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Meteorology Assessment of Historic Rainfall for Los Alamos During September 2013

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ACRONYMS

CoCoRaHS	Community Collaborative Rain, Hail, and Snow Network
COOP	Cooperative Observer Program
DRI	Desert Research Institute
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA	ECMWF Re-Analysis
HADS	Hydrometeorological Automated Data System
HCN	Historical Climate Network
LANL	Los Alamos National Laboratory
MSL	above mean sea level
NWS	National Weather Service
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PW	precipitable water
TA	Technical Area
RAWS	Remote Automated Weather Stations
UTC	Universal Time Coordinated

1.0 INTRODUCTION

For the southwestern United States, a monsoon occurs in the summer in which westerly winds shift to southerly winds causing moisture from the south to be advected to this area. The southwest monsoon can cause dramatic weather and heavy precipitation during the summer as a result of the change in moisture in the atmosphere. According to the National Weather Service (NWS), the southwest monsoon lasts from 15 June through 30 September. An example of heavy precipitation during a southwest monsoon occurred in September 2013. Heavy rainfall occurred from 11–17 September 2013 along the Front Range of the Rocky Mountains in Colorado causing devastating flooding and eight fatalities. Damage to 19,000 homes and commercial buildings with 1,500 buildings destroyed caused an estimated $2 billion in property damages. Rainfall totals throughout the event exceeded 17 inches with Boulder, Colorado, measuring 9 inches in a 24-hour period (Uccellini 2014; Gochis et al. 2015).

Colorado was not the only state to be effected by the September 2013 heavy rainfall. Areas of north and central New Mexico experienced record to near record flooding in numerous locations from 10–18 September 2013. Whitewater Creek in western New Mexico recorded 10.09 inches and a Los Alamos National Laboratory (LANL) meteorology tower recorded 7.66 inches from 10–18 September. Flood damages to state roads and bridges were estimated at over $16 million (FEMA 2013) and caused two deaths (Associated Press 2013; Mikkelson 2013). For Los Alamos, damages to watershed controls, groundwater monitoring wells, and sediment deposits caused an estimated total cost of $7 million (LANL 2013). The objective of this study is to analyze the September 2013 rain event for the New Mexico and Los Alamos regions, specifically examining the following aspects:

- synoptic scale meteorology,
- local upslope dynamics through topographic forcing,
- comparison of the LANL rain gauge network with daily observed and monthly normal precipitation and derived precipitable water (PW), and
- evaluation of the summertime meteorological conditions that cause heavy precipitation events for Los Alamos.

DOE Order 420.1, Facility Safety, requires that site natural phenomena hazards be evaluated every 10 years to support the design of nuclear facilities. The evaluation requires calculating return period rainfall to determine roof loading requirements and flooding potential based on our on-site rainfall measurements. The return period rainfall calculations are done based on statistical techniques and not site-specific meteorology. This and future studies analyze the meteorological factors that produce the significant rainfall events. These studies provide the meteorology context of the return period rainfall events.

2.0 BACKGROUND

2.1 Study Area

The topography of New Mexico is shown in Fig. 1. The southern end of the Rocky Mountains extends into the north central region and the Colorado Plateau spans the northwest region of the state. Several of the eastern counties lie within the western end of the Great Plains. Los Alamos is located on the Pajarito Plateau, east of the Jemez Mountains and the Valles Caldera (Fig. 2). The summit of Pajarito Mountain is ~10,441 ft (3,182 m) above mean sea level (MSL) and the base of the Jemez Mountains is ~7,800 ft (2,380 m) MSL.

