Extreme Events Across New Mexico During the 2018 North American Monsoon

Jorge Torres*

KOB-TV, Albuquerque, New Mexico

Daniel Pagliaro

Pagcore Solutions LLC, Albuquerque, New Mexico

**Corresponding author address:* Jorge Torres, KOB-TV, 4 Broadcast Plaza SW, Albuquerque, NM 87104.

E-mail: jct_02@msn.com

ABSTRACT

The 2018 North American Monsoon season was characterized by localized severe storm and flash flood events in New Mexico. Notable events included flash flooding in Belen and parts of Rio Rancho on 5 July; inundation of San Antonio on 15 July; the 1,000-year flood event in and around Santa Fe on 23 July; and a severe hail event in the Albuquerque area on 30 July. Analysis of these events was conducted to better understand the synoptic, mesoscale, and local conditions that contributed to their occurrence with the goal of helping forecasters better predict similar monsoon-driven severe storm and flash flood events in the future. Additionally, analysis of 464 reporting sites (to include 12 ASOS/AWOS, 105 COOP, and 347 CoCoRaHS) across New Mexico revealed that most of the state experienced below average rainfall, with pockets of above average rainfall along and to the east of the central mountain chain during the 2018 North American Monsoon season. The rainfall distribution pattern developed as the prevalent monsoon pattern evolved from the Type II ”reverse” monsoon pattern in July and early August to the “classic” Type I pattern in late August. The likely causes of the three flash flooding events in July 2018 stem from orographic uplift and outflow boundary interactions, and the diversion of arroyos and streams from their natural watercourses by human development. An amplified jet stream with embedded shortwave troughs that skirt across northern New Mexico is favored for severe thunderstorm activity across the state during the North American Monsoon season.

1. Introduction

Severe thunderstorms and flash flooding caused localized damage across New Mexico during the 2018 North American Monsoon season. Several flash flooding events resulted in extensive damage in the Middle Rio Grande Valley between 5 July 2018 and 30 July 2018, including the 1,000-year flood event in the Santa Fe area on 23 July 2018; flash flooding and mudslides near Rio Rancho and Belen on 5 July 2018 and San Antonio on 16 July 2018; and a severe hail event that struck Albuquerque on 30 July 2018.

Previous studies of the North American Monsoon have largely focused on severe weather and flash flood impacts and attempts to improve forecasting monsoon events in Arizona and northwestern Mexico (Gochis et al. 2004; Gutzler et al. 2005; Maddox et al. 1995). Published research on the North American Monsoon's impacts in New Mexico is much more limited, with some research into local-scale monsoon behavior around the Los Alamos area (Bowen 1996), and synoptic-scale research encompassing the entirety of the American Southwest and northwestern Mexico (Adams and Comrie 1997). This paper attempts to associate rainfall patterns and major severe thunderstorm events across New Mexico to known synoptic-scale North American Monsoon regimes to help forecasters more accurately predict the characteristics of an upcoming monsoon season. Additionally, associating the synoptic-scale regime to major severe weather and flash flood events will help forecasters improve the day-to-day prediction of such events in New Mexico through pattern recognition.

2. Background

a. New Mexico geography

New Mexico's geography (Fig. 1) varies from the relatively flat plains in the east to the rugged mountains and plateaus in the central and western portions of the state. The lowest elevations are found along the lower Pecos River Valley in southeast New Mexico, while the highest elevations are located in the Sangre de Cristo Mountains of north-central New Mexico.

The western third of New Mexico is defined by the Colorado Plateau and the San Juan River Valley in the northwestern corner of the state, with mountainous terrain consisting of pine and juniper forests over the west-central, the basin-and-range province over the southwest corner and the New Mexico Bootheel. The Continental Divide runs north-to-south through the western part of New Mexico, from the Colorado border north of Chama, southwestward to near Gallup, and then through the Datil Mountains and Gila Wilderness to near Silver City, before reaching the Mexican Border southwest of Deming. Average elevations range from around 1,200 to 1,600 m in the San Juan Valley and southwest deserts to 2,100 m over the Northwest Plateau, to over 2,400 m in the Gila Wilderness, with mountain peaks as high as 3,600 m.

The central third of New Mexico is defined by the Rio Grande Valley, which runs north-to-south from the Colorado border north of Taos, to New Mexico's southern border south of Las Cruces. It has an average elevation ranging from 1,200 m in the south to over 1,800 m in the north. Immediately to the west of the Rio Grande Valley and approximately 75 km north of Albuquerque are the Jemez Mountains, which have an average elevation of 2,400 m with the highest peaks approaching 3,600 m. The Tusas Mountains begin north of the confluence of the Chama River and Rio Grande and run northward to west of the Rio Grande, extending into Colorado. To the east of the Rio Grande Valley is the central mountain chain, which consists of the Sangre de

Cristo Mountains in the north, the Sandia and Manzano Mountains in the central region, and the Sacramento Mountains to the south. The average height of these mountain ranges vary from 3,000 m in the Sangre de Cristo range, to 2,300 m in the Sandia and Manzano range, to 2,600 m in the Sacramento Mountains, with the highest peaks ranging from 3,300 m to around 4,000 m in elevation.

The eastern portion of New Mexico is defined by the High Plains, and the eastern foothills of the central mountain chain. The Pecos River Valley runs northwest to southeast from west of Las Vegas, to Santa Rosa and Roswell, before crossing into Texas south of Carlsbad. Average elevation varies from 1,000 m to 1,200 m along the border with Texas to around 2,000 m at the eastern base of the central mountain chain near Raton, Las Vegas, Vaughn, and west of Roswell and Carlsbad.

b. Characteristics of the North American Monsoon

In New Mexico, the North American Monsoon season runs from 15 June to 30 September, and accounts for one-third to one-half of the state's annual precipitation (Douglas et al. 1993; NOAA n.d.).

