HYDROMETEOROLOGICAL ASPECTS OF THE KANSAS TURNPIKE FLASH FLOOD OF 30-31 AUGUST 2003

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Abstract

During the period from 2230 UTC to 0130 UTC 30-31 August 2003, a very small portion of the Kansas Turnpike near Emporia, Kansas was inundated with 6-8 inches of rain. This resulted in extreme flash flooding, six fatalities, and \$250,000 worth of property damage. This flash flood was caused by a type of storm called a low-echo centroid (LEC) storm. This study will focus on the synoptic and mesoscale parameters that favor the development of LEC storms as well as hydrological considerations that contribute to extreme flash flooding. An examination of Weather Surveillance Radar – 1988 Doppler (WSR-88D) cross-sectional imagery reveals the LEC nature of the storm with the highest reflectivity contained in the warm portion of the cloud. A moisture analysis showed that there was a very high influx of moisture into the storm that allowed the storm to develop heavy rainfall characteristics. Additionally, soundings revealed weak instability, weak cloud layer flow, and a deeply saturated sounding which will be shown to be important contributors in the development of highly precipitation efficient storms. The hydrological aspect of this case shows that the natural flow of water was altered and contributed to the extreme nature of this event. The culvert underneath the interstate proved to be inadequate for this volume of water. A meteorological and hydrological comparison of this event with the historic Fort Collins, Colorado flood is made and discussed. These types of storms can become operationally difficult to recognize in a real-time event.

1. Introduction

During the evening of 30 August 2003, a convective storm developed over central Kansas, inundating Jacob Creek with 6-8 inches (150-200 mm) of rain. While moving very slowly, the entire lifecycle of the storm persisted for less than three hours. According to Storm Data (NCDC 2003), Jacob Creek experienced a flow of 4,100 ft³ s⁻¹. Flash flooding caused six fatalities on the interstate with water flowing onto the northeast bound lanes. In addition, this flash flood caused approximately \$250,000 worth of property damage (NCDC 2003).

As shown in Fig. 1a, the radar-derived storm total rainfall from the Wichita WSR-88D (KICT) was between 2 and 3 inches (50 and 75 mm) using the standard Z-R relationship (i.e., $Z=300R^{1.4}$, where Z is the reflectivity in dBZ and R is the rainfall rate in mm h⁻¹). The discrepancy between the radar-estimated rainfall totals and insitu measurements was likely due to the nature of this convective event. In particular, this event displayed a high-reflectivity core that did not exceed 5 km in altitude (referred to as a Low Echo Centroid storm, hereafter a LEC storm; Caracena et al. 1979). The purpose of this paper is to diagnose the meteorological parameters that caused this LEC to develop and the hydrological aspects of the flood.

Section two reviews previous research that is relevant to LEC storms. Section three describes the synoptic-scale environment in which this convection was initiated and sustained. Section four will diagnose hydrological issues associated with this flash flood event. Section five will compare the Fort Collins, Colorado flash flood with the Kansas Turnpike flash flood. The concluding section will summarize the results, noting the factors that appear to promote LEC development.

2. Background

In typical severe thunderstorms, the equilibrium level (EL) temperature is close to the tropopause temperature (Spayd and Scofield 1983, Scofield et al. 1980). In these types of thunderstorms, strong updrafts penetrate several kilometers above the freezing level and the corresponding infrared (IR) satellite imagery reveals cold-topped clouds which are approximately -60°C to -70°C. In addition, the maximum reflectivity is commonly greater than 60 dBZ in severe thunderstorms because of the presence of hail. Unlike severe thunderstorms, the EL associated with "warm-topped" storms is below the tropopause, resulting in a shallower storm height and consequently a warmer IR temperature. One identifying characteristic of LEC storms is that they are warm-topped on IR imagery. Updrafts associated with warm-topped clouds are weaker when compared to updrafts in cold-topped storms due to stronger buoyancy in storms with cold cloud tops. LEC storms do not produce hail because much of the precipitation growth is in the above-freezing portion of the cloud. Maximum reflectivity values of such storms are generally lower than 55 dBZ (Caracena et al. 1979; Baeck and Smith 1998).

Because of the lack of hail production, there is also a dearth of lightning associated with LEC storms. Tall thunderstorms extending well above the freezing level and containing large amounts of ice include strong updrafts, resulting in powerful charge separation within the storm cloud. Small ice particles containing positive charge are forced to rise to the upper portion of the storm, while larger, heavier ice particles containing negative charge fall to the bottom of the cloud (Fleagle and Businger 1980).

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Fig. 1(b).

Because of the lack of ice, this process does not occur frequently in a LEC storm. Some LEC cases have had no lightning observations while others will have less than 20 cloud-to-ground (CG) strikes (Petersen et al. 1999).

LEC storms can have rain-rates as high as 200 mm h⁻¹ while severe storms generally have peak rainfall rates that are less intense (Kelsch 2003). Since, LEC storms tend to occur in a moist environment, with lapse rates closer to the moist adiabatic rate than the dry adiabatic rate, updrafts are weaker than in severe convective cells. However, when LEC storms form at the intersection of strong low-level flow and a meteorological or topographic boundary, enhanced low-level precipitation growth can lead to anomalously intense rainfall. LEC storms typically occur in a moist, low-shear environment that favors warm rain processes (the collision-coalescence process; Rogers and Yao 1991) while typical thunderstorms generate rain by the Bergeron process, which involves ice crystals (Rogers and Yao 1991). The warm rain process is much more efficient at producing precipitation than the cold rain process (Rogers and Yau 1991; Young 1993; Lamb 2001).

