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Examining Severe Weather Events Using Reanalysis Datasets

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1. INTRODUCTION

The National Centers for Environmental Prediction (NCEP) /National Center for Atmospheric Research global reanalysis data (NCEP/NCAR, Kalnay et al 1996) have been shown to be valuable in identifying extreme events over the eastern United States (Hart and Grumm 2001). Grumm and Hart applied these data in identifying significant weather events such as East Coast snowstorms and warm episodes, and demonstrated examples applying the derived climatic anomalies to operational forecast products. In addition, a study of the extended tornado outbreak of May 2003 (Hamill et al 2005) also used the NCEP/NCAR re-analysis data to assess the conditions associated with a prolonged period of devastating tornadoes, revealing the broad utility and benefits of historical reanalyses.

The cited studies relied on the relatively coarse NCEP re-analysis data (Kalnay et al 1996). This global dataset has a horizontal grid spacing of 2.5^{o} x 2.5^{o}, rather coarse to assess the mesoscale conditions associated with significant winter storms and severe weather events. Fortunately, NCEP has recently developed a regional reanalysis dataset, (NARR, Messinger et al. 2003), exhibiting higher resolution and greater accuracy than the NCEP-NCAR Global Reanalysis (GR) data. The current version of the NARR has 32-km horizontal grid spacing and 45 vertical levels. It is expected that this data set will show the mesoscale detail in weather systems, particularly severe weather, that the coarser NCEP/NCAR GR would miss. The objectives of this paper are to demonstrate and document some of these differences.

In addition to the increased resolution and accuracy, the NARR data provides an additional set of variables not available in the NCEP/NCAR GR dataset. Variables such as convectively available potential energy (CAPE) and convective inhibition (CIN) offer new opportunities to investigate severe weather events and identify instability anomalies associated with these events.

A goal of this paper is to present a gridded CAPE climatology and test the validity of CAPE threshold used to forecast the potential for severe weather. Previous studies have shown the relationship between CAPE and shear and CAPE and helicity (Johns and Doswell 1992) . The majority of events occur with CAPE in excess of about 1000 JKg^{-1}. With stronger shear and helicity, strong tornadoes can also occur. Likewise with relatively low shear and helicity, high CAPE

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environments, greater than 2500+ Kg^{-1} , can produce strong and violent tornadoes. These data were not normalized or stratified by season or location. Furthermore, instability parameters which indicated a moderate to high severe weather potential included a CAPE of 2600 J kg^{-1}, which was suggested by Weisman and Klemp (1986). No published study has shown seasonal values of CAPE and the impact of above normal CAPE on severe weather occurrences.

Cortinas et al. (1993) discussed the use of SREH and CAPE calculations for mesoscale model output during a severe outbreak in the Southeast. Their results show that values of both SREH greater than 150 J/kg and positive CAPE were often associated with areas where severe, rotating storms were observed, although SREH and CAPE were highly variable, temporally and spatially, throughout the model simulation. The present study extends those results to other cases where severe weather was observed.

This paper will show the utility of the NARR CAPE climatology in diagnosing severe weather events. Section 2 describes the methods and data. Section 3 presents the CAPE climatology, section 4 presents the cases and section 5 summarizes the preliminary findings.

Event Date	Reference	Severe Weather Summary
28 March 1984	Gyakum and Barker (1988) Grazulis (1993)	Deep cyclone with tornadoes in NC. The 22 tornadoes that killed 57 people, including 42 in North Carolina with 15 in South Carolina, and injured another 800. Documented F4 tornado.[1]
31 May 1985	Forbes (1986) Farrel and Carlson (1989)	Only known F4 tornado in Pennsylvania
2 June 1998	Local Office Study	F3 tornado in Pennsylvania and F4 in Maryland late evening 2 June 1998.
3-11 May 2003	Hamill et al (2005)	Massive multi-day outbreaks of tornados. Focus on the three days with the most tornado reports.

Table 1. Dates, references, and general information on the cases selected from the literature and examined in this paper.

2. METHODS

a. Data sets

NCEP/NCAR GR data are used as the control in this study. A climatology of 21-day centered means and standard deviations are computed for select variables in the GR dataset using 1971-2000 as the climatological period (see Hart and Grumm 2001). In addition, a limited set of NARR centered means and standard deviations are computed for variables such as CAPE and CIN from the complete NARR period (1979-2004). With the exception of the CAPE, all departures from normal are computed using the

[1] Information on F-scale and damage courtesy of the National Weather Service office in Raleigh, North Carolina. See page 1254 Grazulis (1993).