Multiple papers (Adams and Comrie 1997; Bowen 1996; Douglas et al. 1993; Grantz et al. 2007) point out there are three sources of moisture for the North American Monsoon: the Gulf of Mexico, Pacific Ocean, and Gulf of California. Moisture from the Gulf of Mexico advects northwestward into eastern and central New Mexico due to southerly flow around the western periphery of the Bermuda High. With relatively flat terrain spanning the distance from the Texas Gulf Coast to New Mexico, moisture advection from the Gulf of Mexico encounters relatively little resistance making its way into New Mexico. In contrast, the moisture flow from the Pacific Ocean and Gulf of California is driven by the pressure gradient between the summertime thermal low that develops over the Mojave Desert and high pressure to the south. That pressure gradient creates a low-level jet that advects tropical moisture northward from the Gulf of California and into the southwestern United States (Adams and Comrie 1997; Douglas et al. 1993). The Mogollon Rim of central Arizona and the Continental Divide that runs through far western New Mexico effectively preclude the bulk of the moisture originating from the Pacific Ocean and Gulf of California from penetrating deep into New Mexico (Bowen 1996). Thus, the greatest monsoon influence from the Pacific Ocean and Gulf of California is limited to portions of far western New Mexico that lie to the west of the Continental Divide, while the remainder of the state is mainly influenced by moisture from the Gulf of Mexico (Adams and Comrie 1997).

Previous studies, notably Maddox et al. (1995), have identified four major synoptic-scale patterns over the American Southwest during the North American Monsoon season. The following paragraphs tailor the monsoon pattern types as they apply to New Mexico.

Type I - Southern Plains/Four Corners High

The Type I regime (Fig. 2) represents the ”classic” monsoon pattern over New Mexico. Under the Type I regime, two high centers develop: one over the Southern Plains and a second centered around the Four Corners region (Maddox et al. 1995). Southerly flow between the two high centroids facilitates the northward advection of moisture through central New Mexico. Under this regime, convection typically favors the central mountain chain and Continental Divide. Storms will usually develop over the mountains and move in a northerly direction, with a slight component to the east or west, depending on the exact steering flow. This pattern is also favored for monsoon bursts with prolonged periods of widespread heavy rain that typically occur as easterly waves or the remnants of tropical systems from the Caribbean or Gulf of California are shunted northward across New Mexico between the two high centers.

Type II - Great Basin High

The Type II (Fig. 3) pattern is informally called the ”reverse monsoon” pattern in New Mexico. This pattern features a strong high centroid in the vicinity of the Great Basin (although the high could be situated as far east as the Four Corners), with a deep trough positioned over the Great Plains and Mississippi Valley (Maddox et al. 1995). The prevailing steering flow with the Type II pattern over New Mexico is from the north, with a slight east or west component depending on the exact positioning of the synoptic-scale features. Under this regime, backdoor cold fronts commonly drop southward across the eastern plains of New Mexico, then push westward through the gaps in the central mountain chain before stalling near the Continental Divide. These cold fronts draw Gulf of Mexico moisture westward across the eastern plains, through the gaps of the central mountain chain and into the Rio Grande Valley. Strong easterly winds are usually associated with a frontal passage below the favored mountain gaps that open into the Rio Grande Valley. These easterly gap winds often will suppress major convective activity in the Albuquerque area due to the shadowing effect of downsloping despite the abundance of low-level moisture. Thunderstorms will typically initiate along the Continental Divide, Jemez and Tusas Mountains, and central mountain chain and propagate in a southerly direction toward the adjacent lowlands.

Type III - Trapping High

Under this regime (Fig. 4), a sprawling area of upper-level high pressure is centered directly over New Mexico and Arizona that suppresses moisture intrusions into New Mexico. This leads to mid-level warming temperatures, stronger subsidence, and forces the development of showers and storms to rely heavily on the recycling of low-level moisture already in place. Very light steering flow in this pattern leads to slow storm motions and increases the risk for flash flooding from highly localized, but intense rainfall (Maddox et al. 1995).

Type IV - Transitional

The transitional pattern (Fig. 5) develops when the subtropical high over the Southern Plains is displaced to the south and east in response to an approaching shortwave trough and associated cold front from the west. Moisture flux and convection is consistent with typical pre-frontal precipitation patterns observed elsewhere. A wind shift to the west or northwest and rapid cooling and drying occur following frontal passage (Maddox et al. 1995; NOAA n.d.).

3. Methodology

The objective of this study was to identify rainfall and severe thunderstorm distribution patterns, with respect to the prevailing synoptic-scale pattern. To accomplish this, an empirical analysis of meteorological data collected across New Mexico during the 2018 North American Monsoon season was analyzed. Particular focus was given to four major weather events that resulted in significant property damage. Additionally, available historical monsoon data covering the period from 1988 to 2017 was also analyzed in an attempt to associate the prevailing synoptic pattern to precipitation anomalies and severe thunderstorm activity identified in a particular year. The study covered the North American Monsoon season from 15 June to 30 September, a period of 108 days.

a. Data

Data analyzed during this study included surface and upper-air analysis charts; National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) re-analysis data from 2000 to 2018 (Kalnay et al. 1996); rainfall data from National Weather Service (NWS) Automated Surface Observing System and Automated Weather Observing System (ASOS/AWOS) and Cooperative Observer Program (COOP) sites; rainfall data from the Community Collaborative Rain, Hail and Snow (CoCoRaHS) Network; satellite and NEXRAD radar imagery. Historical precipitation data for NWS surface observation and COOP sites, and NEXRAD radar imagery were obtained from the National Center for Environmental Information (NCEI). Long-term precipitation data was analyzed by using the Applied Climate Information System (ACIS) (Hubbard et al. 2004). Satellite imagery was accessed and analyzed using the NCEI's Global ISCCP B1 Browse System (GIBBS) (Knapp 2008). NEXRAD radar imagery from the three sites in New Mexico (Albuquerque, KABX; Cannon Air Force Base, KFDX; and Holloman Air Force Base, KHDX) and El Paso, Texas (KEPZ) were analyzed using the NCEI's Weather and Environmental Toolkit application. Upper-air soundings from Albuquerque (KABQ) for four major storm events on 5 July, 15-16 July, 23 July, and 30 July were analyzed using the Sounding and Hodograph Analysis and Research Program in Python (SHARPpy) (Blumberg et al. 2017).