Storms with warm rain characteristics typically

form in maritime tropical air and have an abundance of relatively small drops. In these warm rain situations, the tropical Z-R relationship, Z=250R^{1.2}, will probably produce more accurate rainfall estimates than the standard Z-R relationship (Kelsch 2003, Baeck and Smith 1998). Figure 1 shows the 3-hour accumulation from the KICT radar as of 0100 UTC 31 August 2003 derived from both Z-R relationships. Instead of 2-3 inches in 3 hours, the tropical Z-R suggests 4-6 inches, which is more consistent with local gauge reports.

Precipitation efficiency (PE) has been defined by Doswell et al. (1996) as the ratio of the mass of water falling as precipitation to the influx of water vapor mass into the cloud. Thus, PE is defined as

$$PE = \frac{\overline{m_p}}{m_i} \tag{1}$$

where m_p is the mass of water falling as precipitation, and m_i is the mass of the cloud's water vapor influx. The value of PE, which can be affected by many parameters can be used by forecasters to determine the potential for a storm's efficiency. Not all of the water vapor influx into the cloud will fall to the surface as precipitation. Factors affecting

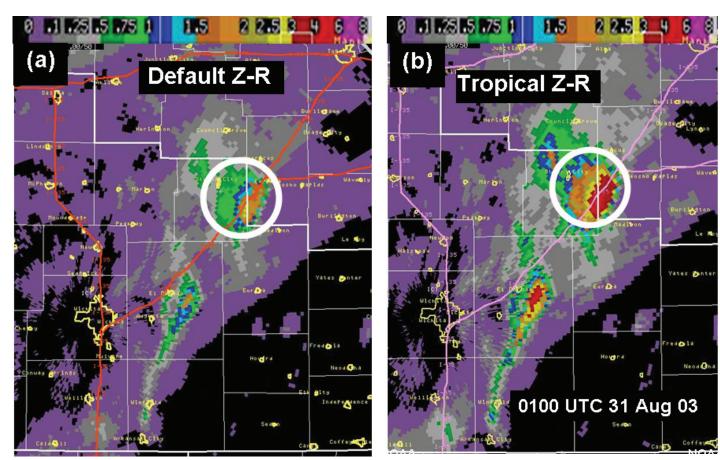


Fig. 1. WSR-88D storm total precipitation (inches; STP) from Wichita, KS for the 30-31 August 2003 heavy rain event using the (a) default Z-R relationship, (b) tropical Z-R relationship.

Fig. 1(a).

PE have been documented by Fankhauser (1988), Doswell et al. (1996), Davis (2001), and Market et al. (2003) and include:

- Warm cloud depth (WCD)
- Cloud base height
- Relative humidity
- Sub-cloud relative humidity
- Updraft strength (Convective Available Potential Energy - CAPE)
- Vertical wind shear.

It is not surprising that when the cloud base height is low and the sub-cloud relative humidity is high, PE is increased. This implies that there will be less entrainment of dry air into the storm, therefore, increased PE. Vertical wind shear at the top of the cloud will transport condensate away from the cell, thus decreasing PE. In addition, some of the droplets will be detrained out of the storm as they rise in the updraft or evaporate as they fall to the surface.

Moisture flux convergence (MFC) has been shown to be a useful parameter in forecasting local thunderstorm formation. However, it can only be used as a short-term predictor of convection and is most useful within a few hours of storm development (Moore and Murray 1982). MFC is defined as:

$$\underbrace{\stackrel{MFC}{\frown \mathbf{\nabla} \cdot qV} = \underbrace{\stackrel{Term \, \mathbf{1}}{\frown q \, \mathbf{\nabla} \cdot V} - \underbrace{\stackrel{Term \, \mathbf{2}}{V \cdot \nabla q}}_{(2)}$$

where *q* is the specific humidity, and *V* is the total wind. *Term 1* is the convergence term and *Term 2* is the advection term (Moore and Murray 1982). The MFC values obtained from (2) should be used in conjunction with other parameters such as stability (Moore and Murray 1982; Banacos and Schultz 2005).

It can be problematic to use only MFC for forecasting where convection will develop. Elevated thunderstorm initiation is typically displaced from the location of maximum surface MFC. Furthermore, the vertical motion associated with surface MFC may be capped, thus preventing convection (Banacos and Schultz 2005). A lack of surface data precludes an accurate representation of MFC. Since MFC is greatly influenced by horizontal mass convergence, Banacos and Schultz (2005) suggested that horizontal mass convergence may be a better-quality field to evaluate by itself or in comparison with the MFC field. Also, horizontal mass convergence occurs in a three dimensional space; therefore evaluating mean MFC through a layer can be a better indicator of forcing for convective initiation than MFC at a single level (Banacos and Schultz 2005). Given the above limitations, other moisture parameters such as precipitable water, and forcing dynamics such as frontogenesis (Petterssen 1936) will also be used to describe the forcing for thunderstorm

formation in this paper.

Flash flooding is also closely tied to the characteristics of the basin in which the rainfall occurs. Severe flash floods typically occur in basins with less than 30 square miles of drainage area, and many are less than 15 square miles in area (Kelsch 2002). Specific thresholds for the amount or intensity of rainfall, or the drainage characteristics of the basin are difficult to define. Flash floods are storm-scale events that occur when the precipitation rate is too great for the basin to accommodate. The amount and intensity of precipitation needed to cause a flash flood depends on basin, soil, and land use characteristics. In almost all cases, human activity increases the runoff efficiency of a basin (Fig. 2). Even in rural and suburban areas, a raised roadbed across a natural drainage can become the local focus for a flash flood when the natural flow is blocked or constricted.