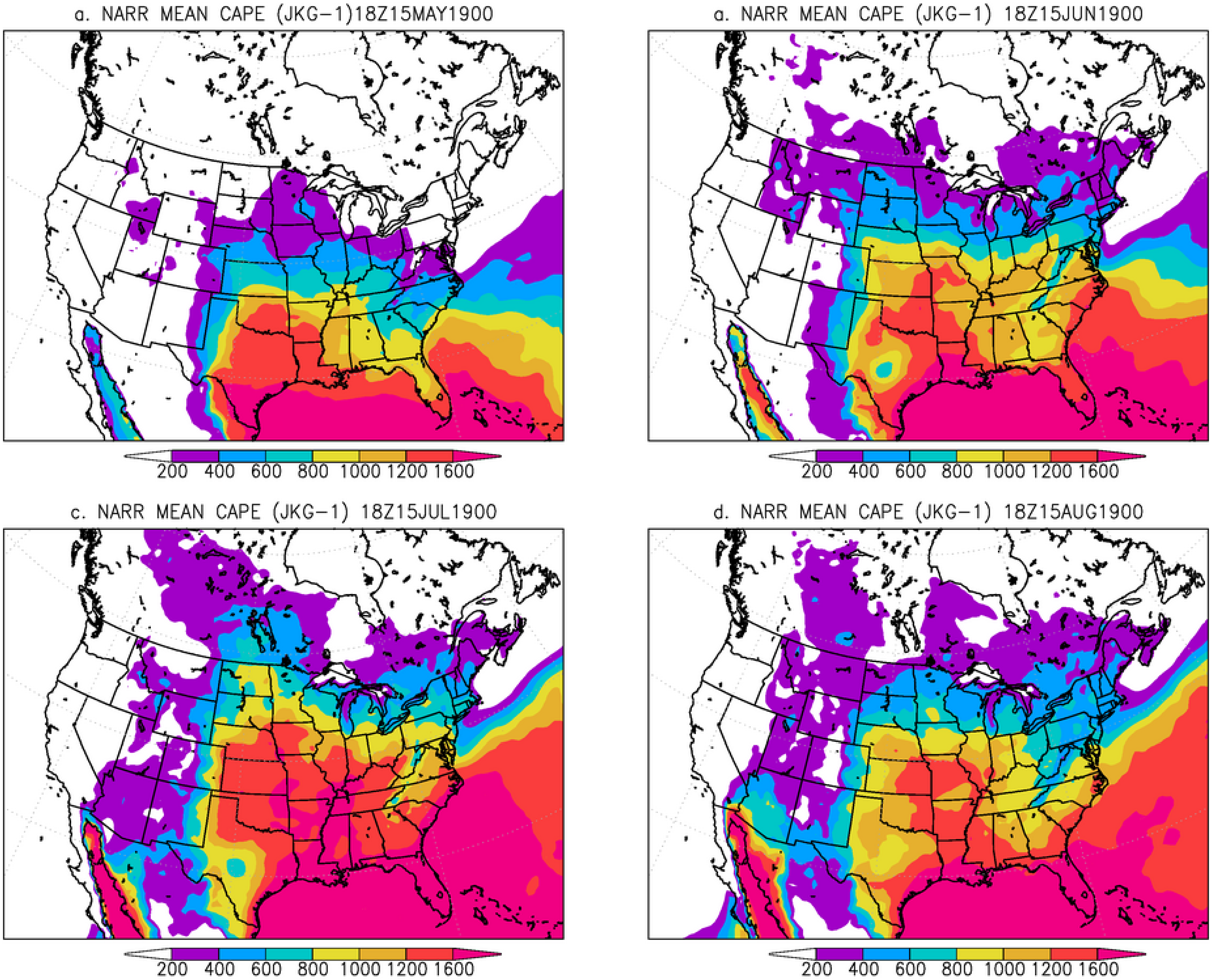

Figure 1 NARR mean CAPE values derived from the 1979-2003 dataset at 1800 UTC showing mean CAPE for a) 15 May, b) 15 June, c) 15 July, and d) 15 August. Contours in JKg-1 as indicated by the color bar.

NCEP/NCAR GR. Examples of NCEP/NCAR GR values of parameters such as mean-sea level pressure (MSLP) and precipitiable water (PWAT) are presented along with the departures of these fields from the climatic means in standard deviations from normal. The same variables are extracted from the NARR data and compared with the NCEP/NCAR GR means and standard deviations, thus revealing mesoscale details in the higher resolution data.

All CAPE data and departures from normal are derived from the NARR dataset. Thus the CAPE climatology is based on finer resolution data than the MSLP and other data fields.

b.Case selection

In order to demonstrate the value of the CAPE climatology and to compare the NARR and NCEP/NCAR GR data the focus is on severe weather events from the published literature. The selected events were associated with unusual tornado

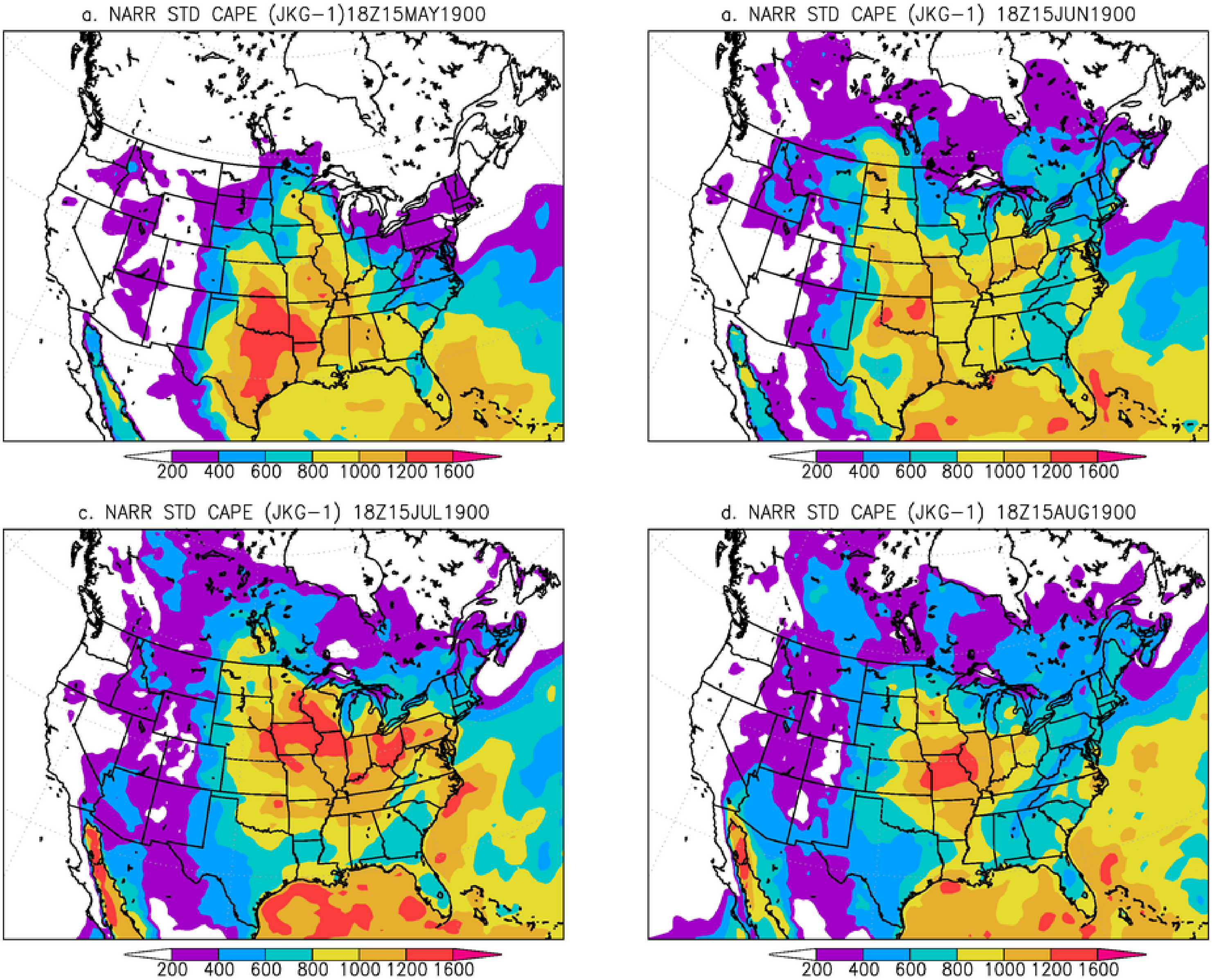

Figure 2 As in Figure 1 except value of one standard deviation of CAPE as indicated by the color scales.

activity and supposedly occurred in a high CAPE environment. Table 1 lists the cases selected and references pertaining to these events. The May 2003 prolonged severe weather event is emphasized due to the use of the NCEP/NCAR GR data in that study (Hamill et al 2005). The specific dates from the May 2003 outbreak were selected based on the total number of tornadoes and the number of F2-F5 tornadoes. May 4th had 81 tornadoes and 26 F2-F5 tornadoes. May 6th and May 10th had 75 and 51 tornadoes respectively (Table 1: Hamill et al 2005).

The value of the climatic anomalies is shown in a severe weather case from the southeastern United States (28 March 1984). Further details on this event can be found in Gyakum and Barker (1988). Two documented cases from Pennsylvania are also used as case studies (31 May 1985 and 2 June 1998). These two local cases were selected based on the occurrence of strong tornadoes, which are rare in Pennsylvania. The 31 May 1985 event was the only known F5 tornado in Pennsylvania. The variety of locations and months selected will demonstrate the power of using standardized anomalies to evaluate the intensity of a weather system and the conditions associated with the severe storms.

3. CAPE CLIMATOLOGY

The 32-km CAPE climatology (1979-2004) for the mid-month point of 15 May, 15 June, 15 July, and 15 August are shown in Figure 1. All CAPE climatological values are calculated using the 1800 UTC data time. These data show the surge of higher CAPE from the Gulf of Mexico in the southern plains in May. By mid-June the mean CAPE at 1800 UTC is in excess of 1200 JKg^{-1} over much of the southern plains and over 2400 JKg^{-1} along the Gulf coast. A surge of CAPE in excess of 800 JKg^{-1} extends into Pennsylvania and New Jersey in mid-July. Farther west, the area of 800 JKg^{-1} extends into eastern North Dakota.

