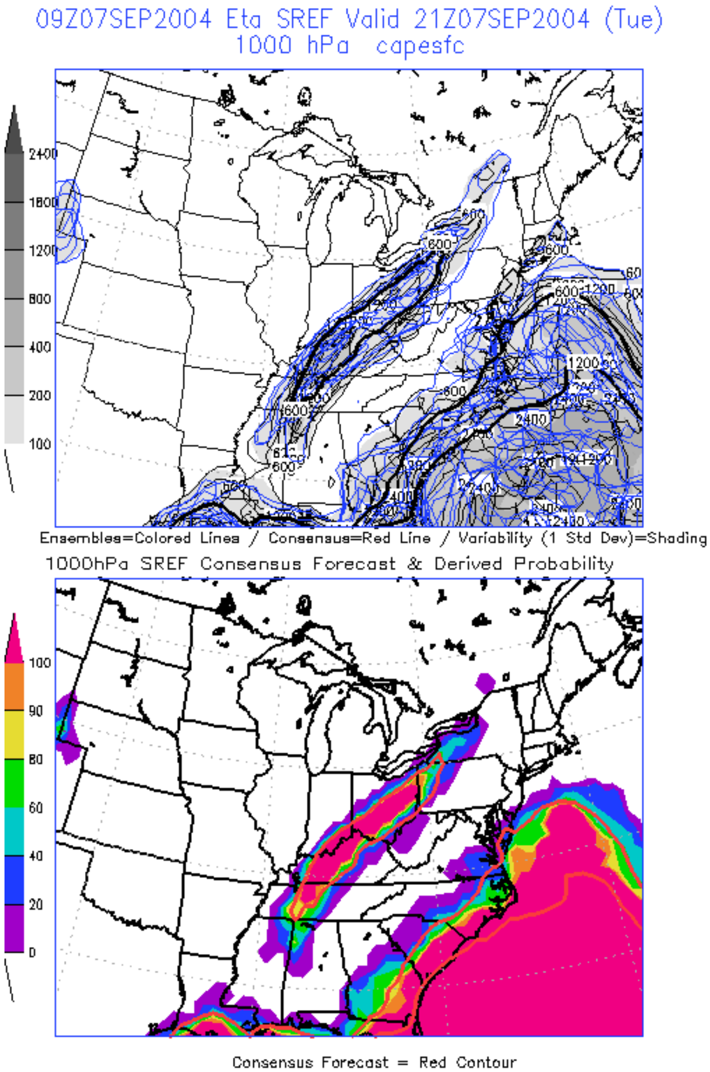

Figure 6 As in Figure 5 except CAPE (JKG^{-1}) forecasts valid at 2100 UTC 07 September 2004. Upper panels shows each member position of the 600,1200, and 2400 JKG^{-1} contour and shading shows the dispersion about the mean. The lower panel shows the probability (percent) of the CAPE exceeding 900 JKG^{-1}. Return to text.