A basin is much more prone to flash flooding when enveloped by the area covered by the intense rainfall, or the wet footprint of a storm complex (Kelsch 2003). LEC storms tend to have a larger wet footprint and slower movement than their severe weather counterparts (Kelsch 2003). Thus, a small drainage basin is more likely to be completely covered by heavy rain over an extended period with regenerative LEC storms. This can greatly increase the flash flood risk, especially in basins where natural hydrologic processes such as percolation have been altered.



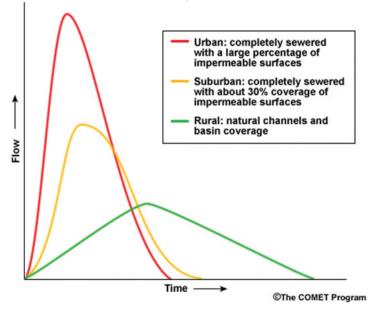


Fig. 2. Schematic hydrographs resulting from equivalent rainfall in hypothetical, similarly sized urban, suburban, and rural basins (from http://www.meted.ucar.edu/hydro/basic/FlashFlood).

3. Event Analysis

The 30 August 2003 storm formed about 12 miles west of Emporia, Kansas at about 2242 UTC. This LEC storm reached peak intensity at 0035 UTC 31 August 2003 with maximum reflectivity values between 50 and 55 dBZ. The location of the LEC storm at peak intensity is shown in Fig. 3. The reflectivity cross-section indicated by the thin, white line is shown in Fig. 4. The 50 dBZ reflectivity extended to a height of 6 km at 0035 UTC, the time of peak intensity. It was determined from the radar imagery that the LEC storm moved to the northeast at 4.6 m s⁻¹, an extremely slow storm movement which contributed to the devastating amount of rainfall. Stratiform precipitation surrounded the storm for its entire lifetime. The LEC storm dissipated at around 0130 UTC about 43 km from its initiation site.

An examination of the Geostationary Operational Environmental Satellite (GOES)-IR satellite imagery at 0045 UTC 31 August 2003 (Fig. 5) revealed that the LEC storm coincided with warm cloud-top temperatures between -30°C and -40°C during its peak intensity. These temperatures corresponded to pressures near 350 hPa. This image was taken 10 minutes after the maximum intensity of the LEC. To the south of the LEC storm in Oklahoma and Texas, there were colder cloud-top temperatures (-60°C and -80°C) associated with thunderstorms that produced high winds, copious lightning, and hail at the time of the LEC storm.

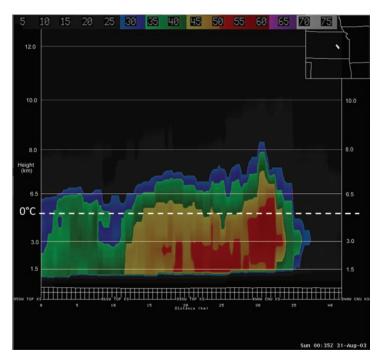


Fig. 4. KTWX WSR-88D cross-section at 0035 UTC 31 August 2003. Reflectivity values greater than 50 dBZ are shaded in red.



Fig. 3. KTWX 0.5° WSR-88D radar reflectivity at 0035 UTC 31 August 2003. The thick line through the LEC storm indicates the orientation of the cross-section shown in Figure 4. Red lines indicate CWA borders.

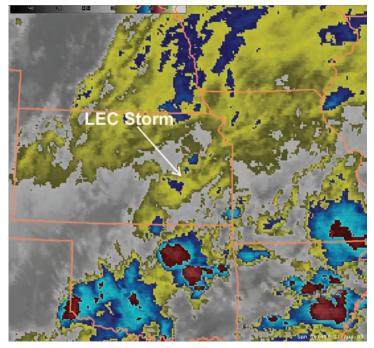


Fig. 5. Enhanced GOES-IR satellite imagery for 0045 UTC 31 August 2003. The location of the LEC storm is indicated by the white arrow.

a. Forcing analysis

Surface observations at 0000 UTC 31 August 2003 were analyzed (Fig. 6). A weak cyclonic circulation in northern Oklahoma was associated with a wave of low pressure on a quasi-stationary frontal zone oriented northeast-southwest and extending from southwest Texas to north-central Oklahoma. From north-central Oklahoma. the quasi-stationary front was east-west oriented extending to Tennessee. There was also an inverted trough extending northeastward from the low pressure center through west-central Missouri. At this time, a large area of precipitation existed across most of eastern Kansas, north of the inverted trough. Both light and heavy rain was reported within this area. In addition, isolated thunderstorms were observed in Texas south of the quasistationary front, which resulted in the development of an outflow boundary extending from the Oklahoma-Texas border through southwest Texas.

An analysis of the 300 hPa winds at 2300 UTC 30 August 2003 (Fig. 7a) using the Rapid Update Cycle II (RUC-II) model (Benjamin et al. 1998) revealed an upper-level jet streak of 61.7 m s⁻¹ (120 knots) in Canada, northeast of Michigan. Upper-level divergence over the Central Plains developed in the right entrance region

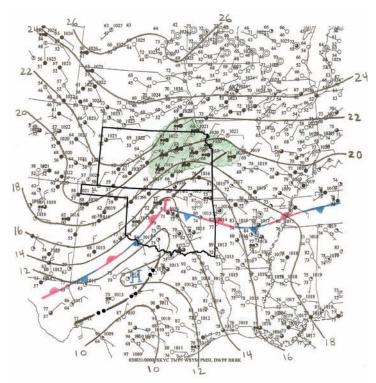


Fig. 6. Surface analysis for 0000 UTC 31 August 2003. Station data are plotted according to standard station model and fronts are analyzed using standard symbols. Solid lines are isobars in hPa, thick dashed lines denote troughs, thick dash-dot-dot lines indicate outflow boundaries, and green scalloped area indicates rain. Kansas and Oklahoma have been outlined for reference.

of this jet in the vicinity of the Kansas storm, and also downstream from a trough over the central Rockies (Fig. 7b). An area of divergence extended from central Kansas through southern Iowa and western Illinois. The low level

Fig. 7(a).

