Insights into Atmospheric Contributors to Urban Flash Flooding across the United States Using an Analysis of Rawinsonde Data and Associated Calculated Parameters

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ABSTRACT

Flooding is routinely one of the most deadly weather-related hazards in the United States, which highlights the need for more hydrometeorological research related to forecasting these hazardous events. Building upon previous literature, a synergistic study analyzes hydrometeorological aspects of major urban flood events in the United States from 1977 through 2014 caused by locally heavy precipitation. Primary datasets include upper-air soundings and climatological precipitable water (PW) distributions. A major finding of this work is that major urban flood events are associated with extremely anomalous PW values, many of which exceeded the 99th percentile of the associated climatological dataset and all of which were greater than 150% of the climatological mean values. However, of the 40 cases examined in this study, only 15 had PW values that exceeded 50.4 mm (2 in.), illustrating the importance of including the location-specific PW climatology in a PW analysis relevant to the potential for flash floods. Additionally, these events revealed that, despite geographic location and time of year, most had a warm cloud depth of at least 6 km, which is defined here as the layer between the lifting condensation level and the height of the −10°C level. A "composite" flood sounding was also calculated and revealed a characteristically tropical structure, despite cases related to tropical cyclones being excluded from the study.

1. Introduction

Floods were the second deadliest United States weather-related hazard in 2013, trailing behind only heat-related deaths. Furthermore, floods were the third costliest U.S. weather-related hazard that year at approximately $2.3 billion (NWS 2015b). In a study that investigated the synoptic and mesoscale environments associated with deadly flooding events for a 10-yr period in the United States, Ashley and Ashley (2008) demonstrated that 58% of the fatalities were associated with flash flooding events, thus further illustrating the high danger associated with such events. Forecasting floods, especially flash floods, is a complex undertaking but is vital for the protection of life and property. In this study, the focus is on flash floods, which are defined as a rapid inundation of water into a relatively small area that begins within 6 h of a causative event, which is typically intense rainfall, a dam failure, or an ice jam (American Meteorological Society 2015; NWS 2015a). In the fundamental study by Maddox et al. (1979) that examined 151 flash flood events in the United States, the authors discussed four typical

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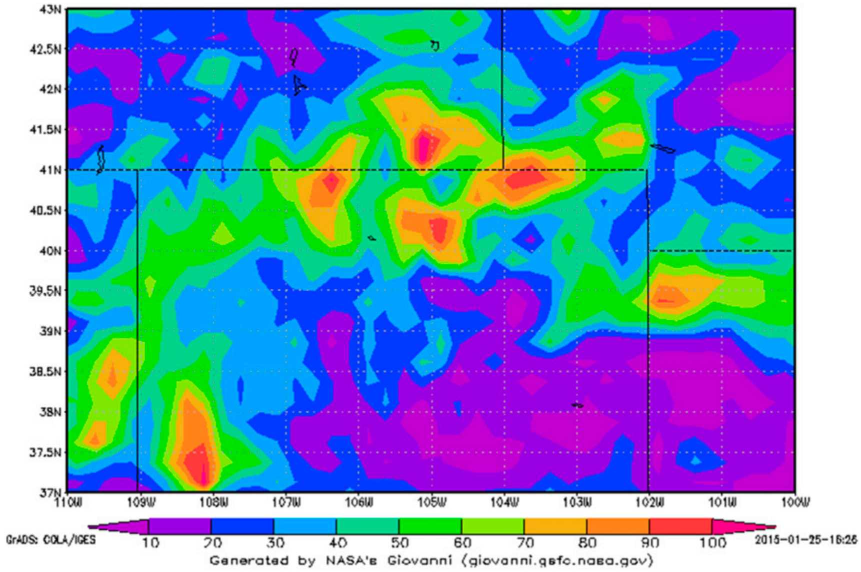

FIG. 1. Estimated rainfall rate (mm day^{-1}) for the September 2013 Colorado flood event over the period 8–17 Sep using the TRMM multisatellite precipitation analysis.

atmospheric patterns and identified general thresholds for *K* index, lifted index, and precipitable water (PW) values for each of the four typical patterns. Numerous studies reference this work with complementary research describing case studies in Minneapolis, Minnesota (Schwartz et al. 1990); Milwaukee, Wisconsin (Roebber and Eise 2001); Las Vegas, Nevada (Li et al. 2003); and Nashville, Tennessee (Durkee et al. 2012). Also, Changnon and Kunkel (1999), Shepherd et al. (2011), and Basara et al. (2011) focused on Chicago, Illinois; Atlanta, Georgia; and Oklahoma City, Oklahoma, respectively, and highlighted extreme precipitable water values during flash flood events, as well as other contributing factors.

In September 2013, the National Weather Service (NWS) described flooding in and around Boulder, Colorado, as ‘‘biblical’’ when multiple days of heavy rainfall led to widespread flooding across the area. A new 24-h rainfall record was set for Boulder when 230.6 mm (9.08 in.) fell between 0000 UTC 12 September and 0000 UTC 13 September 2013, shattering the previous record of 121.9 mm (4.80 in.) set on 31 July 1919 (NCAR/UCAR 2014; NWS 2014b). In mountainous regions, satellite-derived rainfall estimates can be useful, and Fig. 1 illustrates this by displaying the rainfall-rate distribution over the period of 8–17 September 2013 from the National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) satellite-based dataset for this particular event. Notably, the maximum PW value for this event (not shown) was 36.5 mm (1.44 in.), which significantly exceeded the 99th-percentile threshold for this location and time of year. With an observed increase in occurrence of heavy rainfall events over the past century across the United States (Karl and Knight 1998), additional research in this area is necessary and could help improve forecasters’ ability to predict these potentially dangerous events.

The primary hypothesis for the current study is that *local* anomalously high PW values accompany flash flood events and can offer predictive insight. By combining a PW analysis with an assessment of other pertinent thresholds related to flash flooding, forecasters can have enhanced situational awareness of impending flash flood potential.