Historical precipitation data for the CoCoRaHS network was obtained via the CoCoRaHS website. Precipitation reports were manually validated for each NWS ASOS/AWOS, COOP, and CoCoRaHS site. Sites with less than 90 days of precipitation reports were excluded from further analysis. Sites with 90 to 107 days of precipitation reports were manually analyzed for days on which no reports were recorded versus precipitation reports that span multiple days. Precipitation amounts were estimated at sites on days when no report was submitted by either interpolation of precipitation amounts from nearby sites, or by NEXRAD Storm Total Precipitation estimates for sites in data-sparse locations. Precipitation and anomaly data were plotted using the Quantum Geographic Information System (QGIS) application.

The analysis of rainfall distribution for the 2018 monsoon season included data from 464 NWS ASOS/AWOS, COOP, and CoCoRaHS reporting sites across New Mexico. Of these, 12 were ASOS/AWOS stations, 105 were COOP locations, and 347 were CoCoRaHS sites.

Storm reports from the NWS Storm Prediction Center were also analyzed to characterize the distribution pattern for severe events, and associate severe storm distribution with respect to the prevailing synoptic pattern using storm report and synoptic re-analysis information dating back to 2000.

4. Discussion

a. Evolution of the Synoptic-Scale Pattern

In the early onset of the 2018 North American Monsoon, the 300 hPa high was situated near the Four Corners with periodic fluctuations across the Intermountain West. This ridge allowed surface cold fronts from the Great Plains to propagate westward into New Mexico, which resulted in moisture surges and increased wind shear. This set-up falls in line with the defined Type II or "Great Basin High" (Maddox et al. 1995; Kalnay et al. 1996).

The Type II pattern was dominant from early July through early August. In mid-August, the Great Basin High weakened and a new high centroid developed over Texas. As a result, the Type I pattern became prevalent for the latter half of August (Maddox et al. 1995; Kalnay et al. 1996).

Near the end of August, southwesterly flow strengthened over New Mexico in response to a deepening upper-level trough off the West Coast. The prevailing synoptic pattern transitioned to a Type IV setup by 31 August as the upper trough and associated Pacific cold front moved inland, shoving the high centroid over Texas eastward (Maddox et al. 1995; Kalnay et al. 1996).

b. Distribution of Precipitation

Precipitation amounts varied widely across New Mexico (Fig. 6) during the 2018 North American Monsoon season. The lowest amounts (under 25 mm) were recorded on the Northwest Plateau in the vicinity of Farmington, while the highest rainfall amounts were reported around the southern end of the Sangre de Cristo Mountains near Las Vegas (over 400 mm), with locations in the Sacramento Mountains and Gila Wilderness recording 300 to 400 mm. Precipitation amounts in the Rio Grande Valley and the southern deserts ranged from 50 to 200 mm, with sites in the eastern foothills of Albuquerque recording up to 300 mm of precipitation. Locations across the eastern plains varied from 100 to 250 mm, with most sites reporting around 200 mm of precipitation.

Precipitation anomalies for 93 NWS ASOS/AWOS and COOP sites across New Mexico were analyzed and plotted (Fig. 7). Departures from average varied from 30 percent of average on the northwest plateau at Farmington to 385 percent of average at the southern end of the Tusas mountain range near Canjilon. Of the 93 sites analyzed, 61 recorded below average precipitation, while above average rainfall was reported at 32 locations.

Most of New Mexico experienced below average precipitation, although there were scattered pockets of above average precipitation. The largest concentration of above average rainfall stretched from the eastern slopes of the Sangre de Cristo Mountains southeastward to the east-central plains, including the cities of Las Vegas, Santa Rosa, Fort Sumner, and Clovis. Other concentrations of above average precipitation were also recorded on the east side of the Albuquerque metro area, the Sandia and Manzano Mountains, and Sacramento Mountains. More isolated pockets of above average rainfall were reported in the Jemez and Tusas Mountains and in the northeastern corner of the state.

c. Severe Storm Distribution

Severe storm activity for the 2018 monsoon season was concentrated in the northeast quadrant of New Mexico (Fig. 8), although a smaller concentration of severe storm reports also occurred in the Albuquerque metro area. This is consistent with the storm behavior typically seen with the Type II pattern, as shortwave troughs moving southeastward from Colorado to the Texas Panhandle send backdoor cold fronts southward through northeastern New Mexico. The shortwave troughs help draw moisture northwestward into New Mexico, while also providing sufficient vertical shear to initiate severe storm development along and behind the advancing cold fronts.

d. Major Events

Rio Rancho and Belen Flash Floods, 5 July 2018

Slow-moving thunderstorms developed over the Sandia and Manzano Mountains during the late afternoon of 5 July 2018. One cell formed over the north end of the Sandia range and drifted westward across the Rio Grande, resulting in up to 55 mm of rainfall in less than 90 minutes, and flash flooding in the northern part of Rio Rancho, particularly along U.S. Highway 550. A second cell formed over the Manzano Mountains around the same time as the first cell, and moved westward across the Rio Grande. Similar flash flooding occurred with up to 42 mm of rainfall reported in the town of Belen. Most of Belen was inundated with floodwaters due to a levee breach caused by the intense rainfall (NOAA 2018).