These data show the seasonal progression of instability northward from the spring into the summer. This is in line with known seasonal northward progression of severe weather and tornadoes. The impacts on the CAPE appear to be connected with the flow of moisture from the Gulf of Mexico and the southwestern Atlantic Ocean. These data also suggest that a daily value of CAPE on the order of 1200 JKg^{-1} in Oklahoma in mid-June is not as significant as a comparable value in Pennsylvania. The mean CAPE, in excess of 1600 JKg^{-1} from near Brownsville to Cape Hatteras along the coastal areas and along the lower Mississippi and Arkansas rivers, in July shows the impact of moisture on the CAPE climatology.

Figure 2 shows the value of 1 standard deviation about the 25-year mean. In May, 1 standard deviation (SD) above or below the mean is in excess of 1200 JKg^{-1} in the southern plains. This large SD area moves poleward in June and July as does the climatological area of severe weather. These data show the importance of Gulf moisture in bringing surges of high CAPE into the Mid-Atlantic region, where CAPE and its climatological variance peaks in July. These data also reveal a marked westward shift in CAPE variability over the northern plains from May to June. A dramatic decrease in the variability of CAPE by 15 August is clearly evident. The variability of CAPE may provide a better understanding of severe weather patterns over the United States than the mean value of CAPE. Furthermore, normalized values of CAPE should provide insights into when the CAPE may indicate abnormally large values of instability in a region. These data, where the SD of the CAPE is the largest, aligns closely with the isochrones of the arrival times of F2 or greater tornadoes (Concannon et al. 2000, Figure 7).

4. CONVECTIVE CASE EXAMPLES

a. Cases from the literature

Table 1 of Hamill et al. (2005) indicates that May 4th, 6th and 10th were the most active days of the disastrous 2003 tornado outbreak. May 4th had 81 tornadoes and 26 F2-F5 tornadoes. There were 75 tornadoes on the 6th but only 8 F2-F5 tornadoes, and there were 51 tornadoes on the 10th, 11 of which were of F2-F5 intensity. The meteorological conditions favorable for tornadic development during these dates are shown using the NARR data.

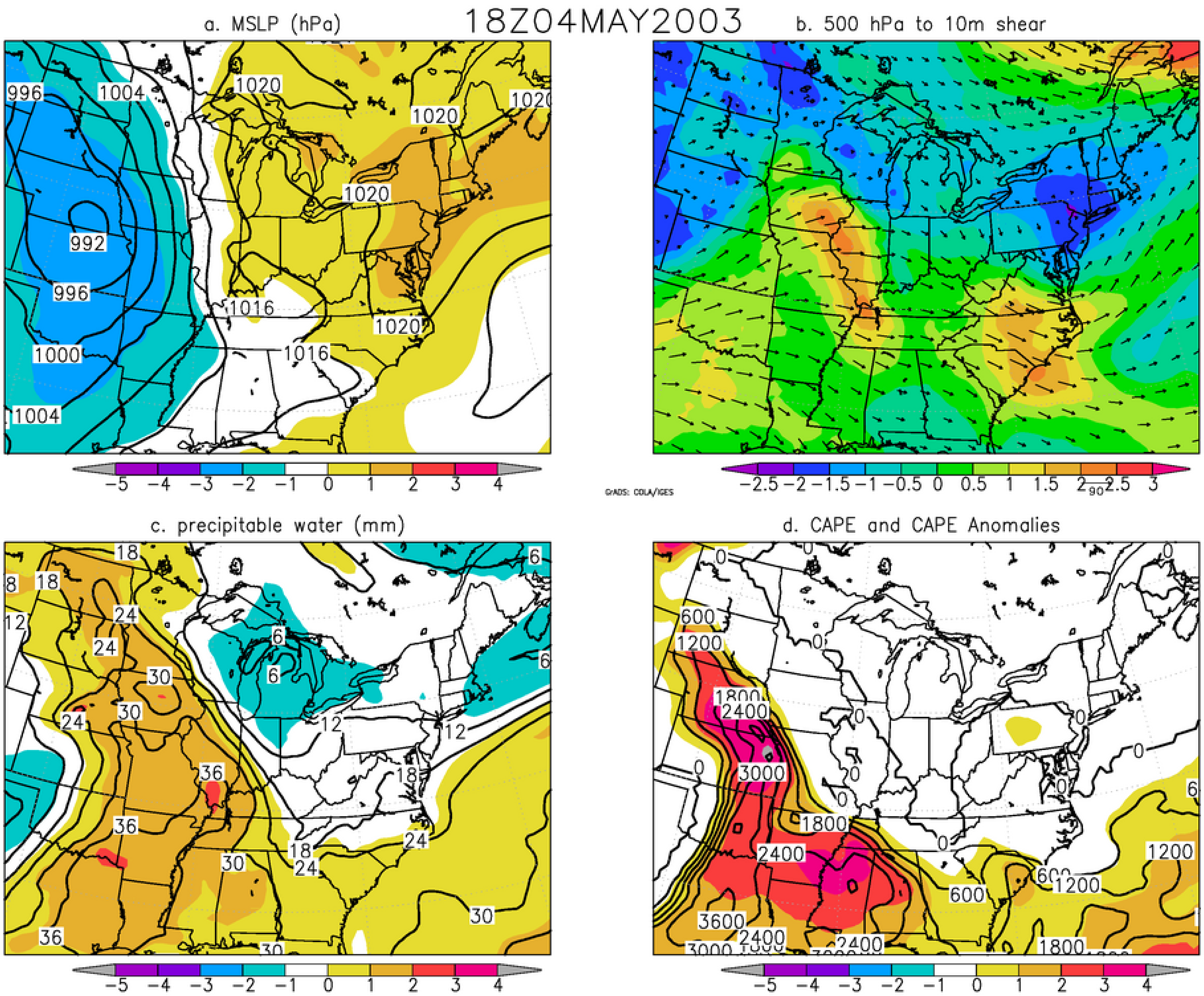

Figure 3 NARR fields valid at 1800 UTC 04 May 2003 with standardized anomalies of a) MSLP (hPa) and anomalies from NCEP/NCAR GR, b) 10m to 500 hPa shear vectors and anomalies from NCEP/NCAR GR, c) precipitiable water (mm) anomalies from NCEP/NCAR GR, and d) CAPE and anomalies as computed from NARR data.

Figures 3 & 4 show the conditions associated with the tornado outbreak of 4th May 2003. The severe weather was concentrated from eastern Oklahoma northward across eastern Kansas and Missouri. On the north side, convection extended into Nebraska and South Dakota, while most tornadic activity occurred across Missouri. The area of high CAPE in Figure 3C outlines this area. The area of high CAPE and shear moved eastward (during that day) as did the area of severe weather and tornadoes (Figure 4). Later in the day, tornado activity moved across Arkansas and Tennessee.