Additionally, a secondary hypothesis posits that soundings will be characterized as having maritime tropical environments, illustrating the important role warm rain processes play in flash flood events. A complementary study for this hypothesis comes from Elsner et al. (1989), who described warm-topped convection contributing to the Milwaukee flash flood event in 1986. Such results support the notion of tropical-like air masses being common for flash flood events as a result of convection having warmer cloud temperatures. Additionally, a Smith et al. (2010) study examined three different flood scenarios in the Delaware River basin and found that, while orographic effects played a significant role in three different causative categories (tropical cyclones, late winter–early spring extratropical systems, and warm-season convective systems), deep atmospheric moisture and the strong low-level transport of that moisture were common to all three categories. They utilized National Lightning Detection Network (NLDN) data to examine convective intensity and found that for all three events lightning strikes were low or nonexistent, further alluding to the tropical nature of all of the studied event types.

The current study also extends the Maddox et al. (1979) analysis by expanding beyond the general guidelines for PW values and examining location-specific precipitable water climatologies and anomalies for given events. This is critical given that PW values vary substantially throughout the United States; one value for a certain location may be extreme, but for another location that same value may be below the mean for that time of year. Additionally, this study presents evidence of links between flash floods and other variables obtained from sounding analyses including mixing ratio, warm cloud depth (WCD), wind shear, and various instability parameters. Finally, this study provides a composite sounding created from the case studies examined in this paper.

As with Doswell et al. (1996), who examined an ingredients-based approach to flash flood forecasting, the authors herein acknowledge that there are important hydrologic components such as antecedent precipitation/soil moisture, size of the drainage basin, and topography of the basin, that are not addressed in this study. Additionally, the differences between flood responses for specific types of land use are not explored. It should also be noted that the current study only examines meteorological floods on the local-scale caused by significant rainfall and not floods related to ice jams, dam breaks, river floods, or tidal floods. Details regarding those types of floods can be obtained from Andersen and Shepherd (2013). The current study is similar to the work of Smith et al. (2010), who examined only flood events caused by typical meteorological flood-generating mechanisms. At the same time, this study does not include cases related to landfalling tropical cyclones, which were studied by Smith et al. (2010).

Further, this study focuses solely on flooding that occurred in urban areas, which are defined here as cities with populations of greater than 50 000 residents at the time of the event. Also, for cases where multiple locations were affected, the largest city was used to identify the case presented, thus primarily highlighting only major urban centers. Additionally, urban flood events were chosen simply because of an increased likelihood of the flood event being reported and because floods in urban areas have significant socioeconomic impacts. The study does not dissect the differences between urban and rural flash flood events because the scope of the methodology is focused on high-impact urban flash flood cases. In fact, it is quite likely that the results of this study are applicable to rural areas in the vicinity of study cities. Cities are simply the organizing framework and have a larger vulnerability to flash flooding (Ashley and Ashley 2008; Shepherd et al. 2011). Finally, the authors acknowledge that the case list is not exhaustive, only a representative sample.

2. Data and methodology

Several data sources were utilized in this study. The first was NWS sounding data obtained from the University of Wyoming's Department of Atmospheric Science (University of Wyoming 2014) and processed sounding data files (via the NSHARP software package) obtained from the Storm Prediction Center. The second primary data source is calculated PW climatologies obtained from the NWS Weather Forecast Office (WFO) in Rapid City, South Dakota (NWS 2014a). The University of Wyoming dataset and the NWS WFO Rapid City PW climatology dataset are both available via Internet-based interfaces where user-defined downloads can be created. The sounding data for 2 days prior to a particular event through 2 days after the event, as well as the PW climatologies associated with the upper-air sites used for each event analyzed, were downloaded. Additionally, online event synopses from the local NWS offices for the various events were consulted, when available.

The case list for this study was built through several means. First, exhaustive online searches were performed to identify well-documented urban flood cases within the United States that occurred from 1977 through 2014. Additionally, science and operations officers within the NWS were contacted regarding urban flood case suggestions from their respective County Warning Areas (CWAs). While nearly 100 cases were identified, several limiting factors existed that diminished the case list size for this paper. Many suggested cases could not be used as a result of the following criteria: 1) the flood was directly related to a tropical cyclone, 2) the flood-affected city was not close enough to an upper-air (UA) site (within 400 km), 3) the flood-affected city did not meet the established population threshold (>50 000), and/or 4) the sounding data were unavailable for unknown reasons. Table 1 lists the cases used in the study, and Fig. 2 shows the locations of the UA sites used for the various cases.

PW was calculated following the Rapid City WFO methodology whereby

$$e = e_o \exp[(17.67T_d)/(T_d + 243.5)], \quad (1)$$

$$\rho_{\mathrm{vapor}} = [e/(R_v T)] \times 10^5, \quad (2)$$

$$\mathrm{PW}_{\mathrm{layer}} = \overline{\rho_{\mathrm{vapor}}} Z \times 10^{-3}, \quad \text{and} \quad (3)$$

$$\mathrm{PW}_{\mathrm{sfc-300hPa}} = \sum \mathrm{PW}_{\mathrm{layer}}, \quad (4)$$

TABLE 1. List of 40 urban flash flood event cases used in this study.

