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AN ASSESSMENT OF KEY ASPECTS OF WARM AND COOL SEASON SEVERE FLASH FLOODING IN THE SOUTHERN APPALACHIANS

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1. INTRODUCTION

One of the most challenging and difficult problems facing forecasters today is quantitative precipitation forecasting, especially the prediction of orographically enhanced heavy precipitation (Lin et al. 2001). The difficulty of forecasting flash floods is a global problem. For example, significant orographic flash flooding events affect such areas as the European Alps, the Western Ghats in India, the Central Mountain Range in Taiwan, the islands of Japan, and the South Island of New Zealand (Lin et al., 2001). These flash floods result in significant loss of life and property.

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In the United States, an area prone to flash flooding is the southern Appalachians. The geographical position of the area places it at a higher risk for flash flooding. Two major moisture source regions lie in close proximity to the southern Appalachians. The Atlantic Ocean lies just to the east of the region, and the Gulf of Mexico lies to the south. Winds from either of these water bodies can advect tremendous amounts of moisture toward the region. Tropical systems sometimes move into the southern Appalachians from both the Atlantic and Gulf of Mexico. However, research on tropical system influenced flash flooding far surpasses research on seasonal flash flooding. Therefore, the focus of this research will be on seasonal flash flooding that were not influenced by the tropical systems.

As tourism and populations in the mountains of the southern Appalachians continue to grow, the importance of flash flood forecasting also grows. According to the United States Census Bureau (USCB), areas such as Pigeon Forge and Gatlinburg, TN., have seen a population increase of nearly 40% in the last ten years (USCB 1990, 2000). Furthermore, The Great Smoky Mountains National Park is now the most visited national park in the U.S., with nearly 10 million visitors each year (Adams, 2003). In the past, mountainous flooding was largely ignored because of the sparse population in the mountains. Today, this is not the case. Consequently, streams running from the mountains are experiencing more and more residential and commercial growth along their riverbanks. These streams are attractive for fishing, canoeing, white-water rafting, and various other recreational activities. In flash flooding situations these streams can become tremendously powerful, sometimes carrying boulder-size debris in their currents. One concern with mountain streams is the warm season flash-flood events that cause a rapid rise in water in a matter of minutes, possibly catching river recreationists by surprise. These events are usually caused by slow-moving thunderstorms up-stream.

The purpose of this research is to examine the pre-storm and storm environments of eight flash flooding events in the southern Appalachians and to provide a ‘climatology’ of several atmospheric variables and parameters. The authors suggest that a better understanding of the atmospheric conditions that lead to these flash flooding events would help in the improvement of forecasting of similar episodes. In addition, it needs to be noted that this study is conducted within the 'framework' of Maddox et. al (1978, 1979, 1986). These studies demonstrated that flash-flooding events may occur under 'benign' atmospheric conditions and thus, can be a challenge for the forecasters. Our literature review suggests that studies focusing on flash flooding in the U.S., in particular in the Appalachian region, are very limited (Gaffin and Hotz, 2000 and Pontrelli, 1999). This provided further motivation for the current research.

2. BACKGROUND

Eight flash flood events that occurred over the Appalachian region during the last decade (1995-2004) were selected from the National Climatic Data Center (NCDC) storm data base (NCDC, 2004) (Table 1). The events were primarily chosen by the availability of data and by their significance. The latter include storm total precipitation, monetary damages, and overall assessments documented by the NCDC. Radiosonde data was obtained from Plymouth State College's (PSC) website. The original source of this data is NCDC. Four events were chosen from the cool season, and four events were chosen from the warm season (Table 1). Two cool season flash flood events occurred in January of 1996.

Table 1. The eight flash flood events and their location, total precipitation, approximate time of occurrence, monetary losses, and pre- storm (PS) and during or shortly after the storm (S) soundings that were used for this study.