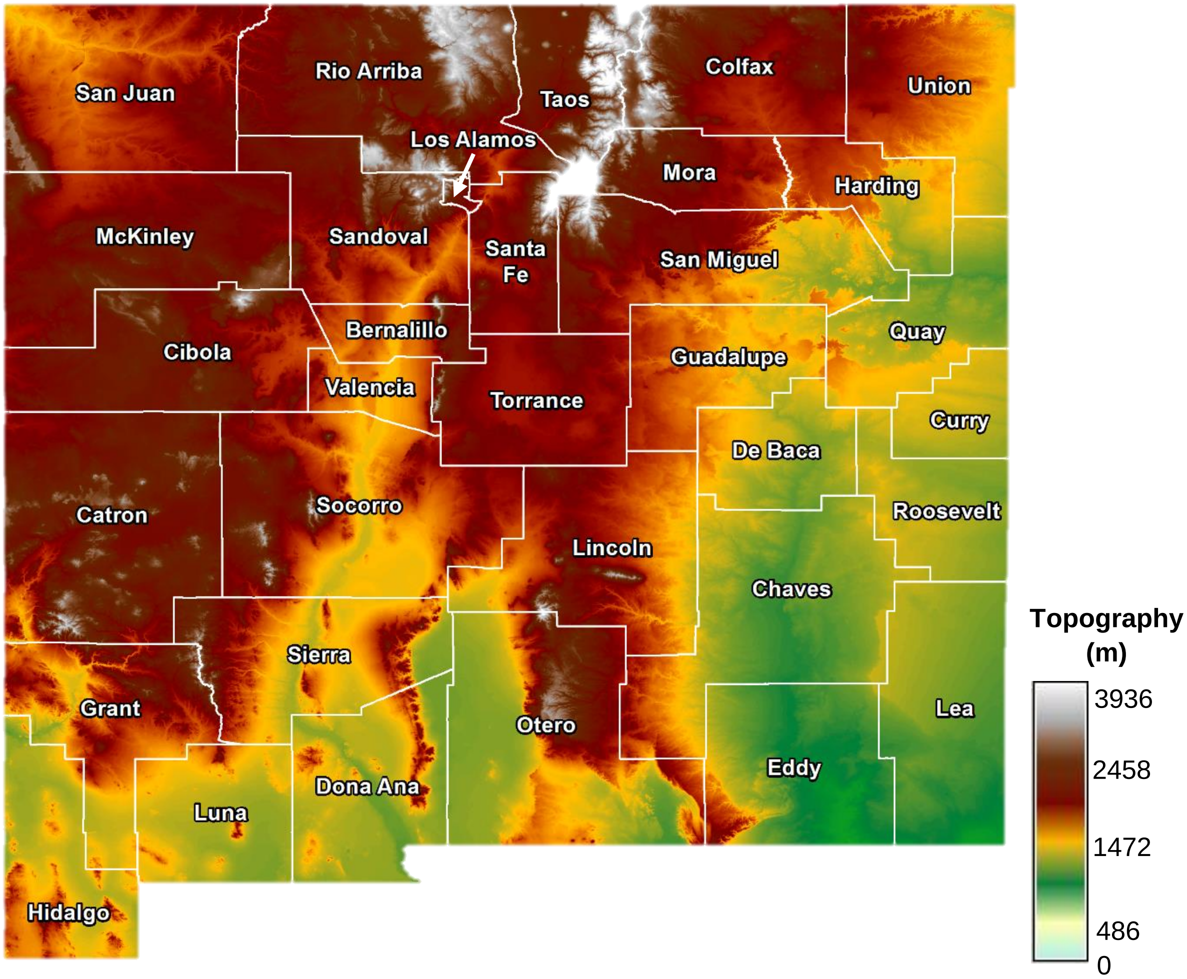


Fig. 1: Topography (color shading) at 60 m resolution and New Mexico counties

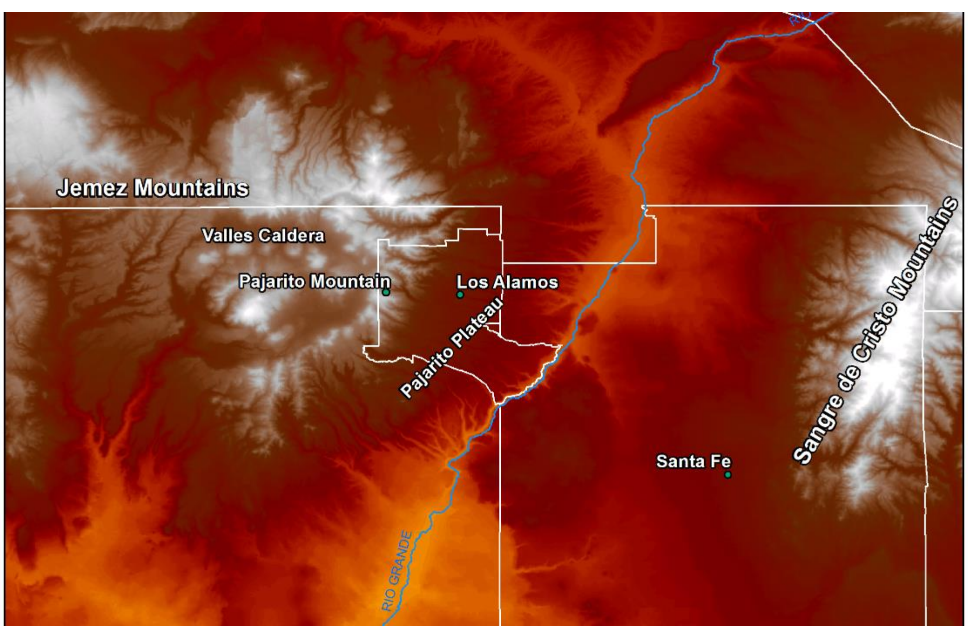


Fig. 2: Topography around Los Alamos

2.2 Large-scale Atmospheric Flow

New Mexico is located on the southern end of the general pathway for storms across western North America, known as storm tracks or jet stream. At times, upper-level low pressure systems can disconnect from the jet stream and situate over the southwest, known as cutoff lows. Cutoff lows can cause heavy rainfall as they can remain stationary over an area for several days. The slow moving cutoff lows are a result of displacement away from the jet stream that would normally force the system downstream. They are most prevalent during the cool season (October–April) over the desert southwest (Bell and Bosart 1994; Lareau and Horel 2012).

During the monsoon season, New Mexico receives moisture from the Gulf of Mexico to the southeast, mainly unimpeded, and from the Pacific Ocean to the southwest. The moisture advection from the Pacific Ocean is interrupted as it travels over complex terrain across southern California and Arizona. For Los Alamos, further blocking of westerly flow occurs from the Jemez Mountains (Bowen 1990). Bowen (1996) showed July through August accounts for 36% of annual precipitation across the Pajarito Plateau from early afternoon thunderstorms forming over the Jemez Mountains.

2.3 Topographic Forcing

The complex terrain across New Mexico (Fig. 1) influences the atmospheric flow and can produce local wind systems. During the day, mountain slopes heat faster than valleys, resulting in winds that are directed from the valley toward higher elevations. For Los Alamos, the wind is directed from the Rio Grande Valley toward the Jemez Mountains. These valley winds are an example of a local wind system caused