The upper two panels in Figure 4 can be directly compared to the data shown in Hamill et al. (2005, Figure 11). With the

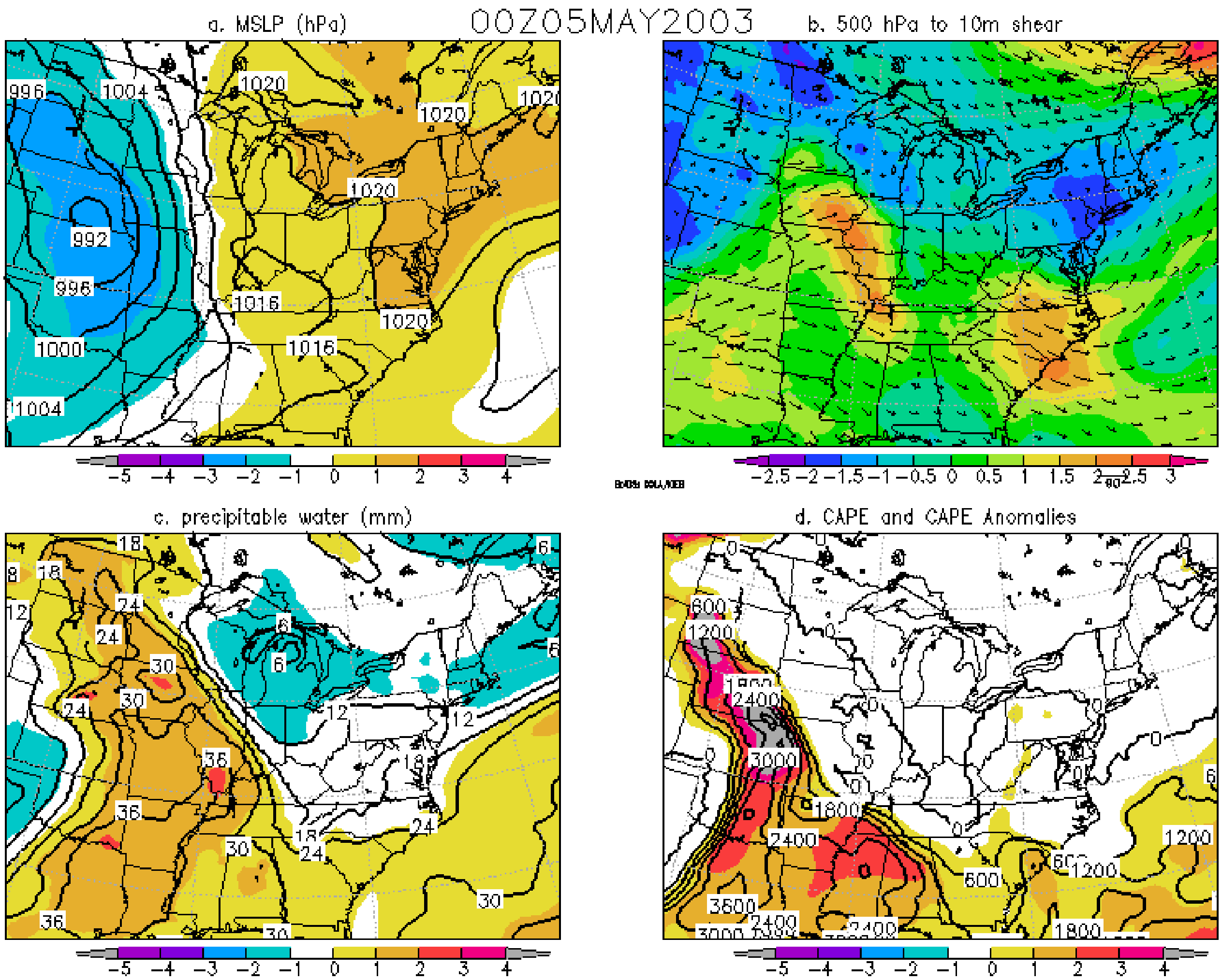

Figure 4 NARR fields valid at 0000 UTC 05 May 2003 with standardized anomalies of a) MSLP (hPa) and anomalies from NCEP/NCAR GR, b) 10m to 500 hPa shear vectors and anomalies from NCEP/NCAR GR, c) precipitiable water (mm) anomalies from NCEP/NCAR GR, and d) CAPE and anomalies as computed from NARR data.

exception of the standardized anomalies of CAPE, the anomalies are derived from the NCEP/NCAR GR data and contoured data are from the NARR. The 990 hPa cyclone center in Hamill et al. (2005) appeared as a 992 hPa low in the NARR data (Fig. 4a), which was about 3 standard deviations below normal. To the east, the surface anticyclone was associated with MSLP values on the order of 1 to 2 standard deviations above normal. The shear used in this study was based on 10 m to 500 hPa winds, slightly different than those shown in Hamill et al. (2005). The two areas of strongest shear are aligned suggesting little difference between using 10m and surface winds or using the NCEP/NCAR GR and the NARR data to derive the shear values. The data in Figure 3 show that the two areas of strongest shear were on the order of 2.5SDs above normal.

By 0000 UTC 5 May 2003, the highest values of CAPE (4800 JKg^{-1}) were over eastern Texas. CAPE in excess of 2400 and 1800 JKg^{-1}, respectively, extended into Tennessee and Missouri (Figure 4d). Though lower than the CAPE in Texas, these values represented much above normal CAPE as indicated by anomalies on the order of 2 to 3 SDs above normal. The overall area of instability compared well the LI values shown in Hamill et al (2005).

At the same time, PWAT values were well over 25 mm across most of the southern plains, with anomalies upwards of 3 SDs above normal in Arkansas (Figure 4C). Using mixing ratio values, Hamill et al. (2005) suggested that there were anomalously high boundary layer moisture in the region affected; the PWAT anomalies in Figure 3c & 4c validate this claim.

Figures 5 & 6 shows the observed conditions at 1800 UTC 6 May 2003 and 0000 UTC 7 May 2003, representing the instability during the large tornado outbreak of 6 May 2003. Tornadoes were widespread from the Red River valley across eastern Oklahoma, eastern Kansas, and Missouri. The area of severe weather and tornadoes then extended eastward across Tennessee and southern Kentucky. By 0000 UTC 7 May 2003, the strongest shear and shear anomalies were over Oklahoma and Missouri. Large CAPE dominated the entire region with the largest CAPE anomalies focused over the central Mississippi valley where the CAPE was on the order of 5 SDs above normal.