Event No.	Time and date	Flood location
1	1200 UTC 1 Mar 1997	Louisville, KY/Cincinnati, OH
2	0000 UTC 12 Mar 2012	Lafayette, LA
3	0000 UTC 19 Mar 2006	Dallas, TX
4	1800 UTC 29 Mar 2007	Tarrant County, TX (Fort Worth)
5	0000 UTC 2 May 2010	Nashville, TN
6	0000 UTC 6 May 1995	Dallas/Fort Worth, TX
7	1200 UTC 9 May 1995	SE LA (Slidell/New Orleans)
8	0000 UTC 25 May 2013	San Antonio, TX
9	0000 UTC 9 Jun 2008	Madison/Milwaukee, WI
10	1200 UTC 13 Jun 2008	Springfield, MO
11	1200 UTC 14 Jun 2010	Oklahoma City, OK
12	0000 UTC 18 Jun 2007	Haltom City/Gainesville/ Sherman, TX
13	0000 UTC 20 Jun 2012	Duluth, MN
14	1200 UTC 25 Jun 2014	Fort Worth, TX
15	1200 UTC 26 Jun 2002	Fort Wayne, IN
16	1200 UTC 6 Jul 2002	San Antonio/New Braunfels, TX
17	1200 UTC 7 Jul 2010	Amarillo, TX
18	1200 UTC 8 Jul 1999	Las Vegas, NV
19	0000 UTC 8 Jul 2004	Baltimore, MD
20	1200 UTC 12 Jul 2000	Springfield, MO
21	0000 UTC 16 Jul 2001	Rapid City, SD
22	1200 UTC 18 Jul 1996	Chicago, IL
23	1200 UTC 22 Jul 2010	Milwaukee, WI
24	0000 UTC 23 Jul 2006	Charlotte, NC
25	0000 UTC 29 Jul 1997	Fort Collins, CO
26	0000 UTC 29 Jul 2004	Dallas, TX
27	1200 UTC 30 Jul 2007	Winston-Salem, NC
28	0000 UTC 6 Aug 2011	Charlotte, NC
29	0000 UTC 7 Aug 1999	Omaha, NE
30	1200 UTC 8 Aug 2007	New York, NY
31	0000 UTC 8 Aug 2013	Nashville, TN
32	1200 UTC 28 Aug 2012	Charleston, SC
33	1200 UTC 1 Sep 2003	Indianapolis, IN
34	1200 UTC 11 Sep 2013	Boulder, CO
35	1200 UTC 13 Sep 1977	Kansas City, MO
36	1200 UTC 13 Sep 1978	SW Little Rock, AR
37	0000 UTC 22 Sep 2009	Atlanta, GA
38	0000 UTC 5 Oct 1998	Kansas City, MO
39	0000 UTC 18 Oct 1998	San Antonio, TX
40	1200 UTC 18 Dec 2009	Charleston, SC

where e is the vapor pressure (hPa); e_o is 6.112 hPa; T_d is the dewpoint (°C); ρ_{vapor} is the vapor density (g m^{-3}); R_v, the gas constant for water vapor, is 461.5 J kg^{-1} K^{-1}; and T is the temperature (K).

The majority of the remaining variables utilized in this study were computed using NSHARP, an interactive skew T and hodograph software program. The only additional variable that required computation was the height of the −10°C level, which was computed via linear interpolation using the raw UA sounding data.

To construct the composite sounding, the most recent sounding closest to the onset of the event was identified for each group of soundings pulled for all cases so that only one was used per case to calculate the composite. Next, a linear interpolation in the natural logarithm of pressure was computed for all observed sounding data. Next, the composite mean sounding was then constructed from the interpolated temperature and dewpoint values. Wind profiles were not included as a result of the variability among sites used in the study. Four cases (Fort Collins, Colorado, July 1997; Las Vegas, July 1999; Amarillo, Texas, July 2010; and Boulder, September 2013) utilized in the sounding parameters assessment were not included in the composite sounding because low-level data for the respective soundings were not available as a result of the elevation above sea level of the UA sites used for those particular cases.

Jessup and DeGaetano (2008) examined the flood checklist employed by NWS forecasters at the Binghamton, New York, WFO (BGM), which utilized thresholds for multiple variables, including precipitable water. Like the current study, the closest station was chosen in the upwind direction prior to the event. Composites of temperature and dewpoint were also calculated. However, several methodological differences exist between the methodology used in the Jessup study and that applied herein. For example, Jessup and DeGaetano (2008) included wind profiles in their calculations while the current study did so only for the individual cases but not for the composite sounding construction. Also, the individual composite soundings calculated in the Jessup and DeGaetano (2008) study utilized data from only one UA station, which was appropriate because of the relatively small study area. However, the current study calculated a single composite for all events studied within the study area's geographic extent. Jessup and DeGaetano (2008) also removed urban floods because they assumed relatively small impact, but the current study explicitly sought only urban events. Finally, and of particular significance, the current study examines a broader set of geographical and climate regimes.

3. Results

Flood cases occurred during all seasons, but 24 of 40 cases (60%) occurred during the summer months of June–August (JJA). Brooks and Stensrud (2000) also concluded that a seasonal cycle of heavy rain events was present across the United States using the Hourly Precipitation Dataset, with the peak occurring during the

FIG. 2. Locations of the UA sites used for the various urban flood cases.

summer months. These results concur with the Maddox et al. (1979) study, as well as the more recent Jessup and DeGaetano (2008) study, which both documented a peak in the annual distribution of floods during the summer months. Of the 40 urban flood cases used in the current study, 30 cases (75%) had PW values above 2 standard deviations (SD) from the mean, and 22 of those 30 (73%) were above the 99th percentile. Further still, 6 of those 22 (27%) were at or near the maximum value for that particular location and time of year, including the catastrophic September 2013 Boulder flood event. The 10 remaining cases had PW values above the 75th percentile, but below 2 SD. Table 2 further illustrates these results by displaying the type of anomaly and which events fell into each category. The PW threshold value evaluated in the Jessup and DeGaetano (2008) study was 150% of normal, and the current study illustrates that a threshold of 150% of normal PW values for a location is a valid threshold, as all 40 of the cases studied here were above that threshold as well (i.e., the 75th percentile). Additionally, it should be noted that 25 (63%) of the 40 cases examined in the current study had PW values less than 50.8 mm (2 in.). While many meteorologists within the NWS acknowledge the importance of anomalous PW values and how they compare to the local climatology, many still use a 2-in. threshold to hone in on days on which flash flooding could be a possibility for their area. *These results clearly identify the need to account for how PW compares to the PW climatology for that particular location and time of year.* Had only the 50.8-mm (2 in.) value been used as the point of heightened awareness, 63% of the devastating floods examined in the current study might have been missed if such a PW threshold were a prime identifier used to alert forecasters to flash flooding possibilities.