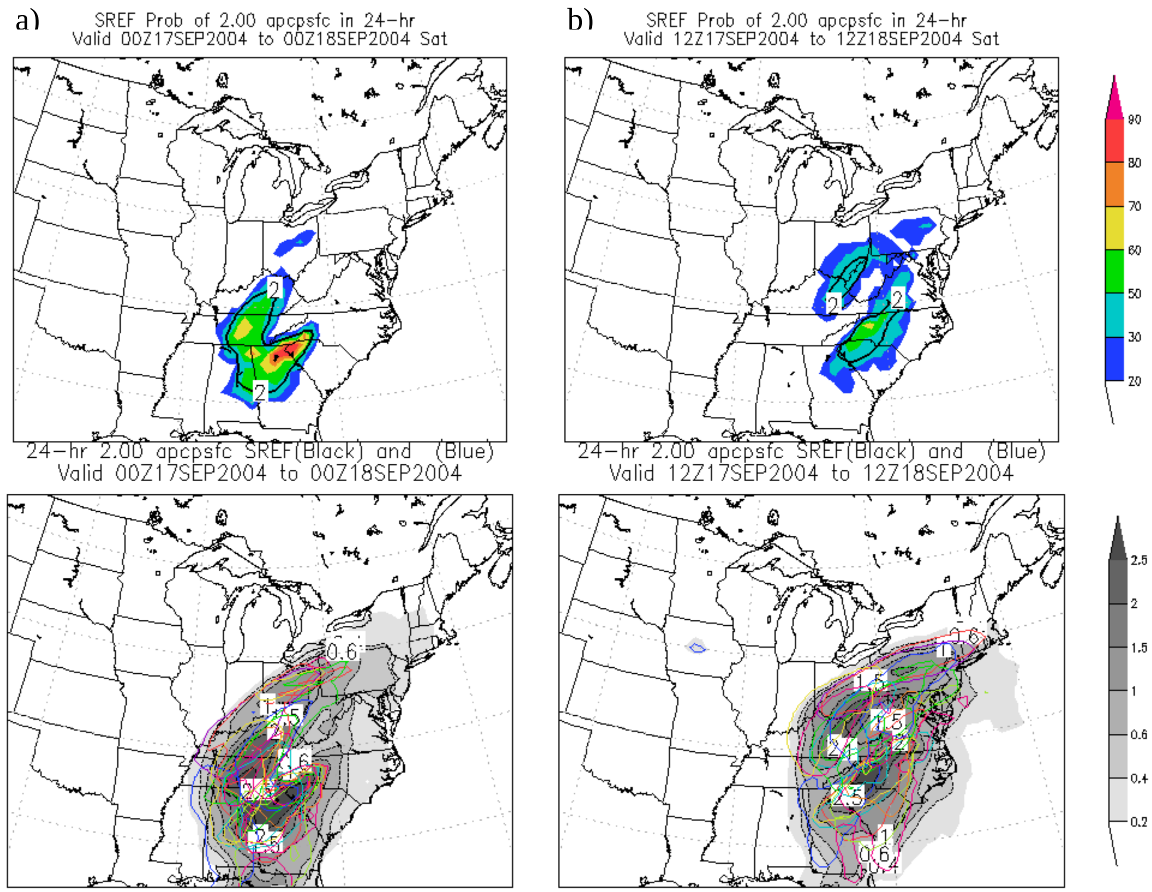

Figure 7 As in Figure 4 except for 2.00 inches of accumulated precipitation over 24 hour from a) forecasts initialized at 0900 UTC 15 September ending at 0000 UTC 18 September and b) forecasts initialized at 2100 UTC 15 September ending at 1200 UTC 18 September 2004. Return to text.