(i) Synoptic Conditions A modified Type I pattern was in place on 5 July 2018. A strong, but diffuse upper-level ridge was present over the Great Plains, with the high centroid located along the border between Nebraska and South Dakota. Meanwhile, a strong (600 dam at 500 hPa) high centroid was situated over the Four Corners region. The monsoon plume stretched from the Gulf of Mexico northwestward across central New Mexico in the weakness between the two high centroids, as evidenced on the 700 hPa dew point analysis at 05/1200 UTC and 06/0000 UTC (Fig. 9a. and c.). The upper-level ridge axis was oriented across far northern New Mexico, resulting in light easterly flow over the Sandia and Manzano range and the adjacent middle Rio Grande Valley. Two shortwave troughs were propagating around the northern periphery of the subtropical ridge: one moving northeastward across western and northern Colorado, and a second that would move

from south-central Nebraska at 05/1200 UTC southwestward to southeast New Mexico by 06/0000 UTC, as evidenced by GOES-15 water vapor imagery (Fig. 9b. and d.). Convection formed over the Sandia and Manzano Mountains by 05/2000 UTC in response to the approaching trough and orographic enhancement from easterly flow riding up the east-facing slopes of the range.

The steering flow would have directed any thunderstorms that formed over the Sandia and Manzano range westward into the Rio Grande Valley. Orographic intensification occurred as the storms ascended the mesas to the west of the Rio Grande, enhancing rainfall amounts. This phenomenon did indeed occur in the case of the cell that impacted Rio Rancho. The collision of outflow boundaries from these and other nearby cells helped spawn new cells that prolonged heavy rainfall around Rio Rancho and Belen.

San Antonio Flash Flood, 15 July 2018

On the evening of 15 July 2018, heavy thunderstorm rainfall of up to 82 mm fell over the Chupadera Mountains of south-central New Mexico. This rainfall overwhelmed Walnut Creek, which is diverted into a series of irrigation ditches at the town of San Antonio, and resulted in a flash flood that inundated San Antonio with water and mud, washed out several roads, and damaged 20 homes and buildings (NOAA 2018).

(ii) Synoptic Conditions The predominant synoptic pattern over New Mexico on 15 July was the Type II regime, with an elongated high centroid stretching from the Great Basin westward into the eastern Pacific. A light northeasterly steering flow was present over New Mexico, with a large, but diffuse moisture plume covering the entire state at 700 hPa. The upper-air sounding from Albuquerque (KABQ) for 16/0000 UTC (Fig. 10) indicated marginally unstable conditions with a Most Unstable Convective Available Potential Energy (MUCAPE) value of 574 j kg^{-1}. A weak cap was present with a Most Unstable Convective Inhibition (MUCINH) value of 24 j kg^{-1}.

The Lifted Index was -1.88. Thunderstorm initiation over the lower Rio Grande Valley occurred with strong surface heating, with upslope enhancement over the Chupadera Mountains to the west. Although the 15 mm of rain that fell over San Antonio was significantly lower than the amount that fell over the Chupadera Mountains, flash flooding inundated San Antonio when heavy rain over the adjacent mountain range overwhelmed Walnut Creek.

(iii) Diversion of Walnut Creek Construction of a railroad, highways, and farms over the span of generations in an around San Antonio resulted in the lower portion of Walnut Creek being diverted from its original course that previously emptied into the Rio Grande, and into a series of ditches to irrigate adjacent farmland. At the railroad tracks, Walnut Creek's natural creek bed ends with a 90-degree southward turn into a ditch that begins immediately after passing underneath the railroad bridge. The ditch then runs along the north side of U.S. Highway 380 for a short distance before crossing under the highway and emptying into another irrigation ditch that runs parallel to the Rio Grande. Compared to the creek's original course, the ditches have much less capacity. More significantly, Walnut Creek no longer connects directly with the Rio Grande, rather it empties into a series of irrigation ditches that are separated from the river by a levee. This diversion exacerbated the inundation of San Antonio when Walnut Creek flooded, as the water from upstream was blocked from emptying into the Rio Grande, forcing the creek to flood adjacent farmland and the town of San Antonio.

Santa Fe Area Flash Floods, 23 July 2018

During the early evening of 23 July 2018, several slow-moving thunderstorms developed across central and northern New Mexico. These storms produced torrential rainfall in the Santa Fe metropolitan area, resulting in devastating flash flooding. CoCoRaHS, COOP, and NWS observation sites measured rainfall amounts between 16.5 mm of rain at the Santa Fe Municipal Airport and 93.8 mm of rain in less than one hour near the Santa Fe Plaza, which equated to a 500-or 1000-year precipitation event.

An upper-level ridge centered over the Desert Southwest on 23 July along with a weak surface backdoor cold front provided the necessary ingredients for record monsoonal rainfall in and near the New Mexico capitol. This unprecedented heavy rain event resulted in 10 roads closed and 100 homes damaged due to flooding. Of those 100 homes, 33 experienced major damage with six destroyed (NOAA 2018).

(iv) Synoptic Conditions A modified Type I pattern was present over New Mexico, with the upper high centroid at 300 hPa straddling the border between southeast New Mexico and West Texas. With the westward displacement of the high centroid, relatively dry air infiltrated much of central and southern New Mexico at the mid-and upper-levels. The richest moisture associated with the monsoon plume was shunted into central Arizona, then curving northeastward into northwest and north-central New Mexico. With the high centroid nearby, the steering flow at 500 hPa over New Mexico was light, generally from a westerly direction over northern and central parts of the state, and from an easterly direction over extreme southern New Mexico.