One of the most extreme examples of PW from the case list was from the flood event that affected Boulder and the Front Range of the Rockies in September 2013. During the 7-day period from 9 September through 15 September, approximately 430 mm (17 in.) of rain fell over the Boulder area (NCAR/UCAR 2014). Numerous swift-water rescues were performed in and around the area and major roads were washed away, making some small mountain communities inaccessible. Multiple fatalities resulted from this flood event, including two teenagers who were swept away by floodwaters in northwestern portions of the city of Boulder (*Denver Post* 2014). The UA site used for this event was located in Denver (DNR), approximately 40 km southeast of Boulder. The maximum event PW value of 36.5 mm (1.44 in.) came from the 0000 UTC 11 September 2013 sounding and significantly exceeded the previous maximum PW value for this location and time of year (Fig. 3).

TABLE 2. Strength of the PW anomaly for each event used in this study.

Max PW anomaly	Event No.
At/near max value	1, 2, 5, 25, 33, 34
At/above 99th percentile	3, 6, 7, 11, 13, 18, 20, 23, 24, 26, 28, 35, 36, 37, 39
Above 2 SD	4, 9, 14, 17, 21, 22, 29, 30, 38
Above 75th percentile	8, 10, 12, 15, 16, 19, 27, 31, 32, 40

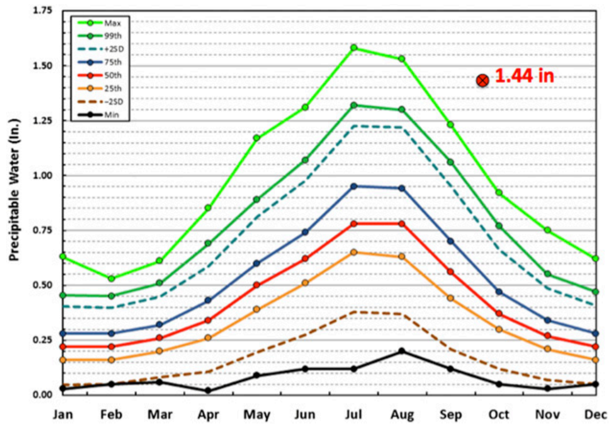

FIG. 3. PW value at 1200 UTC 11 Sep 2013 superimposed on the PW climatology plot for Denver.

Another extreme case came from the Louisville, Kentucky, flood that occurred on 1 March 1997. This flood event set the 24-h rainfall record for the state of Kentucky at 266.2 mm (10.48 in.), which was reported at the WFO in Louisville. The Louisville metro area sustained approximately $200 million in damages from the flood and two interstate highways were closed during the event. Unfortunately, a teenage boy lost his life when his van was swept off the road by a swollen creek in one of the suburbs of the city (NWS 2012). Located approximately 240 km northeast of Louisville, the Wilmington, Ohio, UA site was used in this study as a proxy for the event because of its proximity to the flood-affected city and the prevailing wind direction. Figure 4 is the sounding from the Wilmington UA site for 1200 UTC on 1 March 1997, and Fig. 5 illustrates the PW value for the event (1.42 in.) superimposed on the PW climatology plot for this location. As of 2013, this case provided the maximum PW value for this location and time of year.

Additional moisture parameters were analyzed for this study, including surface dewpoint and relative humidity, as well as various mixing ratio depth calculations. Statistical details for these calculations can be obtained from Table 3. The average surface dewpoint was 19.6°C (67.3°F) with a standard deviation of 3.7°C (6.6°F), and the average surface relative humidity was 85% with a standard deviation of 12%. While 8 of the 40 cases displayed surface relative humidity values less than 75%, all 8 of those cases had surface dewpoints of at least 19°C (66°F). Additionally, three cases yielded surface dewpoints less than 15.5°C (60°F), but all of those cases had surface relative humidity values of at least 83%.

While considering the more widely used dewpoint and relative humidity values does provide some insight into

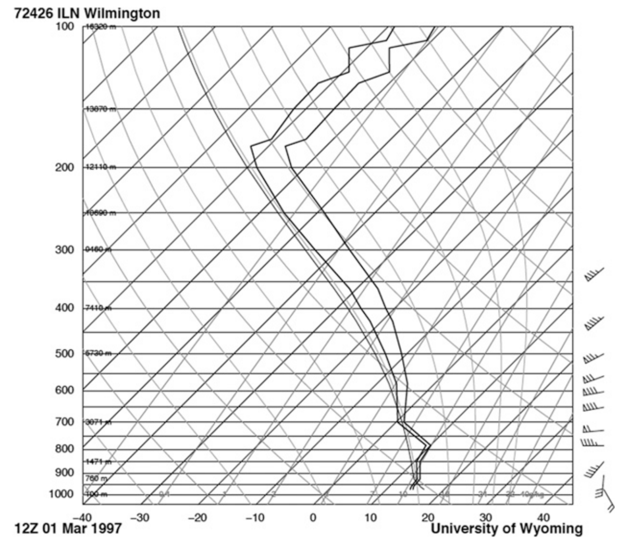

FIG. 4. Skew *T*–log*p* diagram of the UA sounding from the Wilmington site at 1200 UTC 1 Mar 1997.

the low-level moisture for the events, a more robust method for diagnosing moisture may be to examine the various mixing ratio calculations, simply because mixing ratio is the conserved variable and the other two variables are not. However, dewpoint does provide information about the absolute moisture content, and relative humidity provides insight into the degree of saturation, which are both important for different reasons. With the average 0–1-km mean mixing ratio being 14.60 g kg^{-1} (SD of 2.70 g kg^{-1}) and the average 0–3-km mean mixing ratio being 11.99 g kg^{-1} (SD of 1.83 g kg^{-1}), ample low-level moisture was present for the cases examined in this study. Doswell et al. (1996) and Shepherd et al. (2001) state the importance of low-level moisture in minimizing the evaporation of precipitation below the cloud base, which is critical for high precipitation efficiency, and these results illustrate that the low levels were relatively saturated during each case, minimizing the impact of evaporation below cloud base.