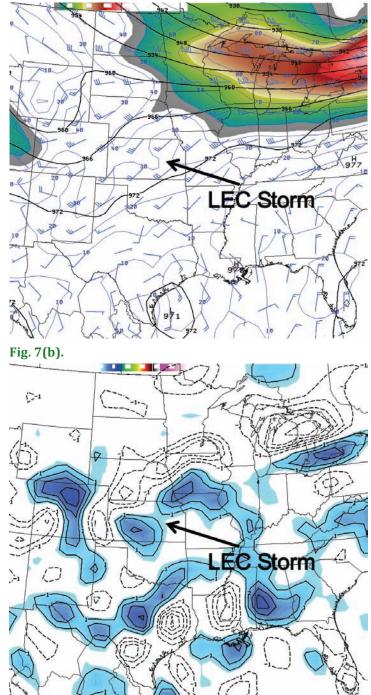


Fig. 7. RUC-II initialization displaying the 300 hPa level chart for 2300 UTC 30 August 2003. The location of the LEC storm is indicated by the black arrow. (a) Solid blue lines are isotachs (every 10 knots). Thick black lines are heights (every 6 dm). Wind speeds greater than 45 knots are shaded. (b) Positive values of divergence are shaded $(x10^{-5} s^{-1})$ and are contoured with solid black lines. Negative values are contoured with dashed black lines.

branch of the circulation associated with the upper level divergence pattern manifested itself as enhanced easterly low level flow over Kansas.

A RUC-II analysis of 500 hPa heights, vorticity, and wind at 1800 UTC (Fig. 8a), showed a weak height gradient in the 500 hPa height field and corresponding cyclonic

Fig. 8(a).

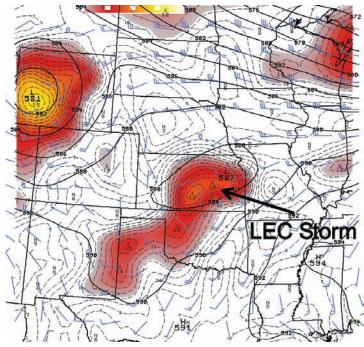


Fig. 8(b).

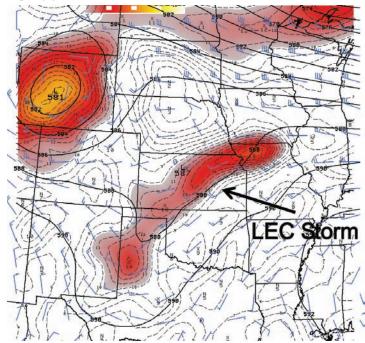


Fig. 8. RUC-II initialization displaying the 500 hPa level chart for (a) 1800 UTC 30 August 2003 and (b) 2300 UTC 30 August 2003 forecast from the 1800 UTC RUC-II. Dashed black lines indicate vorticity (every $1 \times 10^{-5} \text{ s}^{-1}$) and values greater than 10 $\times 10^{-5} \text{ s}^{-1}$ are shaded. Thick black lines are heights (every 2 dm). The location of the LEC storm is indicated by the black arrow.

circulation over central Kansas. A vorticity maximum of $19 \ge 10^{-5} \ s^{-1}$ is seen near this weakness just to the west of the development of the LEC storm. Therefore, positive vorticity advection was occurring over eastern Kansas and implied that upward motion was favored downstream from this 500 hPa vorticity maxima. Fig. 8b displays the same fields at 2300 UTC from the 1800 UTC run of the RUC-II model. The vorticity field became elongated, stretching from southeastern New Mexico through southern Iowa.

There was a strong easterly low-level jet of 15.4 m s⁻¹ (30 knots; Fig. 9) in the vicinity of the LEC storm with a maximum over western Kansas of 20.6 m s⁻¹ (40 knots) as seen from an 850 hPa RUC-II analysis at 2300 UTC. However, slightly to the south, there was a light wind of 7.7 m s⁻¹ (15 knots) from the southeast. This flow pattern at 850 hPa set up a directional convergence zone where the LEC storm formed (Fig. 10a). Figure 10a displays convergence from the 1800 UTC run of the RUC-II model while Fig. 10b shows the 2300 UTC forecast from the same model run. A positive convergence maximum developed and persisted over the area of LEC storm development increasing in magnitude from 1800-2300 UTC with a maximum value of $-3.4 \times 10^{-5} \text{ s}^{-1}$ (Fig. 11). In addition, there was an area of frontogenesis maximized near the storm initiation site due to a frontal zone near 850 hPa indicating low-level warm advection (Fig. 12). The strong convergence values seen in Figs. 10a-b combined with the frontal zone at 850 hPa to enhance the frontogenesis near

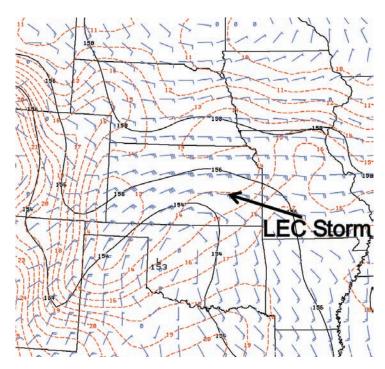


Fig. 9. RUC-II initialization displaying the 850 hPa level chart for 2300 UTC 30 August 2003. Dashed red lines are temperature (every 1°C). Thick black lines are heights (every 2 dm). Wind barbs are in blue (every 5 knots).

the LEC storm location. Values of frontogenesis were on the order of 10.0 K $m^{\text{-}1}$ $10^{10}\,\text{s}^{\text{-}1}.$

The RUC-II model developed precipitation (not shown) across much of eastern Kansas, but model convective precipitation (not shown) was located in close proximity to the LEC storm across southeastern Kansas. The convective

Fig. 10(a).