A backdoor cold front stalled along the Continental Divide, and was undergoing frontolysis. Temperatures were particularly hot across north-central New Mexico, with the Santa Fe Municipal Airport reporting a temperature of 32.7 ^{o}C by 24/0000 UTC. From the Albuquerque sounding at 23/1200 UTC (Fig. 11), the atmosphere was marginally unstable with a MUCAPE value of 216 J kg^{-1} and a MUCINH value of 418 J kg^{-1}. The convective temperature was 27.2 ^{o}C, which was easily exceeded by mid-afternoon. By 24/0000 UTC (Fig. 12) the MUCAPE had increased to 1082 J kg^{-1} and the MUCINH had decreased to 5 J kg^{-1}. Meanwhile, abundant moisture was present as evidenced by the precipitable water value of 22.1 mm at 23/1200 UTC, which increased to 23.1 mm by 24/0000 UTC.

Thunderstorm initiation was largely driven by surface heating, as most of New Mexico was under the influence of the upper-level high centered over the southern part of the state. By mid-afternoon, thunderstorms developed over the Jemez Mountains and along the Continental Divide when the surface temperature exceeded the convective temperature to initiate thunderstorm development. A low-level southerly flow fed moisture into the developing storms, while a light westerly steering flow at and above 500 hPa directed the cells southeastward toward the upper Rio Grande Valley and the Santa Fe area. New cells formed along outflow boundaries that spread out from older thunderstorms. The particular cell that caused the flash flood over Santa Fe formed as a result of an outflow boundary colliding with the low-level southerly inflow. Orographic uplift along the southern end of the Sangre de Cristo Mountains helped enhance the intensity of the Santa Fe storm, resulting in 93.8 mm of rain and flash flooding near the Santa Fe Plaza. The village of La Cienega, about 25 km southwest of the Santa Fe Plaza, received substantially less rainfall, but the village was inundated with floodwaters when Cienega Creek became a raging torrent due to the intense rainfall kilometers upstream.

Albuquerque Severe Hail, 30 July 2018

Two severe thunderstorms dropped hail up to 32 mm in diameter across the east side of Albuquerque during the evening of 30 July 2018. The first cell developed over the Northeast Heights and moved south-southeastward toward the Four Hills area. The second cell formed over the city of Rio Rancho, then intensified as it moved south over the North Valley neighborhoods before reaching downtown Albuquerque. This cell weakened as it continued southward over the Albuquerque International Sunport and Kirtland Air Force Base. Hail from the two cells damaged cars throughout the Albuquerque metro area. One person was treated for injuries caused by the hail (NOAA 2018).

(v) Synoptic Conditions On 30 July 2018, a Type II monsoon pattern was present with the high centroid situated over the Great Basin, and a broad upper-level trough situated over the Upper Midwest (Maddox et al. 1995). At 30/1200 UTC, a 45 m s^{-1} jet streak at 300 hPa was located over north-central Colorado (Fig. 13a). This jet streak supported a shortwave trough moving southeastward through northern Colorado. A strong backdoor cold front pushed westward through the gaps in the central mountain chain, resulting in strong easterly gap winds of up to 17 m s^{-1} at the Albuquerque International Sunport (KABQ). The front reached the Continental Divide later in the morning. A very dry air mass was in place over the Four Corners region. As Gulf moisture surged westward behind the front, the vertical profile of the front itself became more characteristic of a dry line. Surface dew points over the Four Corners were below 0 ^{o}C, while dew points to the east of the Continental Divide approached 16 ^{o}C in the Rio Grande Valley, with higher values reported to the east of the central mountain chain.

Isolated convection developed during the afternoon of 30 July over the highlands of west-central New Mexico, the Jemez Mountains, and Tusas and Sangre de Cristo Mountains of northern New Mexico. The steering flow at 500 hPa was from northwest to southeast. The flow at 300 hPa was more westerly, while the low-level flow from the surface to 700 hPa was generally from the southeast. By the evening of 30 July (31/0000 UTC), the core of the 300 hPa jet streak–now 38 m s^{-1}–was situated near Amarillo, Texas (Fig. 13b). The associated shortwave trough at 500 hPa stretched from the Texas Panhandle westward to east-central New Mexico. The backdoor front stalled along the Continental Divide and completely transformed to a dry line as depicted by the sharp moisture gradient.

The synoptic setup over New Mexico was favorable for the initiation of severe convection. The backdoor front advected ample Gulf of Mexico moisture into eastern and central New Mexico. The same front also forced the Great Basin High to retreat westward, reducing upper-level subsidence and increasing instability as reflected by the surface-based CAPE value of 1,399 J kg^{-1} and CINH of 97 J kg^{-1} from the 31/0000 UTC upper-air sounding at Albuquerque (Fig. 14). The trajectory of the jet streak at 300 hPa would have skirted through the northeast corner of New Mexico, placing the Albuquerque metro area close to the right-entrance region of this feature, where upper-level divergence would be present. The jet streak and mid-level trough interacting with the surface dry line provided sufficient lift and vertical shear to initiate convection over the Jemez Mountains to the north-northwest of the Albuquerque metro area. The steering flow directed these cells southeastward over the Albuquerque metro area. A moist, southeasterly flow below 700 hPa, combined with west-northwesterly flow at 300 hPa provided sufficient vertical shear to enable rapid intensification and sustainment of strength as the cells moved from the Jemez Mountains into the Rio Grande Valley.

5. Conclusion

The 2018 North American Monsoon season started with a Type II pattern that evolved to a Type I regime from mid-August onward. Consistent with the Type II regime, the majority of New Mexico experienced below average precipitation, although there were scattered pockets of above average rainfall that favored the eastern slopes of the central mountain chain and the east side of the Albuquerque metro area. While there were no widespread severe storm or flash flood events in 2018, several localized flash flood and a severe hail storm caused injuries and property damage to locations in the Rio Grande Valley.

