The southern Express: High Impact Spring Storm of 14-17 April 2011
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Abstract:
A developing storm system brought severe weather, with over 1000 reports of severe weather and 267 tornadoes, from the southern plains to the Carolinas over a 3 day period spanning 14-16 April 2011. The tornado outbreak in North and South Carolina was likely the largest and most significant tornado outbreak since the 28 March 1984 event which included 22 tornadoes which killed 57 people.

The rain and severe weather were closely linked to the surge of high precipitable water and strong southerly flow ahead of the advancing frontal system. Thus, high moisture flux values, with anomalies on the order of 4 to 6\(\sigma\) were common during the event and were often found in close proximity to the areas of heavy rainfall and severe weather. The latter areas were also associated with high values of convective available potential energy.

The surge of dry air, with low values of precipitable water clearly played a role in the convection and tornadoes of both 14 and 15 April 2011. The precipitable water anomalies in the southern plains into the Gulf States were -1\(\sigma\) just behind the cold frontal boundary. There may value in using PW anomalies to gain insights into the character of dry lines and their potential to produce severe weather. In this event, similar to 10 May 2010, a surge of abnormally dry air was present during much of the event.

1. INTRODUCTION

A strong surface cyclone tracked out of the southern plains and into the Great Lakes on 14-17 April 2011 (Fig. 1). In the warm air, ahead of the advancing cold front, the system produced over 267 tornadoes over three days (Table 1). Most of the tornadoes were observed from Oklahoma eastward into the Carolinas (Fig. 2). The tornadoes produced deaths (~45) in several States including as many as 22 people in North Carolina. This was likely the largest and tornado outbreak in North Carolina since the 28 March 1984 tri-State tornado outbreak\(^1\). In addition to the 3-day severe weather outbreak, the event produced heavy rains and flooding in the Mid-Atlantic region and even snow on the colder northern flanks of the storm.

The high impact of this event across the southern United States, including the number of tornadoes in North Carolina suggest this storm will be compared to the 28 March 1984 tornado outbreak in the southeastern United States. The storm system which produced that event tracked out across the southern United States and up the East Coast (Barker and Gyakum 1988). That event underwent a period of rapid cyclogenesis, spawned 22 tornadoes from Alabama to North Carolina, and produced over 60 mm of rainfall... Barker and Gyakum (1988) showed the deep cyclone and instability associated with the 28 March 1984 event. The focus of their study was on the synoptic scale conditions and explosive cyclogenesis associated. They provided soundings showing the instability (BG88 Fig. 16) and 3-hourly tracks of the surface cyclone (BG88 Fig. 24) to include the cyclones central pressure. The surface pressure fell to near 966 hPa over Maryland on 29 March 1984. The storm, with central pressure near 986 hPa (Fig. 1g) on 17 April 2011 tracked well to the north and west of the March 1984 storm and was associated with significantly weaker cyclone.

This paper will document the intense cyclone of 14-17 April 2011 and the associated weather. The focus is on the pattern and anomalies of key fields which may

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\(^1\) WIKI http://en.wikipedia.org/wiki/1984_Carolinas_tornado_outbreak
have aided in predicting the storm and may aide in improving forecasts of similar storms in the future. The storm of 28-29 March 1984 will be used as a comparison event.

2. Methods and Data

   The overall pattern was reconstructed using the 00-hour forecasts from the operational GFS. The anomalies were derived using the GFS and comparing it to the 30-year mean and standard deviations computed from the NCEP/NCAR re-analysis data (Kalnay et al. 1996). All anomalies herein are shown as standardized anomalies (Hart and Grumm 2001).

   The GFS is run on a 27 km grid. However the data shown here is on a 1x1 degree grid. This should mitigate some of the resolution issues between the coarser climatology and the model forecast grids. These effects are normally of minimal impact for parameters above the planetary boundary layer. Some variables such as PW are sensitive and will show higher values in higher resolution models than in the re-analysis dataset.

   Forecasts from the NCEP Ensemble Forecast systems (EFSs) will be presented. Standardized anomalies will be presented as described above, computing anomalies from the ensemble mean and the NCEP/NCAR re-analysis data. Probabilities are derived using the ensemble output. These will be raw and uncalibrated probabilities unless specified otherwise.

   For brevity, times will be denoted in the format 16/1800 UTC to signify 1800 UTC 16 April 2011 and time such as 15/1200 would signify 1200 UTC 15 April 2011.