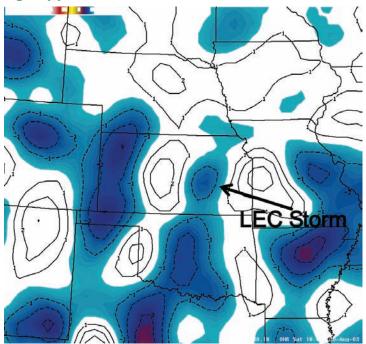


Fig. 10(b).

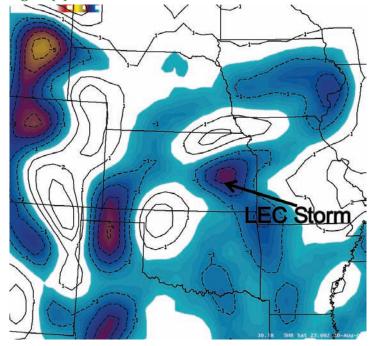


Fig. 10. (a) RUC-II initialization displaying the 850 hPa level chart for 1800 UTC 30 August 2003. Negative values of divergence $(x10^{-5} s^{-1})$ are shaded and are contoured with dashed black lines. Positive values are contoured with solid black lines. (b) Same as (a), except for 2300 UTC 30 August 2003 forecast from the 1800 UTC RUC-II.

precipitation was an indication that convective feedback may have been occurring in the model forecast, which may have altered evolution of the aforementioned 850 hPa parameters. Nevertheless, convergence was present several hours before initiation of the LEC storm indicating that convergence was occurring prior to any convective feedback. Additionally, the model may have under-forecast the strength of the easterly winds and thus the strength of

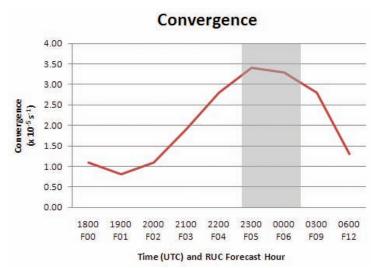


Fig. 11. Graph displaying the hourly surface convergence values $(x10^{-5} \text{ s}^{-1})$ from 1800 UTC 30 August 2003 through 0600 UTC 31 August 2003 at the LEC storm initiation site. Data is from the 1800 UTC 30 August 2003 RUC-II model run. The gray area indicates the time period of the storm lifecycle.

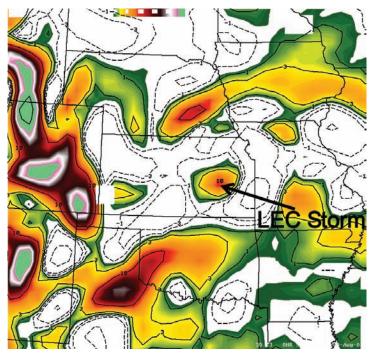


Fig. 12. RUC-II initialization displaying the 850 hPa level chart for 2300 UTC 30 August 2003. Positive values of frontogenesis (K m⁻¹ 10^{10} s⁻¹) are shaded and are contoured with solid black lines. Negative values are contoured with dashed black lines. The location of the LEC storm is indicated by the black arrow.

the low-level convergence as indicated by observational analysis. The KTWX (Topeka 88D) VAD wind profile at 2300 UTC (not shown) showed 850 hPa winds at 20.6 m s⁻¹ (40 knots) while the RUC indicated winds of 15.4 m s⁻¹ (30 knots) slightly more to the southeast.

In summary, large scale lift was present as implied by positive vorticity advection, low-level warm air advection and strong convergence along the frontal boundary. The synoptic environment was similar to those of "frontal" flash flood patterns identified by Maddox et al. (1979), except that the Kansas Turnpike event occurred closer to the 500 hPa trough than suggested by the schematics of Maddox et al. (1979).

b. Moisture analysis

The MFC was calculated at the surface using surface observations and within the 950-850 hPa layer using the RUC-II analysis. At 1800 UTC, a linear band of MFC at the surface (Fig. 13a) and in the 950-850 hPa layer (Fig. 13b) was evident. The deep layer (950-850 hPa) MFC was 1.6 g kg⁻¹ h⁻¹ which was most likely due to convergence associated with the strong easterly 850 hPa winds shown earlier, in close proximity to a southeasterly flow, just to the south. Surface MFC values were on the order of 1.5 g kg⁻¹ h⁻¹. A graph displaying the evolution of the surface and the 950-850 hPa layer average MFC, at the location of storm initiation, is shown in Fig. 14. The gray area indicates the time period of the storm lifecycle. MFC values increased in the hours leading up to the peak of the storm at 0035 UTC 31 August 2003 then decreased after the storm dissipated as seen in the graph. The MFC spike at the time of maximum storm intensity indicated

Fig. 13(a).