While ample atmospheric moisture is critical, more ingredients are needed to create flash flood–producing rainfall events. To illustrate this, a null event from Fort Worth, Texas, is presented here. On the evening of 6 October 2007, abundant moisture was present across north Texas. Figure 6 provides the 0000 UTC 7 October 2007 sounding from this area and shows a surface dewpoint of 22.4°C (72.3°F) and a PW value of 51.33 mm (2.02 in.), which is above the 99th percentile relative to climatology. Isolated showers and thunderstorms developed across the region but the areal coverage and thunderstorm intensity and duration were not sufficient for flash

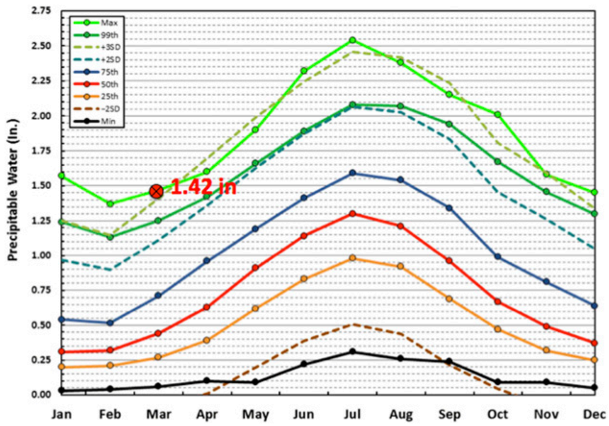

FIG. 5. PW value at 1200 UTC 1 Mar 1997 superimposed on the PW climatology plot for Wilmington.

flooding. Therefore, as Doswell et al. (1996) point out, multiple ingredients are necessary for flash flooding to occur. As such, additional details of the vertical profiles from each of the 40 cases were examined to gather clues about the atmospheric instability, vertical wind profile, heights of various temperature thresholds, and certain commonly used indices (Table 4). While this study does not explicitly perform a vertical moisture flux calculation, which Doswell et al. (1996) explain is very important when analyzing flash flood–producing rainfall events, the current study does indirectly account for this by considering lapse rates and mixing ratio values. Not surprisingly, all of the lapse rate calculations were nearly moist adiabatic, and, as stated previously, the lower-level mixing ratio values were around 14 g kg^{-1}. Reduced lapse rates allow raindrops more time to grow via collision–coalescence processes, thus increasing the precipitation efficiency, and high mixing ratio values depict the available moisture present in the atmosphere necessary for precipitation generation (Vitale and Ryan 2013).

Multiple studies have highlighted the absence of strong vertical wind shear for many flash flood–producing heavy rainfall events (Maddox et al. 1979; Zapotocny and Byrd 2002; Basara et al. 2011). Weak wind shear is associated with weak steering flow and therefore leads to longer residence time and higher rainfall totals over a particular area. The results of this study demonstrate that weak-to-moderate shear values were present for the 40 cases analyzed with an average wind speed increase of approximately 5 kt (2.55 m s^{-1}; 1 kt = 0.51 m s^{-1}) for the 700–925-hPa level (or lowest mandatory level observed, if 925 hPa was below ground level because of the terrain) and 11 kt (5.61 m s^{-1}) for the 500–925-hPa level (or lowest mandatory level observed,

TABLE 3. Statistical analysis of surface and moisture parameters for the events used in this study.

	Avg	SD	Max	Min
Surface T (°C)	22.3	4.7	31.4	9.0
Surface T_d (°C)	19.6	3.7	25.5	6.4
Surface RH (%)	85	12	100	53
Surface–850-hPa mean mixing ratio	14.05	2.36	18.21	7.59
0–1-km mean (g kg^{-1}) mixing ratio (g kg^{-1})	14.60	2.70	19.45	7.60
0–3-km mean mixing ratio (g kg^{-1})	11.99	1.83	14.61	6.78

if the 925 or 850 levels were below ground level because of the terrain). For the directional change, the average for the 700–925-hPa level was veered by 44° and was veered by 67° for the 500–925-hPa level.

The stability of each of the cases was evaluated by examining the most unstable convective available potential energy (MUCAPE), the most unstable convective inhibition (MUCIN), the downdraft convective available potential energy (DCAPE), various lapse rates, and the K index. Results show that most cases exhibited ''tall, skinny'' CAPE profiles (with an average value of 1817 J kg^{-1}) and little to no CIN and had lapse rates near 6°C km^{-1}. Instability profiles like these have updrafts that lead to a longer residence time for the raindrops, allowing them to grow more effectively via the collision–coalescence process (Vitale and Ryan 2013). Additionally, K-index values were indicative of thunderstorm activity with an average value of 37.3.