Date	Location	Rain-fall (in.)	Time of FF	$ loss	Time of sounding	
					PS	S
Jan. 7, '98	S. Appal.	Up to 15.0	Evening of Jan. 7	~35 M	12Z Jan. 7	0Z Jan. 8
Jan. 26, '96	Western N.C.	3.0-4.0	Evening of Jan.26	~30 K	12Z Jan. Jan. 26	0Z 27
Jan. 19, '96	S. Appal.	2.0-3.0	Evening of Jan. 18	~40 K	12Z Jan. 18	0Z Jan. 19
Feb. 16, '95	S. Appal.	7.0	Morning of Feb. 16	~455 K	0Z Feb. 16	12Z Feb. 16
Aug. 4, '01	Madison Co., NC	4.0	9:30 AM	3.7 M	0Z Aug. 4	12Z Aug. 4
June, 22, '01	Buncombe Co., NC	4.0	1:15 PM	1 M	12Z June 22	0Z June 23
July 6, '99	Madison Co., NC	6.0	11:00 PM	3 M	12Z July 6	0Z July 7
July 3, '95	Henderson Co., NC	4.0	4:00 PM	40 K	12Z July 3	0Z July 4

Therefore, the January 26, 1996, flash flood event is referred to as Jan/96A and January 19, 1996, is referred to as Jan/96B.

3. ANALYSIS OF THE COOL SEASON STORMS

Upper air synoptic data were analyzed at the 925, 850, 700, and 500 mb levels to get an understanding of the pre-storm and storm environments of the flash flood events (PSC, NCDC 2004). Skew-T log *p* charts were used along with the synoptic data. In all but one storm, radiosonde data was used from Greensboro, N.C. Greensboro is approximately 260 km east of Asheville, NC. (Figure 1). For January 19, 1996, the sounding from Roanoke, Va, was used for the pre-storm environment (PSC, NCDC 2004). Roanoke is approximately 390 km northeast of Asheville, NC (Figure 1).

The authors understand that flash floodings are inherently meso-scale events. This issue has been addressed by analyzing surface and upper air synoptic interpolated data along with station sounding data. This study used 925 mb interpolated data as surface data because this pressure level coincides with the elevation of the flooding events.

In this study, the pre-storm environment refers to the environment one sounding prior to the flash-flood event. The storm environment refers to the sounding taken during or shortly after the flash-flood event. We have analyzed the position, strength, and tilt of the 500 mb trough as well as the position of the surface lows. In addition, wind profiles, dewpoint depressions (Tdd), and precipitable water (PW) values for 850 mb, 700 mb, and 500 mb pressure levels were analyzed. Finally, 850 mb theta-e trough and ridge patterns were analyzed. Theta-e is a parameter that considers both temperature and moisture. The magnitude of a theta-e trough or ridge can indicate the strength or weakness of temperature and moisture advection (Chaston, 2002).

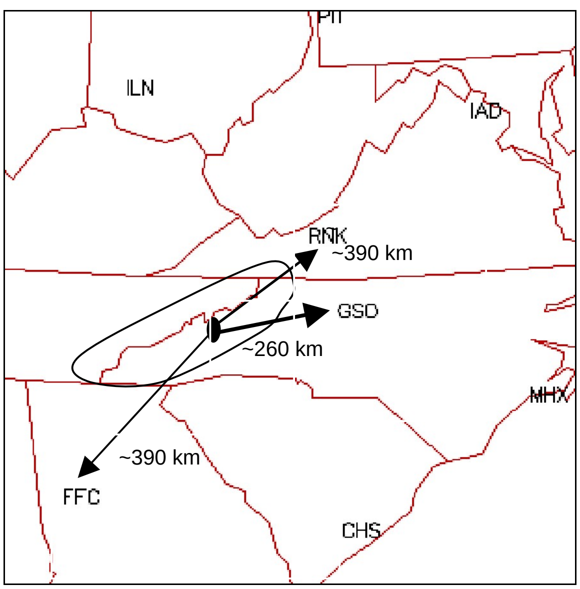

Figure 1. Study region of southern Appalachians is circled with arrows pointing to the different radiosonde sites used. The darkened oval marks the approximate location of Asheville, N.C.

a. The 500 mb trough

Dynamically, the location of a negatively tilted 500 mb trough and the surface low ahead of this trough plays a critical role in the development of storms. These troughs at the large scale can initiate sufficient instability for the development of meso-scale intense rain-producing storms. Daily weather synoptic data of the large-scale setting indicate that during all four cool-season events, a deep 500 mb trough was located in the central United States, placing the southern Appalachians on the right side of a 500 mb trough (NOAA, 2004). Three of these troughs were negatively tilted with surface lows to their east. Feb/95 showed a slightly positively tilted trough. In other words, the large scale settings for these meso-scale events were in agreement with several other severe flash flooding events in the western mountains (Maddox, 1978, Lin et al., 2001).