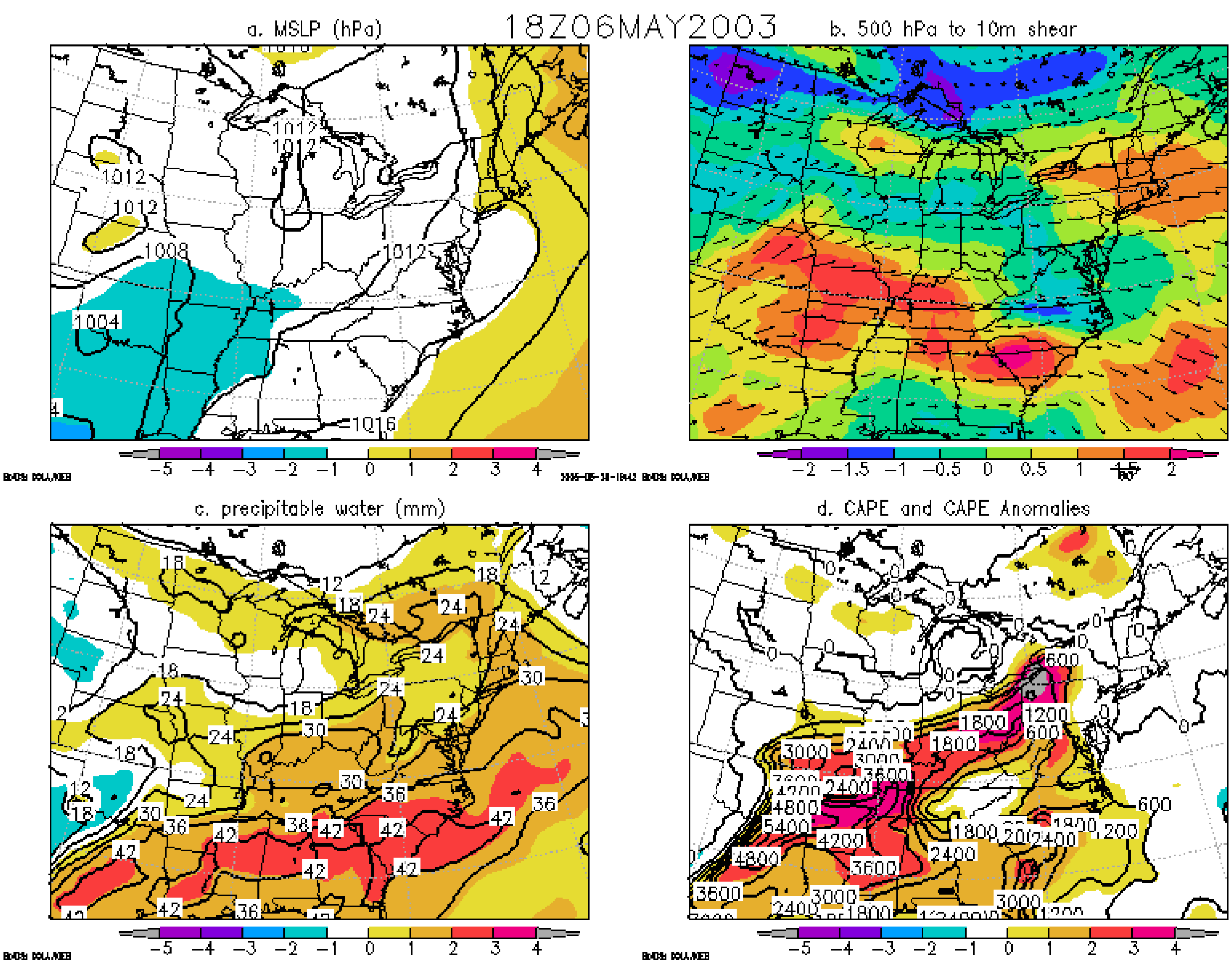

Figure 5 As in Figure 3 except valid at 1800 UTC 6 May 2003. Return to text.

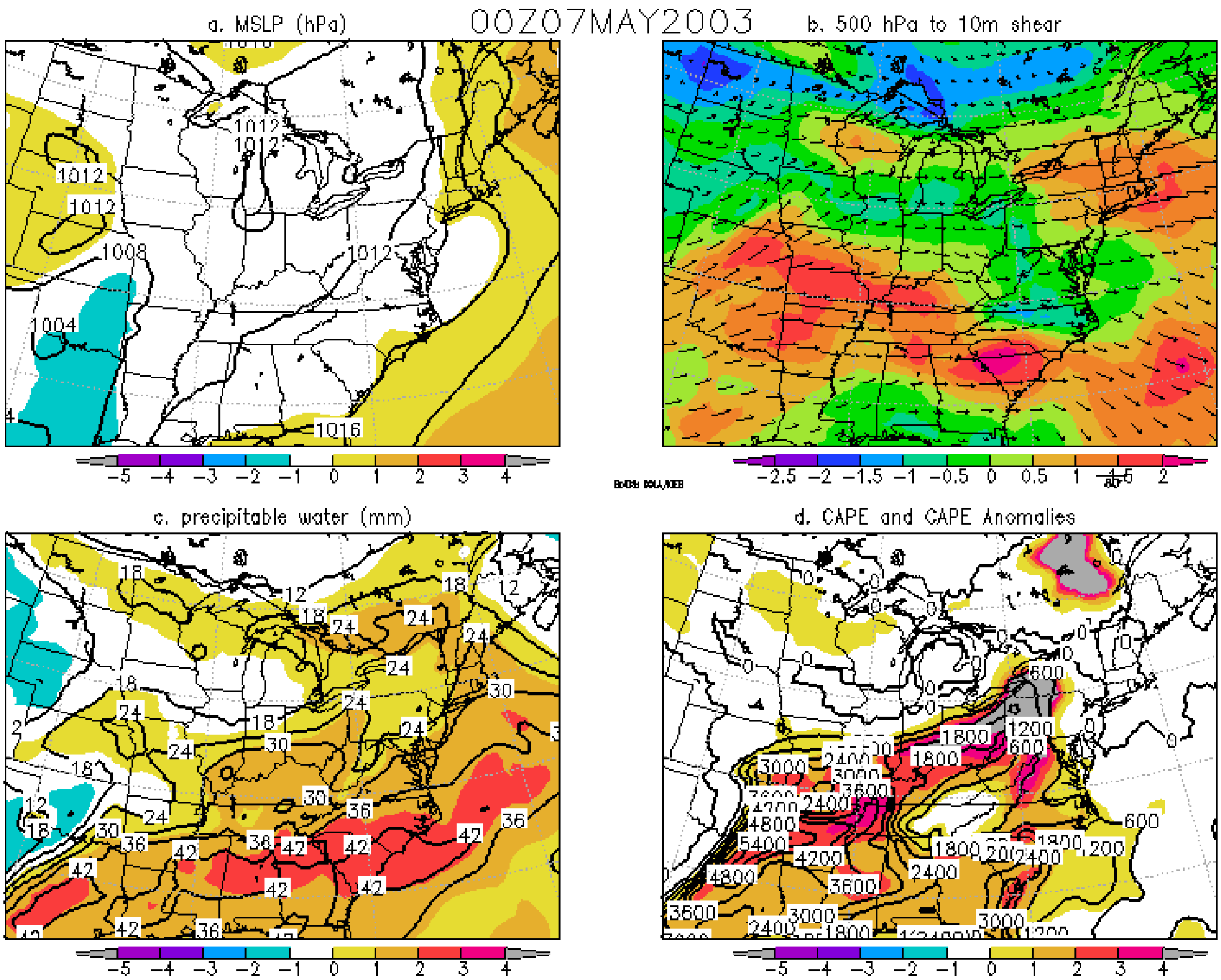

Figure 6 As in Figure 3 except valid at 0000 UTC 7 May 2003.

The PWAT and PWAT anomalies suggested a strong dry line or front to the west of the main area of severe weather in the plains. The MSLP field implied a large scale frontal zone. Though not shown, sporadic reports of wind damage showed severe weather from southern Indiana into southwestern New York in the axis of the maximum CAPE and CAPE anomalies (Figures 5d & 6d).