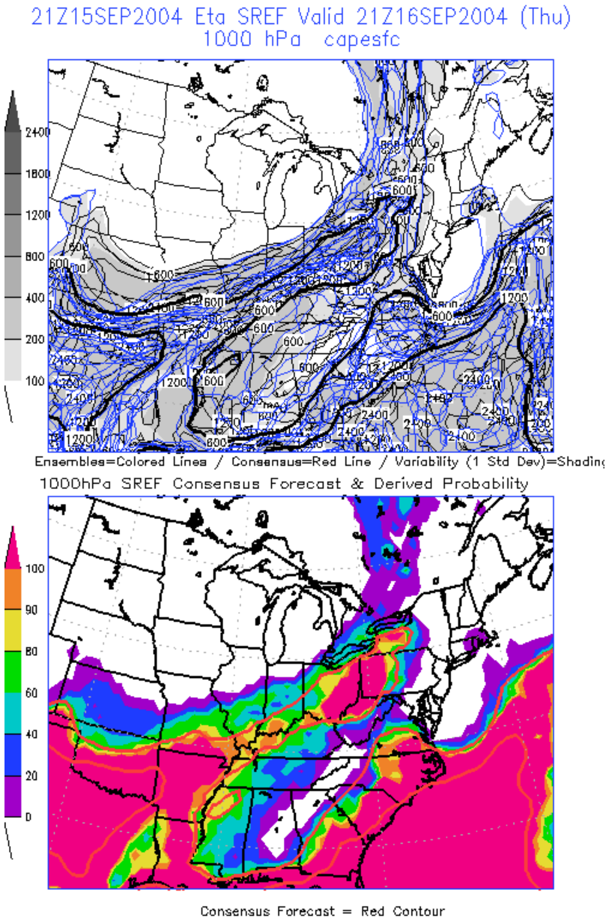

Figure 8 As in Figure 6 except CAPE forecasts initialized at 2100 UTC 15 September 2004 valid at 2100 UTC 16 September 2004. Return to text.

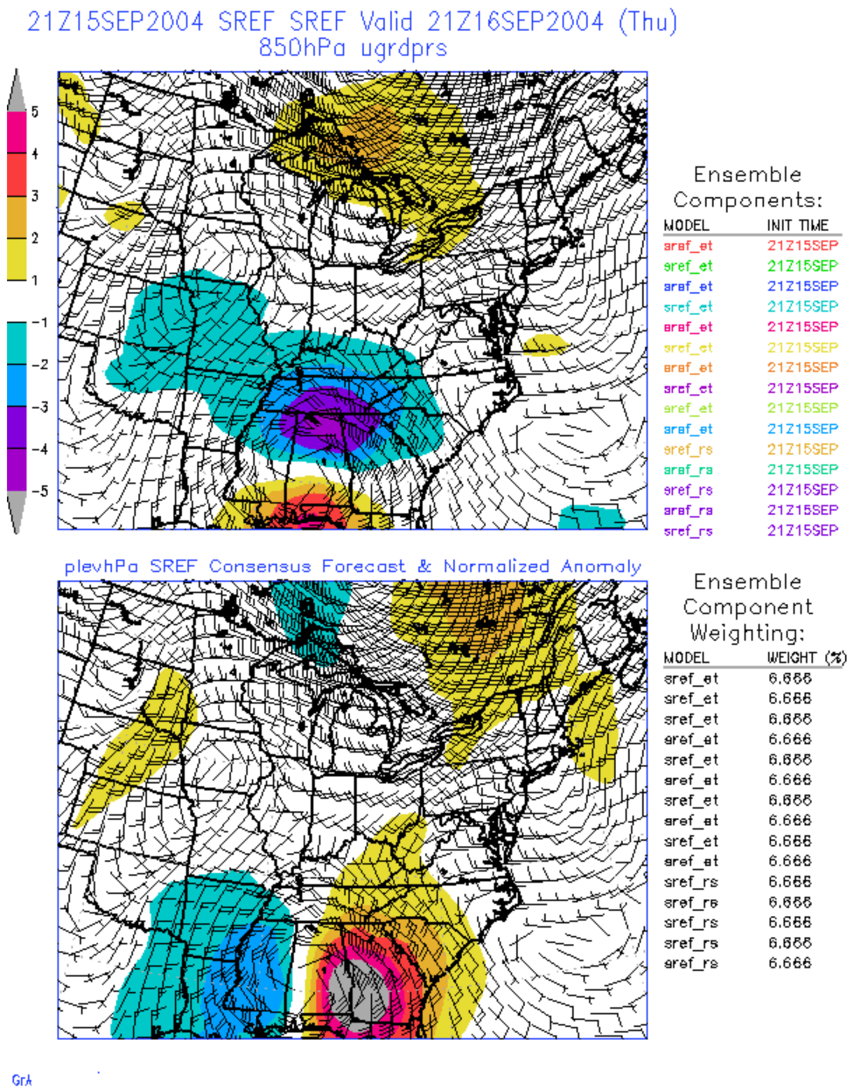

Figure 9. As in Figure 5 except 850 hPa winds initialized at 2100 UTC 15 September 2004 valid at 2100 UTC 16 September 2004. Return to text.