b. Wind profiles for the cool season storms

The interpolated station soundings of pre- and during storm winds for the four cool season storms indicated south, southeasterly, and southwesterly winds from surface to the middle troposphere (synoptic and meso-scale data not shown here). The Greensboro sounding also indicates predominantly southwesterly winds at the 925 and 850 mb levels. Wind speeds at the 925 mb level range from 15 to 35 kts (Table 2). Wind speeds at the 850 mb level range from 25 to 55 kts. All indications are that a low level jet was responsible for the 55 kts at 850 mb for Feg/95 (Sjostedt et al. 1990). This is the only storm to exhibit the presence of a low level jet. Compared to 850 mb, pre-storm wind speed increases were generally not significant at 700 mb and 500 mb levels (Table 2). However, a veering of wind with height can be identified for all four cool season events, indicating further strengthening of instability and potential for precipitation. Assessment of during storm winds generally suggests a notable increase in the wind speed from the pre-storm to storm environments, which is an indication of further temperature and moisture advection (Table 2). Previous studies of flash flooding in the west have also found similar large scale and meso-scale settings (Maddox, 1978, Lin et al. 2001).

Table 2. Pre-storm (PS) and during storm (S) wind direction (degrees) and speed (knots) at 925, 850, 700, and 500 mb. Wind speed is shown in parenthesis.

Date	925 mb		850 mb		700 mb		500 mb	
	PS	S	PS	S	PS	S	PS	S
Jan. 7, 1998	200° (20)	175° (35)	205° (25)	190° (40)	200° (25)	200° (55)	230° (25)	205° (65)
Jan. 26, 1996	205° (15)	135° (35)	200° (30)	170° (45)	235° (30)	210° (45)	245° (45)	250° (45)
Jan. 19, 1996	145° (25)	165° (35)	170° (40)	180° (45)	195° (45)	200° (40)	220° (35)	200° (50)
Feb. 16, 1995	215° (25)	220° (20)	220° (55)	234° (40)	240° (35)	255° (50)	240° (60)	255° (50)

c. Dewpoint depressions (Tdd)

The Tdd at 925, 850, 700, and 500 mb vary for each storm (Table 3). Interpolated data suggest the pre-storm environments in the vicinity of the flash floodings were drier compared to the storm environments. It is remarkable that the sounding from Greensboro suggests that Tdd at 850 mb fell from the low to mid 20s °C to at or near 0 °C for Jan/96A and Jan/96B (Table 3). This indicates rapid moistening of the lower atmosphere. The during storm Tdd ranged from 0 to 2, 1 to 5, and 2 to 21 °C at 850 mb, 700 mb, and 500 mb levels, respectively. In addition, it is found that Tdd during Feb/95 and Jan/96A events were less than or equal to 5 °C at the 500 mb level. It is notable that in all four cool season storms the temperature decreases with height, a further indication of instability. Also, the temperatures warmed at the 925 mb and 850 mb levels from the pre-storm to storm environment, while temperatures cooled for all storms from the pre-storm to storm 500 mb environment (Table 3).

These suggest warm air advection in the lowest levels and cold air advection in the upper levels, further increasing instability and chances for precipitation.

Table 3. Pre-storm (PS) and storm (S) Dew point depressions and temperatures, in degrees Celcius, at 925, 850, 700, and 500 mb. Temperatures in parenthesis.

Date	925 mb		850 mb		700 mb		500 mb	
	PS	S	PS	S	PS	S	PS	S
Jan. 7, 1998	0 (15)	1 (17)	0 (12)	2 (13)	6 (3)	1 (4)	24 (-12)	10 (-10)
Jan. 26, 1996	13 (-1)	1 (8)	24 (-1)	0 (5)	20 (-5)	5 (-2)	18 (-22)	2 (-16)
Jan. 19, 1996	1 (11)	0 (15)	26 (8)	1 (11)	5 (0)	5 (1)	15 (-15)	21 (-12)
Feb. 16, 1995	1 (5)	1 (12)	1 (11)	1 (11)	1 (2)	2 (2)	6 (-15)	5 (-13)