A widespread severe weather event occurred from the Tennessee Valley northward to Wisconsin on 10 May 2003. There were 51 reported tornadoes, 11 of which were in the F2-F5 intensity range. Most of the tornado activity was concentrated from eastern Missouri, Iowa, and across Illinois. Western Illinois was impacted with the most tornado activity on this day. CAPE anomalies were near 5 SDs above normal at 1800 UTC 10 May (not shown) with surface based CAPE in excess of 3600 JKg^{-1}. This area of instability moved eastward and was located over Illinois by 0000 UTC. CAPE anomalies were on the order of 3 to 4 SDs above normal over Illinois at this time. The 10m to 500 hPa shear was strong and also 2 to 3 SDs above normal. In addition, PWAT values exceeding 2 SDs were located over the regions affected by the most tornadoes. These data are summarized in Figure 7. High precipitiable water may serve as a proxy to locations where the lifting condensation levels (LCL) may be low. Markowski et al. (2002) showed the importance of high boundary layer relative humidity and low cloud bases, as potential means to discriminate between tornadic and non-tornadic rear flank downdrafts.

b. Local cases

The tornado outbreak of 31 May 1985 affected Ohio, Pennsylvania, New York and southern Ontario (Farrell and Carlson 1989; Forbes 1985). This outbreak was the largest outbreak over North America since April 1974, the largest outbreak in the eastern United States since 1944, and is still the most significant tornado outbreak to occur in the state of Pennsylvania. (Carlson 1989). The conditions associated with this tornado event at 1800 UTC 31 May 1985 are shown in Figure 8. These data show the deep surface cyclone moving into the Great Lakes with surface pressure anomalies around 4 SDs below normal in upper-Michigan and large shear anomalies over Michigan and Ohio (Figure 8b). Ahead of the cold front, CAPE values

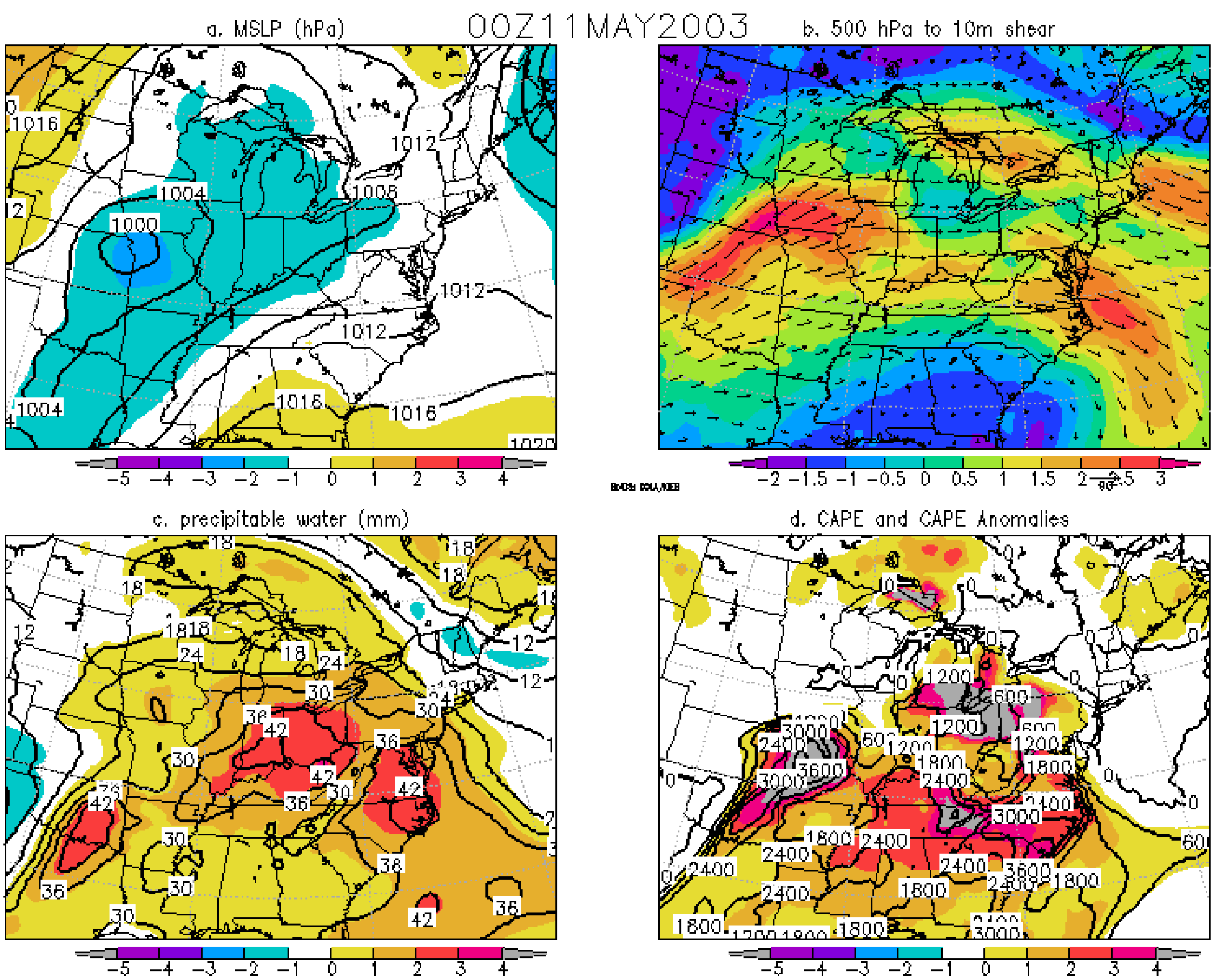

Figure 7. As in Figure 3 except valid at 0000 UTC 11 May 2003.