One of the most critical statistical results from the current study was the WCD, which is defined here as the layer between the lifting condensation level (LCL) and the height of the −10°C level, the same definition as used in the Vitale and Ryan (2013) study. The WCD and −10°C level were calculated in addition to the melting level (height of the 0°C isotherm) because supercooled water is typically present when temperatures are above −10°C, yet below 0°C (WDTB 2014). Warm-rain precipitation processes governed by collision–coalescence instead of the Bergeron process, which requires the presence of ice in the cloud, are dominant if the water is still in liquid form (Vitale and Ryan 2013). Because warm-rain processes are typically more efficient rainfall producers, examining all details related to such processes was important. Figure 7 presents the box-and-whisker plot for the height of the −10°C level. The average height of the −10°C level for the 40 cases examined was 6213 m AGL (20 383 ft AGL) with a standard deviation of 466 m AGL (1529 ft AGL). The highest −10°C level of 6782 m AGL (22 252 ft AGL)

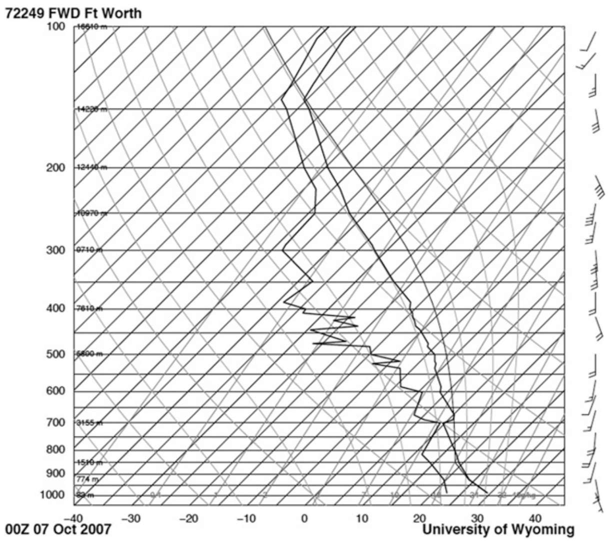

FIG. 6. Skew T–log$p$ diagram of the UA sounding from the Fort Worth site for 0000 UTC 7 Oct 2007.

came from the 13 September 1978 flood case over Little Rock, Arkansas. The lowest height of the −10°C level was 5021 m AGL (16 471 ft AGL) and came from the 18 December 2009 over Charleston, South Carolina. These statistics include cases from all seasons and multiple cases from areas with complex terrain. It is interesting to note that none of the extremes of the height of the −10°C level came from areas of highest terrain.

Despite the removal of events caused by tropical cyclones, the composite sounding calculated from the cases (Fig. 8) used in this study exhibits characteristics of soundings typically associated with convection in tropical environments (NCAR/UCAR 2015). Jessup and DeGaetano (2008) calculated composite soundings and yielded similar results in sounding shape (see Figs. 10 and 11 in Jessup and DeGaetano 2008). They also noted that the flash flood events examined in their paper tended to have low-to-moderate CAPE values when compared with other precipitating events, demonstrating a preference for collision–coalescence warm-rain processes. Davis (2001) points out that the potential for high rainfall rates, one of the key ingredients needed for flash floods, is greater for cloud systems with deep warm cloud layers because cloud droplets have more time to interact and thus lead to better precipitation efficiency when the collision–coalescence process is dominant. Such results further support the tropical characteristics of the composite sounding calculated for the current study.

4. Conclusions

From 1977 to 2014, 40 urban flash flood cases within the United States were identified and examined. Nearly two-thirds of the cases occurred during the summer months of JJA. Additionally, approximately 75% of the urban flash flood cases were associated with PW values that were at least 2 SD above the mean for that location and time of year, and all 40 of the cases were above the 75th percentile (150% of the mean). As mentioned earlier, this compares favorably to many previous studies, including the results obtained from the Jessup and DeGaetano (2008) study that examined common thresholds and composite soundings for flash flood events created for the BGM CWA. Importantly, our results expand the findings to broader geographical and climate regimes rather than one CWA. A key point from the current research is that a universal threshold is

TABLE 4. Statistical analysis of important vertical levels, stability parameters, and upper-level wind changes for the events used in this study.

	Avg	SD	Max	Min
Melting level (m AGL)	4108	502	4791	2734
Height of −10°C level (m AGL)	6213	466	6782	5021
WCD (m)	5866	522	6680	4691
LCL (m AGL)	346.27	299.95	1262.93	17.02
MUCAPE	1817	1155	5146	76
MUCIN	−16	23	0	−85
700–500-hPa lapse rate (°C km^{-1})	5.95	0.79	7.47	3.61
850–500-hPa lapse rate (°C km^{-1})	6.17	0.54	7.23	4.79
0–3-km lapse rate (°C km^{-1})	5.97	0.93	7.79	3.79
3–6-km lapse rate (°C km^{-1})	5.94	0.72	7.56	3.86
K index	37.3	4.1	44.5	26
700-hPa wind speed (kt)	24	16	70	3
Wind speed change between 700 and lowest mandatory (MAN) hPa level (kt)	5	14	52	−20
Wind speed change between 500 and lowest MAN hPa level (kt)	11	16	64	−13
Wind direction change between 700 and lowest MAN hPa level (°)	44	50	200	−16
Wind direction change between 500 and lowest MAN hPa level (°)	67	57	210	−45

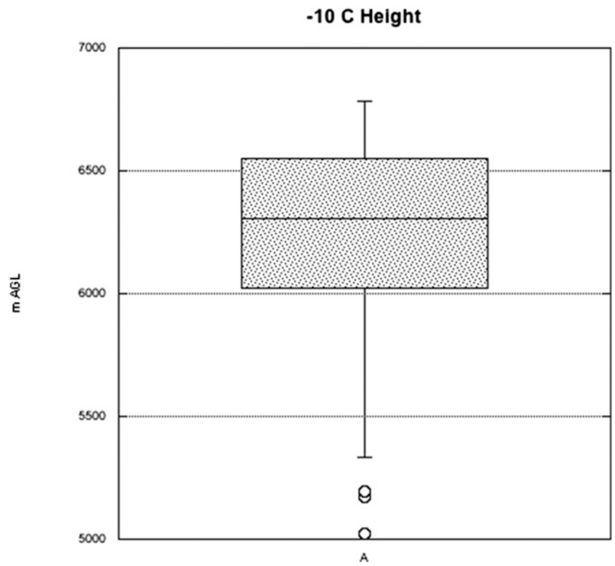

FIG. 7. Box-and-whisker plot of the −10°C height as based on the 40 flash flood cases examined.