d. Precipitable water and mixing ratios

Precipitable water (PW) values for the four cool season storms had a wide range (Table 4). Pre-storm environment station data shows PW values for all four storms varied from 4.32 to 34.04 mm. Jan/98 had the highest pre-storm PW (32.51 mm) and storm environment (34.04 mm) PW values. Jan/96A had the lowest pre-storm and storm environment PW values of 4.32 mm and 22.86 mm, respectively. This storm had one of the highest pre-storm Tdd, 24 °C, at 850 mb (Table 3). However, as noted above, it was decreased to 1 °C during the storm, which was reflected in a rapid rise of PW from 4.32 mm to 22.86 mm (Table 4). Jan/96B had a PW value of 18.54 mm. Jan/98 and Feb/95 showed only slight changes in PW from the pre-storm to storm environments. Interpolated data for the storm area also suggest similar PW values in the vicinity of the flash flooding

An analysis of mixing ratios reveals that they generally reflect the PW patterns (Tables 4-5). For example, Jan/98 had the highest pre-storm and storm PW and mixing ratio. It is also notable that the storm's total precipitation produced follows the PW and mixing ratio in order from the highest precipitation produced to the least (Table 5).

Table 4. Pre-storm and storm precipitable water (mm).

Date	Pre-storm	Storm
Jan. 7, 1998	32.51	34.04
Jan. 26, 1996	4.32	22.86
Jan. 19, 1996	18.54	28.96
Feb. 16, 1995	29.97	30.99

Table 5. Pre-storm (PS) and storm (S) mixing ratios at 925, 850, 700, and 500 mb for the cool season storms.

Date	925 mb		850 mb		700 mb		500 mb	
	PS	S	PS	S	PS	S	PS	S
Jan. 7, 1998	11.8	13.0	10.1	11.4	7.0	7.1	3.1	3.7
Jan. 26, 1996	3.9	7.4	4.2	6.3	3.9	4.5	1.4	2.2
Jan. 19, 1996	8.9	11.4	7.7	7.6	5.6	6.4	2.3	2.0
Feb. 16, 1995	6.1	9.6	9.9	10.0	6.5	2.9	2.4	0.3

e. Theta-e troughs and ridges

As noted above, theta-e can provide guidance in identifying areas of moisture convergence. Typically, a theta-e ridge suggests significant moisture convergence (Chaston, 2002). It is found that, in the vicinity of the storm, 850 mb level theta-e ridge patterns dominated the four cool season events (Table 6). Pre-storm synoptic data also show a theta-e ridge pattern for Jan/98, Feb/95, and Jan/96A (not presented here). Only Jan/96B had a theta-e trough pattern prior to the flash flood event. Jan/98 and Feb/95 had the most pronounced pre-storm ridges. These storms had the highest pre-storm Tdd and PW values (Tables 3-4). Jan/98's pre-storm theta-e ridge extended from the coast of South Carolina northwestward to southern Indiana. Feb/95's pre-storm theta-e ridge extended from the Louisiana coast northeastward to West Virginia. The crest of a theta-e ridge that extended from southern Florida northward to the southern Appalachians was present in the pre-storm environment of Jan/96A. Also, at this time the southern Appalachians were sandwiched between a theta-e trough to their west that extended from Ohio to the central Gulf coast and a theta-e trough that extended down through the Carolina's. Jan/96B had a theta-e low located in central North Carolina that had a trough that extended to central Florida. All four storms had theta-e ridges in place during the storm. Jan/98, Jan/96B, and Feb/95 had very pronounced storm environment theta-e ridges that extended from the Atlantic Ocean west to northwestward across the southern Appalachians. Jan/96A had the most pronounced during storm theta-e ridge that extended from the Gulf coast northward to Michigan.

Table 6. Theta-e troughs and ridges for the storms.