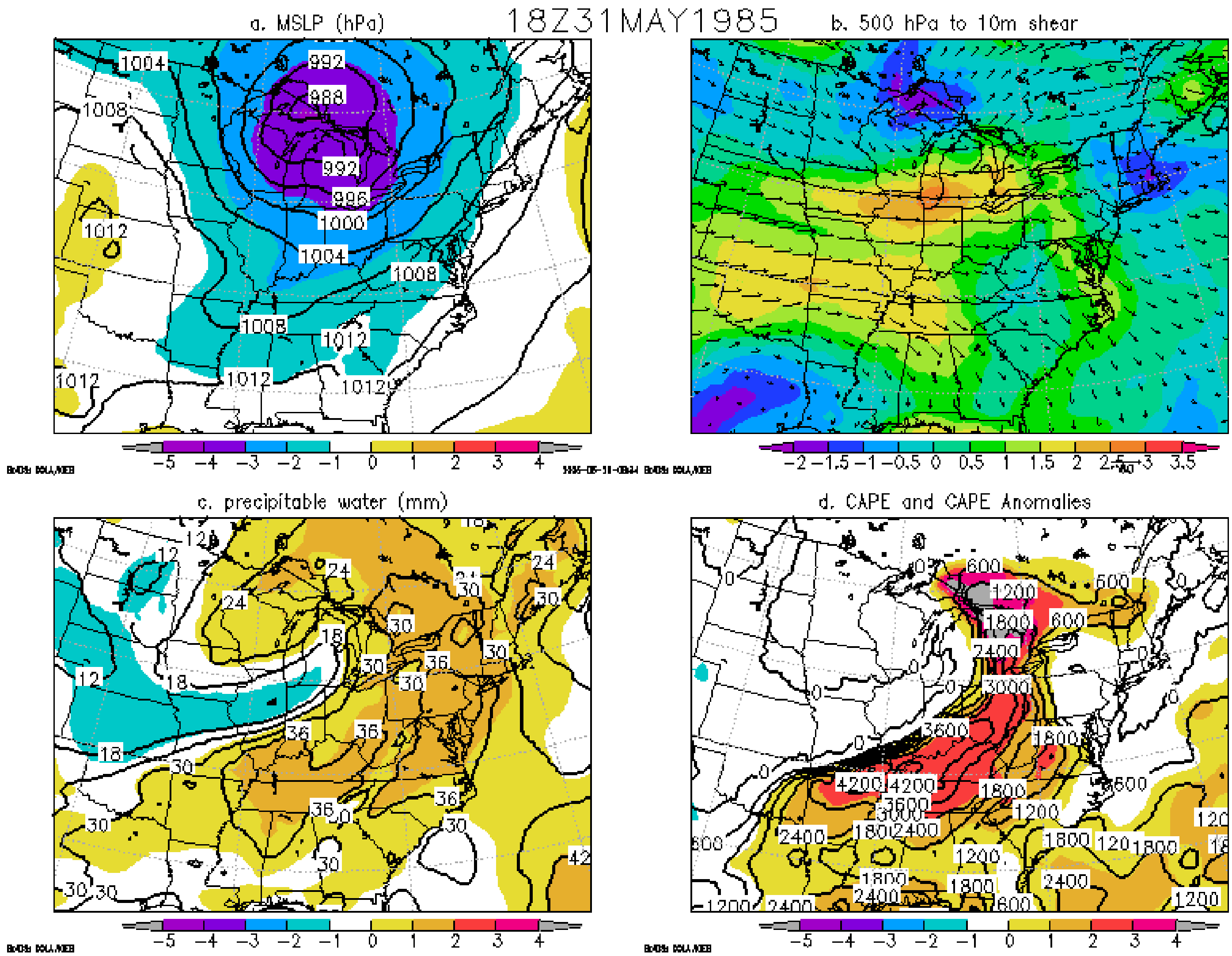

Figure 8. As in Figure 3 except valid at 1800 UTC 31 May 1985. Return to text.

were 2 to 3 SDs above normal, with an exceptionally large +5 SD CAPE anomaly over most of Michigan. In the warm air ahead of the front PWAT values were typically 2 to 3 SD above normal. By 0000 UTC 1 June 1985, the area of instability and shear moved eastward into Pennsylvania.

The conditions associated with the southeastern United States tornado outbreak of 28 March 1984 is shown in Figure 9. These data reveal a strong surface cyclone with a broad area of central pressures that were 4 to 5 SDs below normal (Figure 9a). The circulation associated with the deep cyclone transported copious amounts of moisture into the region (PWAT anomalies +1 to +2 SD). There was also a surge of anomalously large CAPE in the warm sector, with CAPE anomalies on the order of 2 to 4 SDs above normal. In South Carolina and Georgia CAPE anomalies exceeded 4 SDs. These conditions produced on the most devastating tornado outbreaks in North and South Carolina. There were over 22 reported tornadoes and 3 confirmed F4 tornadoes in North Carolina.

Figure 10 shows the conditions at 0000 UTC 3 June 1998. The severe weather event of 2 June 1998 produced an F3

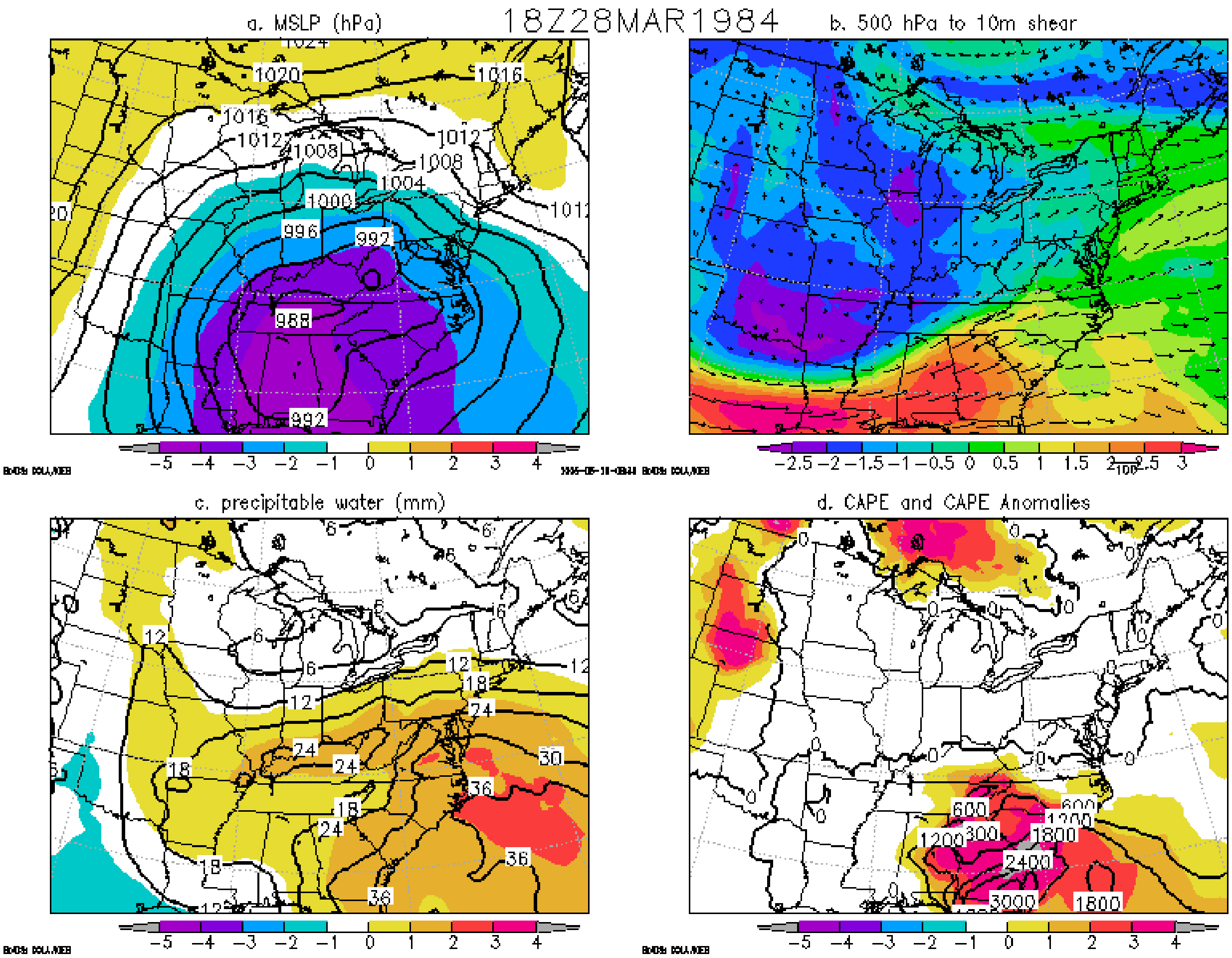

Figure 9. As in Figure 3 except valid at 1800 UTC 28 March 1985. Return to text.

tornado in southwestern Pennsylvania and an F4 tornado near Frostburg, Maryland. The tornado activity occurred late in the day and conditions near 0000 UTC best represent the conditions associated with this event. A deep cyclone, with a central pressure around 994 hPa moved over Michigan at 1800 UTC on the 2nd. MSLP anomalies were 3 to 4 SDs below normal in this region. By 0000 UTC the surface cyclone had moved across New York causing northward surge of the high CAPE into Pennsylvania from the southwest (Figure 10d). CAPE values exceeded 2400 JKg^{-1}.over portions of southwestern Pennsylvania and western Maryland, corresponding to 3 to 4 SDs above normal for that time of year. The strongest shear anomalies were south and west of the region and PWAT anomalies were well over 3 SDs in all of western PA.