   The comparative storm of 28-29 March 1984 is examined using the Japanese reanalysis data.

3. The Storm system and impacts

   i. The pattern and key anomalies

   The evolution of the 500 hPa pattern over the United States from 15/0000 through 17/1200 UTC is shown in Figure 4. These data show the initial short-wave over Kansas at 15/0000 UTC moving eastward and then into the Great Lakes by 17/0000 UTC. The positive height anomalies east of this wave were significant in this event and indicated a weakly blocking ridge. At the surface (Fig. 1) a 1036 hPa anticyclone with +2 to +3σ pressure anomalies were present. This strong anticyclone implied a strong gradient and strong low-level southerly winds. These winds likely played a significant role in the precipitation and severe weather over the eastern United States.

   An enhanced westerly jet, with 2 to 4σ above normal winds was present over the ridge in eastern North America (Fig. 5). To the west of the 250 hPa and 500 hPa trough, a strong Pacific jet moved onshore (Fig. 5a) and moved rapidly eastward, rounding the trough and providing a jet exit appearance from 16/0000 (Fig. 5c) through 17/0000 UTC (Fig. 5e).

   This upper level system allowed a surge of warm moist air, with 2 to 3σ above normal precipitable water (PW) anomalies, to move into the central plains, across the Mississippi Valley and into the eastern United States from 15/0000 through 17/0000 UTC (Fig. 6). In addition to the surge of moisture ahead of the system, it dragged dry air, with -1σ PW anomalies eastward. It will be shown that this dry air played a critical role in the severe weather from Oklahoma and Texas eastward into the Carolinas.
j. Regional patterns-southern Plains

The PW pattern over the southern plains from 15/0000 through 06/1600 UTC (Fig. 7) shows the plume of high PW moving poleward ahead of the upper-level system (Fig. 4). To the west, an intrusion of dry air, with -1σ PW anomalies was present. This surge of dry air and the boundary between the dry and moist air delineated the severe weather and tornadoes over the southern plains (Fig. 2) quite well on 14-15 April. As the dry intrusion and -1σ PW anomalies surged southward into Louisiana, Mississippi, and Alabama, the severe weather and tornadoes developed over these two States and moved eastward. Most of the tornadoes on 15 April were over Mississippi and Alabama.

The 850 hPa winds showed a strong low-level jet (Fig. 8) in the moist air just east of the dry intrusion. The strong winds likely provided strong low-level shear critical to maintain convection. Though not shown, the v-winds depicted the strong low-level jet better in Oklahoma. One potential key feature in the wind fields may have been the strong north-northwesterly jet behind the 850 hPa cyclone which may have allowed the dry air to surge south and eastward. The 850 hPa jet behind the low was at time 6σ above normal.

The RUC 1-hour analysis (Fig. 10) shows the surge of high CAPE in to the southern plains related to the evolution of the convection late on 14 April 2011.

k. Regional patterns-East

The GFS PW fields from 15/1800 through 17/0000 UTC (Figure 10) show the surge of high PW form the Gulf of Mexico into the Ohio Valley at 15/1800 UTC and the surge of dry air into Louisiana. This conveyor belt or river of moist air moved eastward and a surge of +2 to +3σ PW air was over North Carolina from 16/1200 through 16/1800 UTC. This deep moisture reached into the Mid-Atlantic region with over 35mm of PW over New Jersey by 17/0000 UTC.

The accompanying 850 hPa winds (Fig. 11) showed the strong southerly jet extending from the Carolinas into Pennsylvania and southern Ontario. The GFS analysis showed areas of 6σ wind anomalies at times in the northern reaches of this strong southerly jet (Figs. 11c & Fig 11e). This low-level jet and the deep moisture plume contributed to the heavy rainfall in Pennsylvania and to the severe thunderstorms and tornadoes from Pennsylvania southward into the Carolinas.

The strong winds and plume of high PW air produced high values of moisture flux (MFLUX: Fig. 12). High values of moisture flux, with 5 to 6σ above normal MFLUX values were common ahead of the strong cold in the warm moist air and along the strong southerly jet. A strong association is presented here with anomalous MFLUX values and the severe weather in the Carolinas and the heavy rainfall in the Mid-Atlantic region. These MFLUX data capture the high values and large MFLUX anomalies which were associated with the severe weather in Mississippi and Alabama on 15 April (Figs. 12a-c). Note the 5 to 6σ MFLUX anomalies in the southern States at 16/0000 UTC (Fig. 12b).