Storm activity that produced flash flooding was enhanced by orographic uplift and perpetuated by colliding outflow boundaries. In two of the three flash flood events, the heaviest rainfall occurred kilometers upstream of the locations subject to the most destructive flooding. Diversion of a waterway from its natural watercourse by human development was a major factor in at least one of the flash flood events in this study.

Finally, the Albuquerque severe hail event of 30 July 2018 was attributable to a synoptic pattern where a backdoor cold front swept westward across New Mexico, stalled near the Continental Divide, and evolved into a dry line. This study concludes that where a backdoor cold front stalls becomes a focal point for severe storms under the Type II regime. This is particularly the case when the jet stream is in close proximity to New Mexico and embedded shortwave troughs skirt through the state and interact with the frontal boundary. In response, upper-level divergence and vertical shear enhance storm initiation, intensification, and longevity.

6. Acknowledgements

The authors would like to thank Mr. Kerry Jones from the National Weather Service Forecast Office in Albuquerque, and Dr. David DuBois from the New Mexico State Climatologist's Office in Las Cruces for taking the time to peer review this manuscript and validate the findings contained herein.

References

Adams, D. K., and A. C. Comrie, 1997: The North American Monsoon. *Bulletin of the American Meteorological Society*, **78 (10)**, 2197–2214.

Blumberg, W. G., K. T. Halbert, T. A. Supinie, P. T. Marsh, R. L. Thompson, and J. A. Hart, 2017: SHARPpy: An open-source sounding analysis toolkit for the atmospheric sciences. *Bulletin of* *the American Meteorological Society*, **98 (8)**, 1625–1636.

Bowen, B. M., 1996: Rainfall and climate variation over a sloping New Mexico plateau during the North American Monsoon. *Journal of Climate*, **9 (12)**, 3432–3442.

Douglas, M. W., R. A. Maddox, K. Howard, and S. Reyes, 1993: The Mexican Monsoon. *Journal of Climate*, **6 (8)**, 1665–1677.

Gochis, D. J., A. Jimenez, C. J. Watts, J. Garatuza-Payan, and W. J. Shuttleworth, 2004: Analysis of 2002 and 2003 warm-season precipitation from the North American Monsoon Experiment event rain gauge network. *Monthly Weather Review*, **132 (12)**, 2938–2953.

Grantz, K., B. Rajagopalan, M. Clark, and E. Zagona, 2007: Seasonal shifts in the North American Monsoon. *Journal of Climate*, **20 (9)**, 1923–1935.

Gutzler, D. S., and Coauthors, 2005: The North American Monsoon Model Assessment Project: Integrating numerical modeling into a field-based process study. *Bulletin of the American Meteorological Society*, **86 (10)**, 1423–1430.

Hubbard, K. G., A. T. DeGaetano, and K. D. Robbins, 2004: A modern applied climate information system. *Bulletin of the American Meteorological Society*, **85 (6)**, 811.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR reanalysis 40-year project. *Bull. Am. Meteorol. Soc*, **77 (3)**, 437–471.

Knapp, K. R., 2008: Scientific data stewardship of International Satellite Cloud Climatology Project B1 global geostationary observations. *Journal of Applied Remote Sensing*, **2 (1)**, 023 548.

Maddox, R. A., D. M. McCollum, and K. W. Howard, 1995: Large-scale patterns associated with severe summertime thunderstorms over central Arizona. *Weather and Forecasting*, **10 (4)**, 763–778.

NOAA, 2018: The Top 5 Weather Stories of 2018 (NWS Albuquerque, NM). https://www.weather.gov/abq/Thetop5weatherstoriesof2018 (Accessed April 8, 2019).

NOAA, n.d.: North American Monsoon patterns for New Mexico. https://www.weather.gov/abq/northamericanmonsoon-typicalpatterns (Accessed October 12, 2018).

LIST OF FIGURES

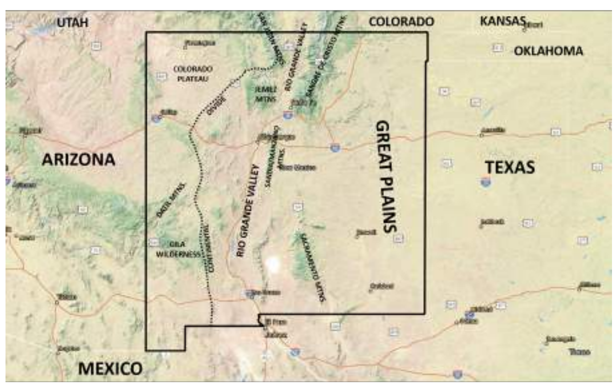

FIG. 1. Map of New Mexico with major geographic features annotated.

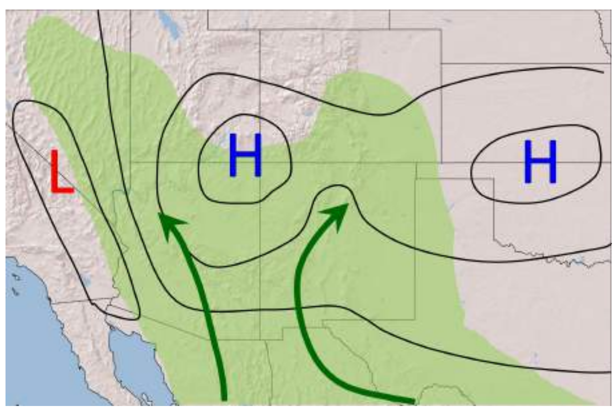

FIG. 2. Synoptic depiction for the Type I ”classic” monsoon pattern. The typical location of the monsoon moisture plume is depicted in green. The green arrow indicates the direction of moisture flux. Adapted from Maddox et al. (1995) and NOAA (n.d.).