5. CONCLUSIONS

The value of the National Centers for Environmental Predictions (NCEP) / National Center for Atmospheric Research (NCAR) global reanalysis data and the NARR data in diagnosing the large scale conditions with severe weather events were shown. These new climatologies, such as the surface based CAPE climatology, will help in studying future or past case studies, and can be used to better estimate the severity of extreme events from operational forecast model output.

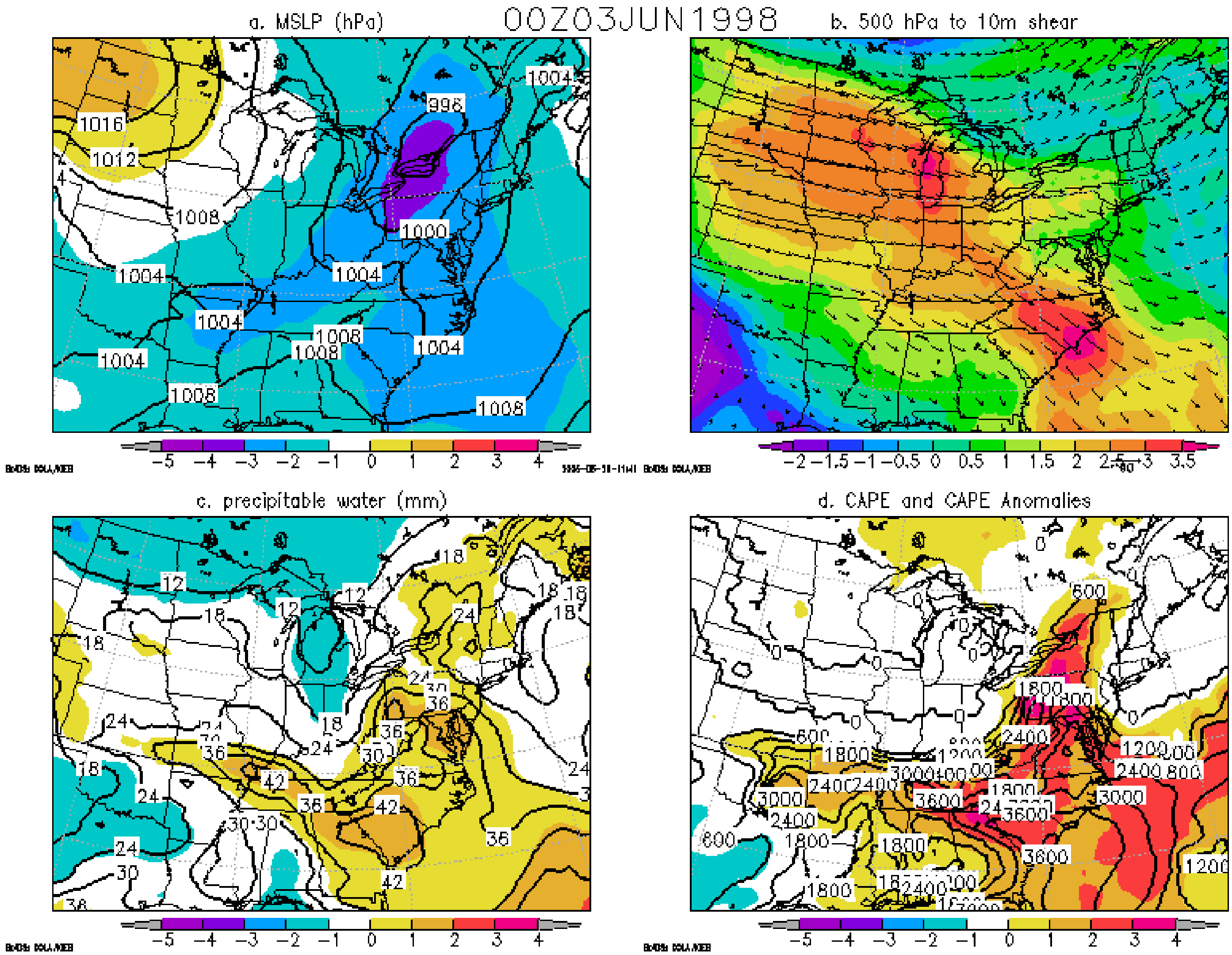

Figure 10. As in Figure 3 except conditions valid at 0000 UTC 03 June 1998. Return to text.

The NARR data has several advantages over the GR data. These include the increased number of variables and the higher spatial and temporal resolution. The higher spatial resolution has a significant impact in the boundary layer. And as demonstrated here, the new variables, such as CAPE will provide research opportunities related to severe weather events.

The high resolution CAPE data showed the mean values of CAPE at the monthly mid-points from 15 May through 15 August. These data, combined with the standard deviation of CAPE over the same time period exhibited both the northward progress of CAPE and the variation of CAPE between months. The large variation of CAPE appeared to match the northward progress of severe weather over the United States from spring to summer. The large standard deviation of CAPE on 15 May (Figure 2a) was closely aligned with the highest probability of a tornado on 20 May as shown by Brooks et al. (2003). Comparing Figure 2c with Figure 7d (from Brook et al. 2003) demonstrates the northward and eastward expansion of the tornado day probabilities in the area of largest variance of CAPE, suggesting a link between CAPE variance and tornado frequency. This implies that the normalized CAPE departure could be used to determine the potential or increased threat for severe weather when applied to model forecasts.

Using documented cases from the literature and locally known severe weather events, an attempt was made to document the value of climatic anomalies in diagnosing conditions associated with severe weather. The concept of using climatic anomalies to diagnose past or future events was as described by Hart and Grumm (2001). With the exception of the application of the NARR CAPE data, the diagnostic parameters were similar to those presented by Hamill et al (2005). The results here suggest that below normal MSLP pressures are often associated with severe weather outbreaks east of the Rocky Mountains. Some events, such as the 31 May 1985 and 28 March 1984 events were associated with very intense cyclones to the north and west of the affected area. All the events shown were associated with above normal values of CAPE. In nearly every case presented, the CAPE anomalies in the affected regions were 3-4 SDs above normal. These results and follow-up studies may be able to develop threshold CAPE anomalies associated with severe weather outbreaks, including putting them into context by season and geographic region of the country.

CAPE alone is not a sufficient condition to develop convection let alone severe storms. The high values of CAPE during the warm season along the Gulf Coast and Southern Plains clearly demonstrate this. Instability must be released to facilitate convective development. The presence of a strong surface cyclone, deep moisture, and the shear shown in these cases suggest favorable synoptic scale forcing which can ultimately release the instability. The NARR data and the NCEP/NCAR GR data facilitate identifying such conditions.

Future research will include applying new NARR derived climatologies to deterministic and ensemble forecast output. Areas where CAPE is forecast to depart significantly from normal should provide clues favorable for convective development. Areas where the anomalous CAPE is in close proximity to strong shear, above normal PWAT, and a strong cyclone to the west may indicate areas and times favorable for large scale severe weather outbreaks.

A more regional climatic evaluation of CAPE and other NARR parameters to determine severe weather is planned. The goal is to identify key parameters and anomalies associated with large severe and significant tornado outbreaks.

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