Hourly RUC CAPE data showed the surge of 600 JKG-1 to 1800 JKG-1 of CAPE into North Carolina between 16/1700 and 16/2000 UTC (not shown) and about 600 JKG-1 into Virginia at 16/2200 UTC. However, to capture the sense of the event in southern US, 6-hourly data is shown from 15/1800 UTC through 17/0000 UTC (Fig. 13). These
data show the surge of high CAPE over Mississippi and Alabama on 15 April and the surge of high CAPE into the Carolinas on 16 April 2011.

l. Observations
The observed severe weather and rainfall was shown in Figures 2 & 3 respectively. These data showed the concentration of severe weather and tornadoes east of the frontal system, which was more like a dry line on 14-15 April over Oklahoma and Kansas. The severe weather was relatively well aligned with the high MFLUX plume, which was co-located with the high CAPE from eastern Oklahoma to North Carolina. Generally lower CAPE to the north limited the convective activity. The northern edge of the severe weather on 16 April into Pennsylvania, despite relatively low CAPE implies the importance of shear with modest CAPE in strongly forced situations.

The heavy rainfall was associated with the strong southerly winds and high MFLUX values. The connection caused the observed QPE to be somewhat streaky.

m. Forecasts
The severe weather was potential was generally well predicted by the models. The ensemble forecast systems showed the potential CAPE and advancing frontal system quite well. For brevity, the focus here is on the forecasts of the heavy rainfall in the Mid-Atlantic region.

Three GEFS forecasts of 50 mm or more QPF in the Mid-Atlantic region for the 48-hour period ending at 17/1200 UTC are shown in Figure 14. These data show a focus of the heavy rainfall over southern Pennsylvania. Though not shown, the probability of in excess of 50 mm of QPF increased from forecasts initialized at 15/0600 and 15/1200 UTC. Additionally, the GEFS indicated that most of the QPF would fall between 16/1200 and 17/0000 UTC.

The SREF QPFs (Fig. 15) showed a similar high QPF threat to that indicated by the GEFS. The SREF had a lower probability of 50 mm or more QPF but focused on the same general region as the GEFS. Both forecast systems focused the heavy rainfall in the period from 16/1200 UTC through 17/0000 UTC as shown in the point or plume diagram for Somerset, PA (Fig. 16). The GEFS produced more QPF than the SREF. This was true in the plan view and plume diagrams.

The 4km NAM forecasts of simulated radar are shown in Figure 17. These data show that the high resolution model was able to predicted intense rainbands and convection over the Carolinas and over Pennsylvania. The forecaster need to know the stability to ensure they understood the character of the echoes implied by these forecasts. The 4km NAM produced linear bands of 48 to 96 mm or QPF over central Pennsylvania (not shown).

4. Conclusions
A strong surface cyclone tracked out of the southern plains and into the Great Lakes on 14-17 April 2011 (Fig. 1). In the warm air, ahead of the advancing cold front, the system produced over 267 tornadoes over three days (Table 1). Most of the tornadoes were observed from Oklahoma eastward into the Carolinas (Fig. 2). The tornadoes produced deaths (~45) in several States including as many as 22 people in North Carolina. This was likely the largest and tornado outbreak in North Carolina since the 28
March 1984 tri-State tornado outbreak. In addition to the 3-day severe weather outbreak, the event produced heavy rains and flooding in the Mid-Atlantic region and even snow on the colder northern flanks of the storm. The plume of deep and anomalous moisture ahead of the frontal system produced the heavy rainfall and was associated with the focused regions of severe convection.

This event shared many of the characteristics of previous high impact weather events. The event had a deep cyclone, a surge of high PW air northward, ahead of an advancing cold front, surge of low PW air behind the front, a strong southerly jet in close proximity to the surge of high PW air, which produced high values of MFLUX. The heavy and convection were linked closely to the high MFLUX values and high PW air.

The cyclone with this event was not as deep as the cyclone associated with March 1984 southeastern United States severe event (Fig. 18). During that event (Barker and Gyakum 1988) a deep cyclone tracked across the south and up the East Coast. The JRA25 data indicated -5σ pressure anomalies with the cyclone, though Barker and Gykaum (1988) showed that the observed cyclone was likely as deep as 966 hPa not the 972-973 hPa values shown here.