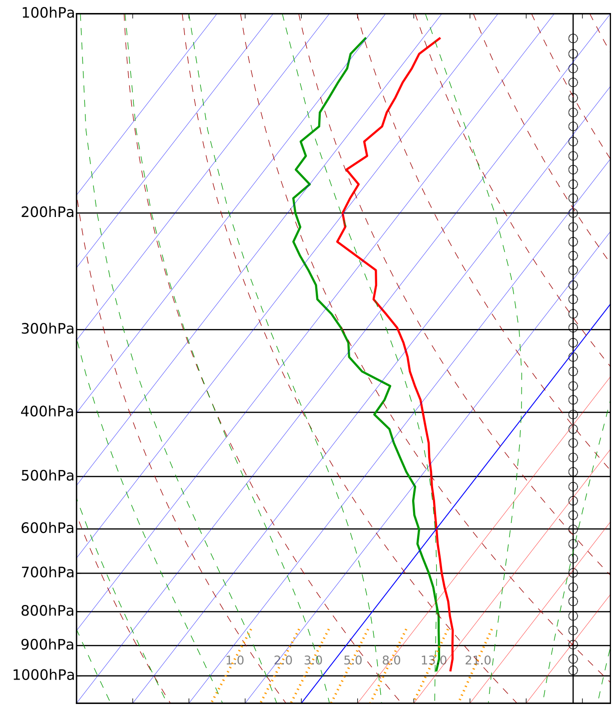

FIG. 8. Skew T–log$p$ diagram of the composite sounding of temperature (°C; red line) and dewpoint (°C; green line) calculated using 36 of the flash flood cases examined in this study.

not an appropriate way to analyze PW. With only 15 of the 40 cases (38%) examined in the current study having PW values that exceeded 50.8 mm (2 in.), applying the common ''broad brush'' value often used by forecasters to heighten their awareness of flash flooding potential means that over half of the devastating floods examined in this study would have been missed by forecasters had PW been a primary indicator for heightened flash flood potential. This clearly demonstrates the need to include the climatology for the location in question to attain proper perspective of the degree to which the value is anomalous. However, as Doswell et al. (1996) state, it is the assembly of multiple ingredients that is important. While the PW anomaly is a strong indicator for alerting forecasters to the potential for a heavy rainfall event, that variable alone is not sufficient to produce a flash flood event for any location. Current results have shown that instability and wind shear also play an important role. Commonalities emerged from the 40 cases studied including the following: WCD values near 6 km, MUCAPE between 1000 and 2200 J kg^{-1} K, and weak-to-moderate speed and directional wind shear. Given the tropical-like presentation of the composite sounding computed from these case studies, these values compare well to other studies mentioned previously.

The calculated composite sounding created from our cases resembled a tropical atmospheric sounding, despite cases directly associated with tropical cyclones being removed from the dataset. This sounding shape is similar to the composite sounding appearance obtained by Schumacher and Johnson (2009), who analyzed six different heavy rainfall events that resulted in flash flooding. The biggest difference between the two composites was the depth of the moisture, with the moisture for the current study extending farther into the midlevels of the atmosphere than the composite sounding from the Schumacher and Johnson (2009) study.

Based on the results from the current study, PW anomalies are one of the necessary conditions for urban flash flood events. Because forecasting and detecting flash floods is one of the greatest challenges facing forecasters as a result of the fact that key meteorological and hydrological situations must coexist in order to yield a flash flood event (Davis 2001), any detailed insight into the subject can help with the forecast process. While other key ingredients are needed to produce a flash flood, the findings from this study could improve situational awareness and aid forecasters attempting to recognize scenarios in which urban flash flood events caused by extreme rainfall could occur. This would, in turn, help better prepare the public and potentially save lives and property, the primary mission of the National Weather Service.

In the future, the authors plan to add additional cases to the list to make the results more robust with a larger population sample size. Additionally, using the results from the current study, the authors plan to perform an analysis for a particular UA location, calculating the variables outlined here and comparing those values to flash flood reports, further exploring the usefulness of the results in operational meteorology. Also, a flash flood index could potentially be constructed using both results and would be calculated for observed soundings to help identify regions where some of the atmospheric ingredients common to flash flood events have come together. An additional prospect for future work would be to conduct an analysis similar to the study conducted by Smith et al. (2010) that utilized the NLDN. This could be applied to the cases studied here using the correlation that deep tropical-like systems are not electrified because of a lack of glaciation.

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REFERENCES

American Meteorological Society, 2015: Flash flood. *Glossary of Meteorology*, Amer. Meteor. Soc. [Available online at http://glossary.ametsoc.org/wiki/Flash_flood.]

Andersen, T. K., and J. M. Shepherd, 2013: Floods in a changing climate. *Geogr. Compass*, **7**, 95–115, doi:10.1111/gec3.12025.

Ashley, S. T., and W. S. Ashley, 2008: Flood fatalities in the United States. *J. Appl. Meteor. Climatol.*, **47**, 805–818, doi:10.1175/2007JAMC1611.1.

Basara, J. B., B. G. Illston, and G. D. McManus, 2011: Atmospheric contributors to the 14 June 2010 flash flood in Oklahoma City. *Int. Symp. on Earth-Science Challenges*, Norman, OK, University of Oklahoma and Kyoto University, p. 79.

Brooks, H. E., and D. J. Stensrud, 2000: Climatology of heavy rain events in the United States from hourly precipitation observations. *Mon. Wea. Rev.*, **128**, 1194–1201, doi:10.1175/1520-0493(2000)128<1194:COHREI>2.0.CO;2.

Changnon, S. A., and K. E. Kunkel, 1999: Record flood-producing rainstorms of 17–18 July 1996 in the Chicago metropolitan area. Part I: Synoptic and mesoscale features. *J. Appl. Meteor.*, **38**, 257–265, doi:10.1175/1520-0450(1999)038<0257:RFPROJ>2.0.CO;2.