Date	Pre-storm	Storm
Jan. 7, 1998	Ridge	Ridge
Jan. 26, 1996	Ridge	Ridge
Jan. 19, 1996	Trough	Ridge
Feb. 16, 1995	Ridge	Ridge

4. ANALYSIS OF THE WARM SEASON STORMS

Synoptic data, interpolated synoptic (for meso-scale applications) data, and station soundings were used for analyses of warm season flash floodings. In the case of July/95, the storm environment sounding was taken from Peachtree City, Ga, because of missing data from both Greensboro and Roanoke. The pre-storm sounding for July/99, was taken from Roanoke, Va, because of missing data from Greensboro. Peachtree City is located approximately 390 km southwest of the southern Appalachians (Figure 1).

a. The 500mb trough

The daily synoptic data for all four warm season flash floods indicate that weak 500 mb troughs and ridges dominated these events (NOAA, 2004). July/99 and Aug/01 showed weak 500 mb ridge patterns. For July/95 the southern Appalachians were located on the eastern side of a weak 500 mb trough. This trough was most pronounced over the Rockies. June/01 also showed a 500 mb trough pattern that was digging down through the Tennessee valley and into the Gulf of Mexico. This trough encompasses the eastern half of the nation. The highest winds for this trough rarely exceed 40 knots.

Of the above four warm season flash flooding events, only July/95 and June/01 were influenced by a front (NOAA, 2004). The daily weather map for July/95 shows a stationary front draped from North Carolina to Georgia and back into Mississippi. The daily weather map for June/01 shows a slow-moving cold front extending down through the Ohio Valley to the Tennessee Valley and southern Mississippi and into Texas. The parent cyclone with the front is located near Toronto, Ontario, Canada. The daily weather maps for both July/99 and Aug/01 show high pressure in control of the southern Appalachians. Aug/01 shows a meso-high situated southwest of the southern Appalachians (NOAA, 2004).

b. Wind profiles

Interpolated synoptic data suggest south-southwesterly and westerly winds in the vicinity of the flash flooding. The wind profiles from Greensboro, NC, at 925 mb, 850 mb, 700 mb, and 500 mb for each of the four warm season events also indicate the presence of weak south-southwesterly and westerly winds (Table 7). For example, the 850 mb pre-storm environment winds range from 10 to 20 kts. Similarly, weak pre-storm winds were recorded for the 700 mb (5-15 kts) and 500 mb (15-20 kts) levels.

The storm environment also shows weak southwesterly, westerly, and northerly winds for all of the warm season events throughout the atmosphere (Table 7). For example, at the 925 mb level generally southwesterly winds ranged from 10-30 kts. In addition, weak during storm winds were observed for 800 mb (5-30 kts) 700 mb (5-15 kts) and 500 mb (5-23 kts) levels.

Table 7. Pre-storm (PS) and during storm (S) wind direction (degrees) and speed (knots) at 925, 850, 700, and 500 mb. Wind speed is shown in parenthesis.

Date	925 mb		850 mb		700 mb		500 mb	
	PS	S	PS	S	PS	S	PS	S
Aug. 4, '01	190° (10)	240° (10)	220° (10)	240° (5)	355° (15)	310° (5)	10° (20)	350° (10)
June22, '01	245° (15)	235° (30)	235° (15)	225° (30)	230° (10)	220° (15)	230° (20)	200° (20)
July 6, '99	315° (10)	245° (10)	330° (20)	300° (10)	245° (5)	285° (5)	195° (15)	190° (5)
July 3, '95	210° (5)	140° (20)	180° (10)	235° (15)	235° (15)	255° (23)	260° (20)	265° (23)

c. Dewpoint depressions

Warm season Tdd for the four flash flood events change significantly from 925 mb to 500 mb (Table 8). The soundings for all four generally indicate a moist and warm pre-storm atmosphere from 925 mb to 850 mb and a much drier and colder atmosphere at 500 mb. For example, June/01 had a 925 mb pre-storm Tdd of 4 °C and 500 mb pre-storm Tdd of 25 °C (Table 8). This storm also had a 925 mb temperature of 22 °C and a 500 mb temperature of -10 °C. In the storm environment, the 500 mb Tdd dropped to 0 °C. Only July/99 showed large Tdd in the pre-storm and storm environment.