possible convective feedback occurring in the model. The MFC values also reveal that the area over which the LEC formed was continually being supplied with moisture. For the entire time period of the event, the surface MFC was located along and to the southwest of the inverted surface trough.

c. Stability and wind shear analysis

Model soundings at 1800 UTC 30 August 2003 were analyzed using the RUC-II analysis for two locations: upwind (south) from the storm (Fig. 15) and at the storm location (not shown). The upwind location was about 110 km south-southeast of the LEC storm's location, which was determined to be representative of the storm inflow based on examination of the 850-300 hPa wind (not shown). The upwind sounding showed a small amount of CAPE with a value of 163 J kg⁻¹ and an LI of -2°C. The shape of the CAPE was "tall and skinny" since the positive (gray) area was distributed over a larger depth of the sounding. Additionally, the CAPE was nearly evenly distributed from the LFC to the EL. This is in contrast to "short and fat" CAPE in which most of the positive area is in the lower troposphere and is often associated with severe storms. The EL was at a height of 350 hPa while the tropopause height was at 150 hPa (as determined by the temperature profile). Normalized CAPE (NCAPE), defined as CAPE divided by the depth of the layer where CAPE is present, was calculated. NCAPE can distinguish between tall and skinny and short and fat CAPE profiles with values less than 0.1 m s⁻² indicating *tall and skinny* profiles (Blanchard 1998; Storm Prediction Center, cited 2009). Values of NCAPE for this sounding were 0.021 m s⁻². Easterly low



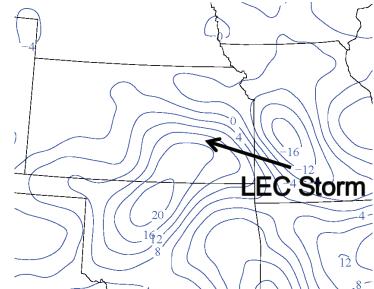


Fig. 13. (a) Observational analysis for 1800 UTC 30 August 2003 displaying surface MFC (x10 g kg⁻¹ h⁻¹), (b) RUC-II initialization at 1800 UTC 30 August 2003 displaying 950-850 hPa average MFC (x10 g kg⁻¹ h⁻¹).

level winds were mostly confined to the boundary layer as the winds veered with height (indicating warm advection); however, there was weak speed shear with height. Wind speeds within the positive CAPE area ranged between 7.7 m s⁻¹ (15 knots) and 12.9 m s⁻¹ (25 knots).

The sounding taken at the storm location at 1800 UTC (not shown) showed mostly weaker instability parameters

Moisture Flux Convergence

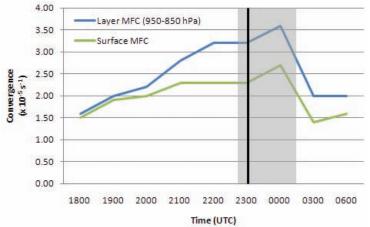


Fig. 14. Graph displaying the hourly surface and 950-850 hPa layer MFC values (x10 g kg⁻¹ h⁻¹) from 1800 UTC 30 August 2003 through 0600 UTC 31 August 2003 at the LEC storm initiation site. The gray area indicates the time period of the storm lifecycle. The vertical, solid black line indicates when convective precipitation was developed in the RUC-II model.

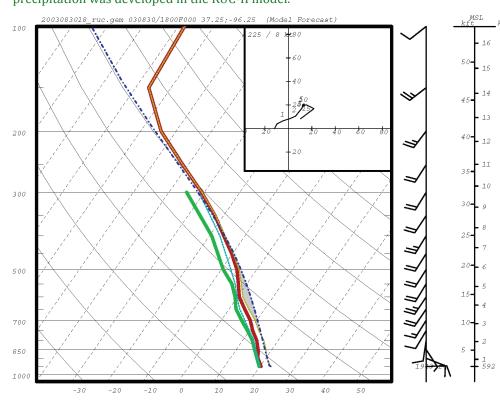


Fig. 15. RUC-II initialization sounding diagram 110 km upwind (south-southeast) for 1800 UTC 31 August 2003. The vertical scale on the left is in hPa and the horizontal scale is in °C. The red line is temperature while the green line is the dew point.

than the upwind sounding. The CAPE decreased to 30 J kg⁻¹ and was also determined to be *tall and skinny* since the NCAPE was determined to be 0.007 m s⁻². The easterly wind continued to be confined to the boundary layer as the wind veered with height. There was speed shear from the surface to 850 hPa where stronger easterly winds were sustained. The profiler data (Fig. 16) from Neodesha, Kansas (about 120 km south-southeast of the LEC storm) confirms the weak speed and directional shear seen in the model wind profiles above the low-level frontal zone. Low level speed shear increased near the storm location than seen in the profiler data due to the stronger winds at 850 hPa. The oval in Fig. 16 indicates the time period of interest where the wind values range from 2.6 m s⁻¹ (5 knots) to 10.3 m s⁻¹ (20 knots). Thus, there was weak speed and directional wind shear from the LCL to the freezing level (hereafter referred to as the warm-cloud depth, or WCD).

The freezing level in the storm sounding was just over 4.0 km at 525 hPa. What sets this storm sounding apart from the upwind sounding is the fact that the EL was at a height of 480 hPa while the tropopause level was at 150 hPa (as determined by the temperature profile). This low EL height provided an upper level *lid* on the convection during the time of this storm. Average winds in this sounding from the LCL to the EL were calculated to be 7.2 m s⁻¹ (14 knots). It was this weak flow in the cloud-bearing layer that caused the slow storm movement.