Davis, R. S., 2001: Flash flood forecast and detection methods. *Severe Convective Storms*, *Meteor. Monogr.*, No. 50, Amer. Meteor. Soc., 481–525.

Denver Post, cited 2014: Colorado flooding: Two new fatalities announced, one is Lyons man Gerald Boland. [Available online at http://www.denverpost.com/breakingnews/ci_24131875/larimer-county-adds-1-number-people-presumed-killed.]

Doswell, C. A., III, H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560–581, doi:10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2.

Durkee, J. D., L. Campbell, K. Berry, D. Jordan, G. Goodrich, R. Mahmood, and S. Foster, 2012: A synoptic perspective of the record 1–2 May 2010 mid-South heavy precipitation event. *Bull. Amer. Meteor. Soc.*, **93**, 611–620, doi:10.1175/BAMS-D-11-00076.1.

Elsner, J. B., W. H. Drag, and J. K. Last, 1989: Synoptic weather patterns associated with the Milwaukee, Wisconsin flash flood of 6 August 1986. *Wea. Forecasting*, **4**, 537–554, doi:10.1175/1520-0434(1989)004<0537:SWPAWT>2.0.CO;2.

Jessup, S. M., and A. T. DeGaetano, 2008: A statistical comparison of the properties of flash flooding and nonflooding precipitation events in portions of New York and Pennsylvania. *Wea. Forecasting*, **23**, 114–130, doi:10.1175/2007WAF2006066.1.

Karl, T. R., and R. W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Meteor. Soc.*, **79**, 231–241, doi:10.1175/1520-0477(1998)079<0231:STOPAF>2.0.CO;2.

Li, J., R. A. Maddox, X. Gao, S. Sorooshian, and K. Hsu, 2003: A numerical investigation of the storm structure and evolution during the July 1999 Las Vegas flash flood. *Mon. Wea. Rev.*, **131**, 2038–2059, doi:10.1175/1520-0493(2003)131<2038:ANIOSS>2.0.CO;2.

Maddox, R. A., C. F. Chappell, and L. R. Hoxit, 1979: Synoptic and meso-α aspects of flash flood events. *Bull. Amer. Meteor. Soc.*, **60**, 115–123, doi:10.1175/1520-0477-60.2.115.

NCAR/UCAR, cited 2014: Inside the Colorado deluge. [Available online at http://www2.ucar.edu/atmosnews/perspective/10250/inside-colorado-deluge.]

——, cited 2015: Forecast applications. Skew-t Mastery. UCAR COMET MetEd. [Available online at http://www.meted.ucar.edu/mesoprim/skewt/.]

NWS, cited 2012: The flood of March 1997. [Available online at http://www.weather.gov/lmk/flood97.]

——, cited 2014a: Precipitable water plots. National Weather Service Weather Forecast Office: Rapid City, SD (UNR). [Available online at http://www.crh.noaa.gov/unr/?n=pw.]

——, cited 2014b: September 11-18, 2013 floods. [Available online at http://www.crh.noaa.gov/images/bou/precip/Sep2013Flood.pdf.]

——, cited 2015a: Glossary. [Available online at http://w1.weather.gov/glossary/index.php?letter=f.].

——, cited 2015b: Summary of natural hazard statistics for 2013 in the United States. [Available online at http://www.nws.noaa.gov/om/hazstats/sum13.pdf.]

Roebber, P. J., and J. Eise, 2001: The 21 June 1997 flood: Storm-scale simulations and implications for operational forecasting. *Wea. Forecasting*, **16**, 197–218, doi:10.1175/1520-0434(2001)016<0197:TJFSSS>2.0.CO;2.

Schumacher, R. S., and R. H. Johnson, 2009: Quasi-stationary, extreme-rain-producing convective systems associated with midlevel cyclonic circulations. *Wea. Forecasting*, **24**, 555–574, doi:10.1175/2008WAF2222173.1.

Schwartz, B. E., C. F. Chappell, W. E. Togstad, and X. Zhong, 1990: The Minneapolis flash flood: Meteorological analysis and operational response. *Wea. Forecasting*, **5**, 3–21, doi:10.1175/1520-0434(1990)005<0003:TMFFMA>2.0.CO;2.

Shepherd, J. M., B. S. Ferrier, and P. S. Ray, 2001: Rainfall morphology in Florida convergence zones: A numerical study. *Mon. Wea. Rev.*, **129**, 177–197, doi:10.1175/1520-0493(2001)129<0177:RMIFCZ>2.0.CO;2.

——, T. Mote, J. Dowd, M. Roden, P. Knox, S. C. McCutcheon, and S. E. Nelson, 2011: An overview of synoptic and mesoscale factors contributing to the disastrous Atlanta flood of 2009. *Bull. Amer. Meteor. Soc.*, **92**, 861–870, doi:10.1175/2010BAMS3003.1.

Smith, J. A., M. L. Baeck, G. Villarini, and W. F. Krajewski, 2010: The hydrology and hydrometeorology of flooding in the Delaware River basin. *J. Hydrometeor.*, **11**, 841–859, doi:10.1175/2010JHM1236.1.

University of Wyoming, cited 2014: Weather. Dept. of Atmospheric Science, University of Wyoming. [Available online at http://weather.uwyo.edu/upperair/sounding.html.]

Vitale, J. D., and T. Ryan, 2013: Operational recognition of high precipitation efficiency and low-echo-centroid convection. *J. Oper. Meteor*, **1**, 128–143, doi:10.15191/nwajom.2013.0112.

WDTB, cited 2014: Introduction to the top-down methodology. Topic 6, Lesson 1, AWOC Winter Weather Track, Warning Decision Training Branch, Norman, OK. [Available online at www.wdtb.noaa.gov/courses/winterawoc/IC6/lesson1/player.html.]

Zapotocny, C. M., and S. F. Byrd, 2002: An examination of the eastern Nebraska and western Iowa flash flood event of 6-7 August 1999. *Natl. Wea. Dig.*, **26**, 7–26.