Table 8. Pre-storm (PS) and storm (S) Dew point depressions (C) at 925, 850, 700, and 500 mb. Temperature (C) in parenthesis

Date	925 mb		850 mb		700 mb		500 mb	
	PS	S	PS	S	PS	S	PS	S
Aug. 4, '01	8 (23)	2 (21)	3 (16)	6 (17)	12 (7)	8 (5)	35 (-8)	2 (-9)
June 22,'01	4 (22)	2 (18)	3 (16)	1 (14)	4 (5)	0 (5)	25 (-10)	0 (-9)
July 6, '99	6 (24)	10 (28)	3 (19)	8 (21)	10 (11)	9 (10)	19 (-8)	10 (-7)
July 3, '95	2 (19)	2 (21)	0 (14)	4 (17)	8 (6)	6 (7)	22 (-10)	18 (-9)

d. Precipitable water and mixing ratios

PW values were quite similar for the four storms. They range from 31.75 to 36.58 mm for pre-storm environment and 33.27 to 46.99 mm for the storm environment (Table 9). Data suggests that for all cases there were notable increases in atmospheric PW during the storms. Mixing ratios for the four storms also indicate a very moist atmosphere (Table 10). Interpolated data also shows similar high values in the areas close to the flash flooding and precipitation events.

Table 9. Precipitable water (mm) for the warm season storms.

Date	Pre-storm	Storm
Aug. 4, 2001	31.75	38.86
June 22, 2001	36.58	46.99
July 6, 1999	32.51	33.27
July 3, 1995	36.58	41.15

Table 10. Pre-storm (PS) and storm (S) mixing ratios at 925, 850, 700, and 500 mb for the warm season storms.

Date	925 mb		850 mb		700 mb		500 mb	
	PS	S	PS	S	PS	S	PS	S
Aug. 4, '01	19.5	16.7	13.4	14.5	8.9	8.1	4.3	3.8
June 22,'01	17.8	13.8	13.2	11.8	8.1	7.8	3.6	4.0
July 6, '99	20.5	26.2	16.1	19.2	11.6	11.1	4.2	4.6
July 3, '95	14.9	17.0	11.8	14.1	8.4	9.0	3.6	3.8

e. Theta-e troughs and ridges

Theta-e ridges dominated all but one of the four warm season flash flood events (Table 11). The pre-storm environment of July/99, Aug/01, and June/01 indicated the presence of a very pronounced theta-e ridge building in from the southeast. In the pre-storm environment of July/95 a weak theta-e trough was present. At the same time, a theta-e ridge was present over the central and eastern portions of the Carolinas. Theta-e ridges were present in the storm environment of all four storms.

Table 11. Theta-e troughs and ridges for the storms.

Date	Pre-storm	Storm
Aug. 4, 2001	Ridge	Ridge
June 22, 2001	Ridge	Ridge
July 6, 1999	Ridge	Ridge
July 3, 1995	Trough	Ridge

5. FINAL RESULTS AND FUTURE RESEARCH

Further assessment of results found differences and similarities between the four cool and four warm-season events. For instance, all four cool season events were part of strong 500 mb troughs with relatively higher wind speeds located within the troughs. None of the warm season events were part of a strong trough. Rather, two of the warm season events were part of a weak 500 mb ridge pattern. The other two warm season storms were part of a weak 500 mb trough pattern. Only two of the warm season flash flood events were influenced by an approaching front. All four cool season events were influenced by surface low-pressure systems that approached the southern Appalachians from the southwest. Cold-air damming influenced only one cool season event. A low-level jet influenced only one cool season storm.

Wind speeds for the cool season and warm season flash flood events were quite different. The cool season events show much higher wind speeds. The most notable difference between the cool and warm season wind speeds is at the 925 mb level. The cool season storm environment 925 mb winds range from 20 to 35 kts for the four storms. The warm season 925 mb level storm environment winds range from 10 -30 kts. The degree of atmospheric moistness also varies for the storm environment of the cool and warm season events. For example, Tdd ranges from 0 to 5 °C and 1 to 9 °C for lower atmosphere during cool season and warm season, respectively.

PW and mixing ratios were greater for the warm season flash flood events than for the cool season. However, the cool season storms showed a greater difference between the pre-storm and storm environment moisture content, indicating the importance of moisture advection in the flash flooding. Also, in the storm environment all eight events had theta-e ridges in the vicinity of flash flooding. Six of the eight events had theta-e ridge axis extending northwest from the Carolina coast to the southern Appalachians. In the warm season events moisture and instability were already generally in place in the pre-storm environment. Unlike the cool season, weak winds during the warm season flash flood events created slow-moving thunderstorms that produced heavy rainfall over a small area.

The results presented in this paper are initial findings of an ongoing research. We plan to conduct further analyses of meso-scale data to improve our understanding of various forcings that produced these storms.

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