The PW for this event was around 1.90 in (as determined from the upwind sounding), which is about 120% of normal (not shown). Despite only being slightly above normal, the amount of PW in this case is above the heavy rain threshold found in other studies (e.g., Junker et al. 1999) where values often exceed 1.5 in. The sub-cloud mean RH (not shown) was greater than 85% over the area of interest (based on observational analysis) while the RUC-II analysis at 0000 UTC 31 August 2003 showed values greater than 95% in the same area. The combination of high RH values and surrounding light to moderate stratiform precipitation contributed to little evaporation taking place in the sub-cloud layer. Surface observations at KEMP (Emporia, Kansas) (not shown) indicated that the cloud bases were as low as 600 feet above ground level (AGL) at the time closest to maximum intensity of

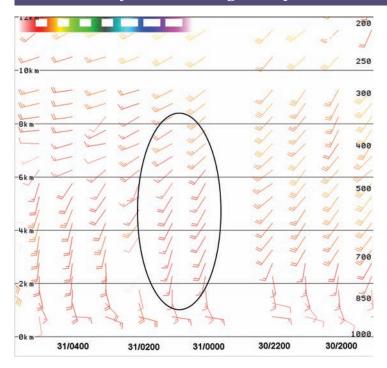


Fig. 16. Profiler data from Neodesha, Kansas from 2000 UTC 30 August 2003 through 0500 UTC 31 August 2003. The vertical axis on the left represents height (m) while the oval represents the area of height and time of interest.

the LEC and averaged around 800 feet AGL over the entire event. These low cloud bases allowed little time for the rain to evaporate between the base of the cloud and the surface. It also should be noted that the WCD (not shown) approached 4.1 km (based on observational and RUC-II analyses), which is a very large depth. In addition to the radar data, this is also an indication that this was a LEC storm. Surface relative humidity near 100%, the MFC, high sub-cloud mean RH, and a deep WCD all indicated that the atmosphere where the LEC storm formed was extremely moist.

4. Hydrological Issues Related to this Event

Interstate Highway 35, the Kansas Turnpike, lies on top of a raised roadbed as it cuts across the Jacob Creek drainage basin. Jacob Creek must pass through a culvert as it flows from the upstream (east) side of the highway to the downstream side. The white circle in Fig. 17 indicates that approximately two square miles of drainage area was upstream (east) of the interstate highway. This small catchment area received as much as six inches of rainfall in a few hours (Fig. 1b). Because 1.75 inches (445 mm) of rain fell during the 24 hours preceding the LEC storm event, surface runoff was increased by nearly saturated soil.

By 0130 UTC, the volume of water moving through Jacob Creek became too great for the culvert under the high-

way and water began to pond upstream of the highway (Fig. 18a-b). By 0200 UTC, water had backed up onto the highway and was partially held back by the concrete barriers separating the northbound and southbound lanes (Fig. 18c). Shortly after 0200 UTC, the water reached the top of the barriers and the highway became impassable (Fig. 18d). At this point many vehicles were abandoned, although the occupants of at least one vehicle remained. They felt relatively safe because their vehicle was banked up against the heavy barriers in the highway median. At about 0230 UTC, a dozen of the concrete barriers broke free from the force of the water and vehicles, releasing a surge of water downstream (Fig. 18e). Seven vehicles were carried up to 1.5 miles from the interstate. Six fatalities occurred, including all five occupants of one vehicle that had stopped next to the concrete barrier on the upstream side (northeast bound lanes) of the interstate. This incident shows the great sensitivity a drainage basin may have to repeated bursts of intense rainfall, nearly saturated soil, and the impact of unnatural structures in the floodplain.

5. Comparison to the Fort Collins, CO Flash Flood

A classic example of a LEC storm producing flash flooding occurred in Fort Collins, CO on 28 July 1997. In that storm, over 10 inches (250 mm) of rain fell in less than six hours resulting in five fatalities (Kelsch 1998; Petersen et al. 1999). Boundary layer flow from the east advected high equivalent potential temperatures (θ_e) into Colorado. The low-level winds were oriented perpendicular to the Colorado Front Range, providing the lifting needed for the unstable air to reach the level of free convection

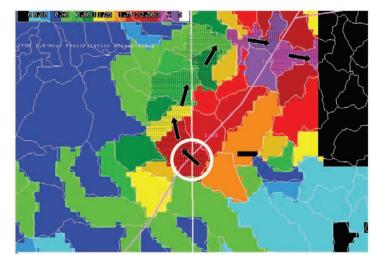


Fig. 17. FFMP image of 3-h basin accumulation as of 0148 UTC 31 August 2003. The intersection of Jacob Creek and I-35 is circled. The upstream area is to the right (east) of the Interstate and the arrows show the downstream direction.

Fig. 18(a).



Fig. 18(c).



Fig. 18(b).



Fig. 18(d).



Fig. 18(e).

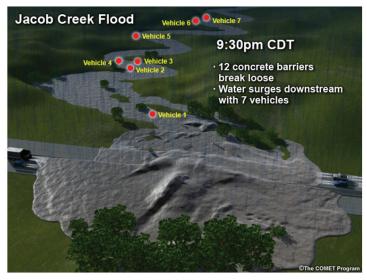


Fig. 18. Visual representation of the Jacob Creek flood from

- (a) 0100-0130 UTC (yellow arrow indicates location of upstream culvert)
- (b) 0130-0200 UTC
- (c) 0200 UTC
- (d) 0200-0229 UTC
- (e) 0230 UTC

Hydrometeorological Aspects of the Kansas Turnpike Flash Flood of 30-31 August 2003

(LFC). Satellite imagery indicated that the Fort Collins storm complex was warm topped (generally warmer than -40°C). In addition, the storm complex had no hail, weak mid-tropospheric winds, no tornadoes or funnel clouds, and produced little lightning. These factors suggest that the warm-rain process was the likely mechanism for precipitation growth in this storm (Kelsch 1998).