The large scale pattern on 28 March showed a surge of high PW air with 2 to 3σ above normal PW anomalies into the Carolinas from 1200 to 1800 UTC along with a strong low-level jet. The conditions at 1800 UTC 28 March are shown in Figure 19. These data show the coupled 250 hPa jet with wind anomalies over New England and the southern United States; a deep 500 hPa trough with -3σ height anomalies over the Gulf States; strong southwesterly wind and the surge of high PW air. The 850 hPa winds peaked from the south-southeast in these data at 1200 UTC (not shown) and the winds had become more southwesterly by 1800 UTC. There were some markedly different characteristics between the 16 April 2011 and 28 March 1984 events, though both were associated with surge of high PW air into the same general region.

The severe weather in the southern plains and eastward into the Gulf States was associated with a surge of low PW and -1σ below normal PW anomalies. The anomalous dry air played a key role in the severe weather over Oklahoma and southern Kansas on the evening of 14 April 2011. The 10 May 2010 outbreak in Oklahoma was another good example of negative PW anomalies indicated a particularly strong dry line (Grumm 2010). That event produced a significant tornado outbreak in Oklahoma and the PW anomalies with the dry line ranged from -1 to -2σ below normal (See Grumm 2010 Fig. 6e-f). The dry air behind the front clearly played a role in the severe weather event.

The strong low-level jet and moisture plume, denoted by the surge of high PW air, were associated with the severe weather and the heavy rainfall. The high values of MFLUX were observed within this area of strong low-level winds and high PW values. Across the southern United States, the instability, from the southern plains to the Carolinas was critical for the deep, upright convection. Clearly, the high PW air a potential indicator of relatively high CAPE air too. Where there is high CAPE and high PW values, the potential for severe weather is often quite high.

Farther north, the higher static stability limited convection but contributed to heavy rainfall. It should be noted in portions of the Mid-Atlantic region, from West Virginian into New York, the MFLUX values were high and at times exceeded 6σ above

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normal. The lack of CAPE and the stable low-level air limited the development of deep convection in the region, however heavy rainfall and flooding was observed. Though not shown both NCEP deterministic models forecast MFUX values to be 5 to 6$\sigma$ above normal during the period of heavy rainfall (not shown). The GEFS and SREF tended to under forecast the higher end precipitation which was observed. Most GEFS and SREF forecasts implied 1.5 to 2.0 inches of QPF over central Pennsylvania. Observations suggest rainfall amounts ranged from 1.5 to 4.0 inches. Shorter range higher resolution models forecast higher amounts (not shown) but also under predicted the rainfall. Areas where the MFLUX reaches or exceeds 6$\sigma$ above normal are regions where with some confidence forecasters can and should anticipate rainfall amounts higher than often indicated in the NCEP 12km NAM and 27km GFS.

This case is another case that shows the value of MFLUX in predicting both heavy rainfall and severe weather. In regions of high CAPE; CAPE in excess of 1200 JKg$^{-1}$; in close proximity to areas of high MFLUX are areas where deep convection and the potential for severe weather should be considered. This association of high moisture flux and severe weather was shown in the extraordinarily prolific severe weather event of 3-4 April 2011 (Grumm 2011). During that event, the line of intense storms which produced over 1000 reports of severe weather was in close proximity to an area of 5 to 6$\sigma$ above normal 850 hPa moisture flux. The juxtaposition of high MFLUX and high CAPE is a useful signal for anticipating strong upright convection.

The moisture flux in this case worked well in the Gulf States and in the southeastern United States (Fig. 11). These data clearly indicated an enhanced potential for severe weather. Though no MFLUX data were shown for the southern Plains, there were relatively high values of MFUX in that region on 15-16 April 2011. In southeastern Oklahoma, at 15/0000 UTC MFLUX values exceed 200 gm$^{-1}$kg$^{-1}$s$^{-1}$ and anomalies were in excess of 3$\sigma$ above normal.

It is interesting to note that during this event, the 850 hPa winds were forecast and observed to be over 20 to 30 ms$^{-1}$ from the south over much of the eastern United States. Widespread synoptic scale high wind events with southerly flow are relatively rare events with strong southerly winds. The massive 1036 hPa anticyclone over New England implied some cold air damming along the East Coast. The low-level static stability profiles likely showed cold air damming which kept most regions decoupled during the event. Thus, despite the strong southerly winds, often 5 to 6$\sigma$ above normal, reports of high wind and wind damage, outside of lee side areas and outside of convection were difficult to find.