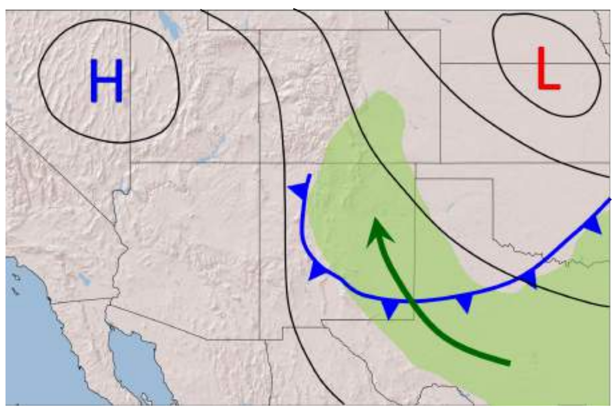

FIG. 3. Synoptic depiction for the Type II "reverse" monsoon pattern. The typical location of the monsoon moisture plume is depicted in green. The green arrow indicates the direction of moisture flux. Adapted from Maddox et al. (1995) and NOAA (n.d.).

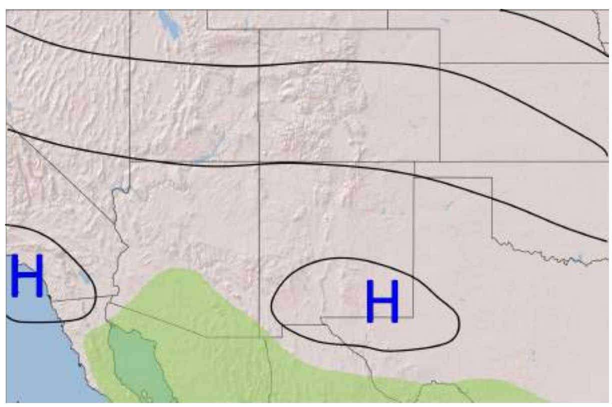

FIG. 4. Synoptic depiction for the Type III monsoon pattern. The typical location of the monsoon moisture plume is depicted in green. Adapted from Maddox et al. (1995) and NOAA (n.d.).

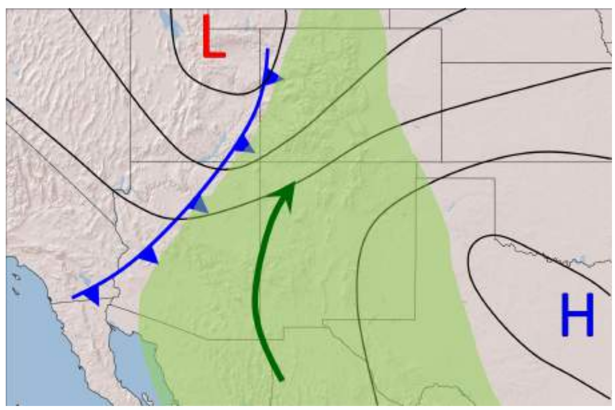

FIG. 5. Synoptic depiction for the Type IV monsoon pattern. The typical location of the monsoon moisture plume is depicted in green. The green arrow indicates the direction of moisture flux. Adapted from Maddox et al. (1995) and NOAA (n.d.).

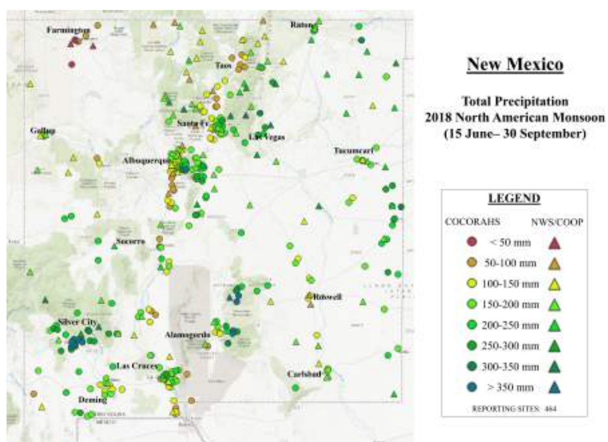

FIG. 6. Precipitation distribution across New Mexico from the 2018 North American Monsoon season.

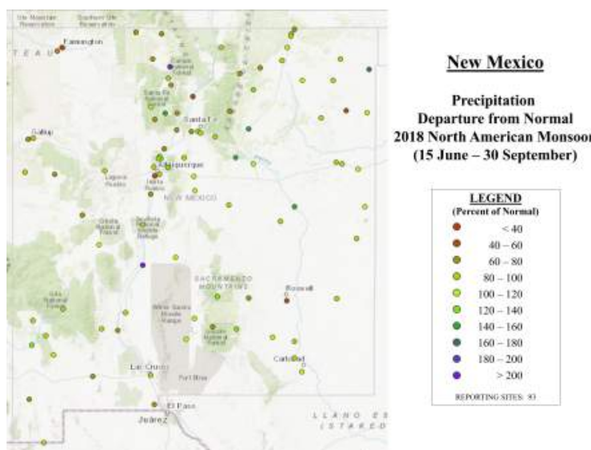

FIG. 7. Precipitation anomalies across New Mexico from the 2018 North American Monsoon season.

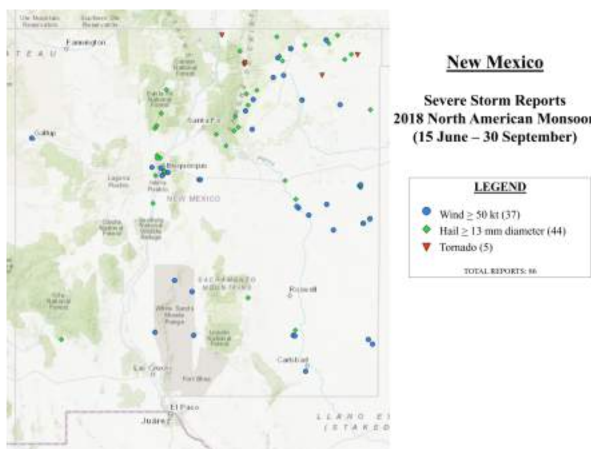

FIG. 8. SPC severe storm reports for New Mexico during the 2018 North American Monsoon season.