The environment associated with this storm, as indicated by a local skew-t plot 55 miles to the south in Denver, CO (not shown), was not typical of environments associated with significant severe weather outbreaks. Characteristics from the 0000 UTC, 29 July 2007 Denver, CO sounding included the following:

- relatively small CAPE (868 J kg⁻¹),
- high freezing level (3.6 km AGL),
- moderate LI of -2.8°C,
- LCL at 764 hPa (700 m AGL) with a LFC at 690 hPa while the pressure at the surface was 840 hPa,
- large precipitable water (PW) (1.3 in, about 179% of normal),
- light to moderate mid-tropospheric winds (10 to 20 knots) from the southwest, and
- minimal CG lightning (0.5 flashes per minute; Petersen et al. 1999).

The Fort Collins flash flood showed similar characteristics to the Kansas Turnpike flash flood. Table 1 summarizes a brief comparison of meteorological parameters between the Fort Collins and Kansas Turnpike flash flood. The synoptic patterns were quite different in these two cases. In the Fort Collins flash flood, the region was under the influence of weak south to southwesterly flow aloft in association with a negatively tilted 500 hPa ridge. The Kansas Turnpike case was characterized by a cut off low to the west of the area. However in both cases, the flood event was located north of a surface frontal boundary. Despite having higher moisture content, the Kansas Turnpike case contained precipitable water values only 120% of normal while the Fort Collins event showed 179% of normal. In addition, there was more instability in

the Denver sounding when compared to the model RUC-II sounding from the Kansas Turnpike case.

One important difference in these two cases was the hydrological response. Topography was a main factor in the Fort Collins flash flood. The Fort Collins area had already received heavy rainfall the day before which only exacerbated the runoff flowing down from the mountains. Spring Creek was the main drainage area within the city of Fort Collins and several retention areas upstream of Fort Collins along this creek filled to capacity and began to overflow. In addition, the complex of storms moved to the north-northeast following the main drainage area of Spring Creek. The flash flood in the Kansas Turnpike case was caused by the raised roadbed of the interstate, a manmade feature. The culvert underneath the highway was unable to accommodate the amount of water flowing through the basin which resulted in the powerful flow of water over the interstate. Flash flood events and in particular, LEC storms, are not all similar as seen in these events. Both meteorological and hydrological differences can exist but the end result can be the same with devastating flash floods, resulting in property losses and deaths.

6. Conclusions

The heavy rainfall and flash flooding that occurred on the evening of 30 August 2003 over the Kansas Turnpike was caused by a LEC storm that formed near Emporia, Kansas. This study was conducted to determine what caused this LEC storm to form and assess its hydrological impacts. These characteristics can be useful to operational forecasters in better anticipating LEC storms because of their subtle heavy rain signatures.

Large-scale lift was strong, as indicated by the 300 hPa wind and divergence analysis. A region of upper-level divergence was located across central Kansas through southern Iowa and western Illinois associated with the upper level jet to the east and an upper level trough to the west. The 500 hPa analysis showed a weak cyclonic circulation and a vorticity maximum just to the west of

Meteorological Parameter	Fort Collins, CO	Kansas Turnpike
САРЕ	868 J kg-1	316 J kg-1
Freezing level	3.6 km AGL	4.2 km AGL
LI	-2.8 °C	-2.0 °C
LCL	764 hPa (700 m AGL)	911 hPa (365 m AGL)
PW	3.4 cm (179% of normal)	4.8 cm (120% of normal)

Table 1. A comparison of meteorological parameters between the Fort Collins, CO and Kansas Turnpike flashfloods.

the LEC storm. There was warm air advection on the 850 hPa wind plot with veering winds in the boundary layer which allowed for an influx of moisture. Additionally, light mid-tropospheric winds limited the amount of dry air entrainment into the LEC storm which increased the storm's PE. A maximum of frontogenesis along a frontal boundary and mass convergence at 850 hPa also assisted in initiating the storm.

Moisture flux convergence also played a role in initiating and sustaining the LEC storm. There were strong values of MFC both at the surface and aloft. The shape and amount of CAPE also played an important role in the development of the LEC storm. This case contained *thin or skinny* CAPE which limited extensive vertical development of this LEC storm. In addition, the amount of CAPE was small as indicated by the model sounding diagrams.

This LEC storm was extremely precipitation-efficient. Many factors were uncovered that contributed to the high PE of this LEC storm. Soundings and surface observations indicated an environment favorable for low cloud bases. This, in combination with the high RH in middle levels and the sub-cloud layer, contributed to high PE. The large WCDs also indicated that there was a large portion of the cloud in which the warm-rain process was occurring. The vertical wind profile also contributed to the high PE of LEC storms. The winds were observed to be light and unidirectional above the low-level frontal zone. This means the cloud was more upright and less rain evaporated before reaching the ground. A slow storm motion was also an important contributing factor in the extreme amount of rainfall in a short amount of time.

The hydrologic response in this case was also quite remarkable. The repeated bursts of intense rainfall occurred in an area upstream of the interstate highway that drained into a basin the size of about only two square miles. The small drainage area and the preexisting high soil moisture overwhelmed the culvert that would normally accommodate Jacob Creek as it flows downstream and under the highway. The natural flow of water was blocked by the raised roadbed of the highway and thus the roadway became the focus for impounded water that was subsequently released in a sudden and dramatic surge.

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