Most the high winds and wind damage during the cold air damming phase was confined to the lee of the higher elevations. Areas to the lee of the Alleghenies reported persistent strong winds and wind gusts over 55 kts. There was also some sporadic wind damage, behind the frontal system on 17 April, though the 850 hPa winds behind the system were not as strong as those ahead of the system. This is the region, where the isentropes slope to the surface, that high winds can and occasionally do occur. Static stability plays a critical role in allowing strong winds aloft from reaching the surface during southerly flow events over most of the eastern United States and often limits their ability to reach the surface.

5. Acknowledgements
The Storm Prediction Center is acknowledge for their easy access to data and easily used website to examine current, recent, and past severe weather events.

6. References


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Table 1. Storm reports by date and type from the storm prediction center. [Return to text]
Figure 1. NCEP GFS 00-hour forecasts of mean-sea level pressure (hPa) and pressure anomalies (standard deviations) in 6-hour increments from a) 0000 UTC 15 April 2011 through f) 1200 UTC 17 April 2011. Isobars every 4 hPa. Return to text.
Figure 2. Storm reports by day and type from the Storm Prediction Website.

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Figure 3. Total estimated quantitative precipitation (in) for periods of a) 0000 UTC 15 April through 12Z 18 April 2011 and b) 0000 UTC 16 April through 1200 UTC 17 April 2011. Data from the Stage-IV gridded 6-hourly dataset plotted in mm. Contours are every 25 mm shading is as indicated by the color bar to the right of each images. Return to text.
Figure 4. As in Figure 1 except for GFS 500 hPa heights (m) and height anomalies in 12 hour increments from a) 0000 UTC 15 April through f) 1200 UTC 17 April 2011. Return to text.
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Figure 9. RUC initializations showing the convective available potential energy (CAPE) and the CAPE anomalies. Data are in 1-hour increments from a) 1800 UTC 14 April through f) 2300 UTC 14 April 2011. Return to text.
Figure 9 NCEP GEFS precipitable water (mm) and precipitable water anomalies in 6-hour increments from a) 1800 UTC 15 April through f) 0000 UTC 17 April 2011.  
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Figure 10. As in Figure 9 except for GFS 850 hPa winds (ms-1) and total wind anomalies.  

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Figure 11: As in Figure 9 except for GFS 850 hPa moisture flux (gm*kg⁻¹s⁻¹) and moisture flux anomalies. Return to text.
Figure 13. RUC analysis showing surface based CAPE and CAPE anomalies in 6-hour increments from a) 1800 UTC 15 April through f) 0000 UTC 17 April 2011. Return to text.
Figure 14. GEFS forecasts of 50 mm or more QPF in the 48 hour period ending at 1200 UTC 17 April 2011. Upper panels show the probability of 50mm or more QPF and the ensemble mean 50mm contour. Lower panels show the ensemble mean QPF and each of the 21 GEFS members 50 mm contour. Forecasts are initialized, from left to right at 0000 UTC 14 April, 1200 UTC 14 April and 0000 UTC 15 April 2011. Return to text.
Figure 15. As in Figure 14 except for SREF forecasts of 50 mm or more QPF for 48 hour period ending at 1200 UTC 17 April from SREF initialized at 1500 UTC 14 April, 0300 UTC 15 April and 2100 UTC 15 April 2011. Return to text.
Figure 16. GEFSS and SREF precipitation plume for a point near Somerset, PA. The SREF 3-hourly data (gray) were used to make the cumulative plumes for each of the 21 SREF members. The GEFS 6-hourly data were used to make the GEFS cumulative plumes. The cumulative plumes for each ensemble forecast system are color coded by precipitation type as indicated to the left of the image. Return to text.
Figure 12. 4km NAM initialized at 1200 UTC 16 April showing simulated radar over the eastern United States at 2100 and 2200 UTC 16 April 2011.
Figure 18. JRA25 data showing the mean sea level pressure (hPa) and pressure anomalies associated with the 28 March 1984 severe weather event. Data are every 6 hours from a) 0600 UTC 28 March through f) 1200 UTC 29 March 2011. Return to text.
Figure 19. As in Figure 18 except valid at 1800 UTC 28 March 1984 showing a) 500 hPa heights and height anomalies, b) 250 hPa winds and wind anomalies, c) 850 hPa winds and wind anomalies, and d) precipitable water and precipitable water anomalies. Return to text.