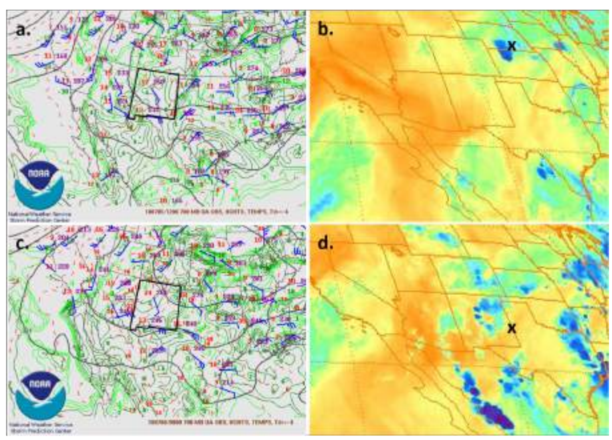

FIG. 9. 700 hPa analysis and water vapor imagery for 1200 UTC 5 July 2018 (a. and c., respectively), and 0000 UTC 6 July 2018 (b. and d. respectively) (Knapp 2008).

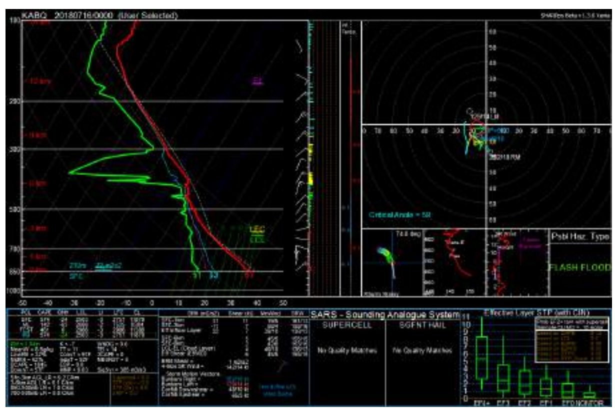

FIG. 10. Albuquerque (KABQ) upper-air sounding for 0000 UTC 16 July 2018.

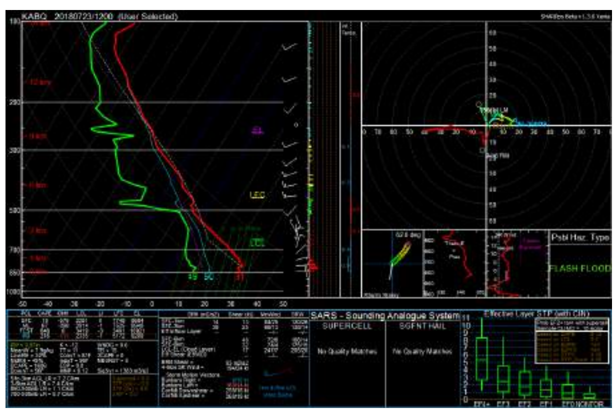

FIG. 11. Albuquerque (KABQ) upper-air sounding for 1200 UTC 23 July 2018.

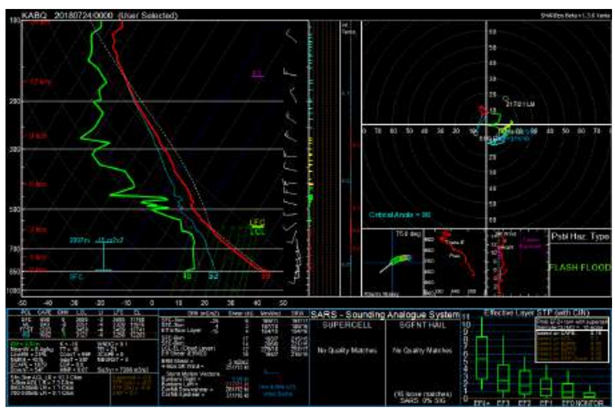

FIG. 12. Albuquerque (KABQ) upper-air sounding for 0000 UTC 24 July 2018.

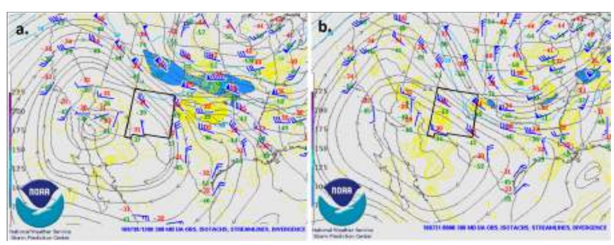

FIG. 13. 300 hPa analysis for 1200 UTC 30 July 2018 (a) and 0000 UTC 31 July 2018 (b).

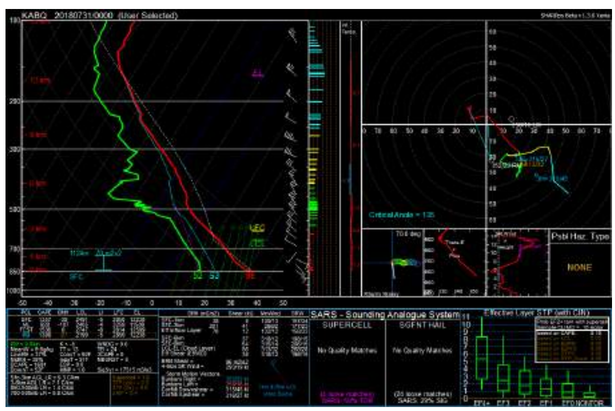

FIG. 14. Albuquerque (KABQ) upper-air sounding for 0000 UTC 31 July 2018.