by the differential heating across the varying topography. Another influence topography can have on the atmosphere relates to the distribution of precipitation along a slope depending on the orientation of the wind with respect to a mountain barrier. As air encounters a mountain, it must flow around or upward over the barrier. An unstable atmosphere and high wind speeds contribute to an upward flow over the mountain, known as upslope flow. Assuming the air is moist, the air cools and expands as it rises, water droplets condense to form a cloud, and precipitation can occur. As the air descends the mountain (downslope flow), it warms causing evaporation and subsequently dissipates clouds. For Los Alamos, southerly-southeasterly (westerly-northwesterly) winds generally correspond to upslope (downslope) flow as they ascend (descend) the Jemez Mountains. Local upslope winds typically occur during the day and downslope winds occur at night as a result of differential heating/cooling on a slope. The process of winds flowing over mountains is referred to as topographic forcing and can be computed by the basic equation:

$$u\frac{\partial H}{\partial x}+v\frac{\partial H}{\partial y} \qquad (1)$$

where u and v are the horizontal wind components (m s^{-1}), H is the terrain height (m), and x and y are the horizontal distances between grid points. Equation (1) shows that stronger wind speeds and a large slope in terrain cause an increase in topographic forcing. Positive (negative) topographic forcing relates to upslope (downslope) flow. This study focuses on positive topographic forcing or upslope flow that may have enhanced precipitation during summertime storms.

Precipitation generally increases on a mountain slope with increasing elevation as a result of the slope causing uplift and instability of air (Spreen 1947; Smith 1979). The relationship between elevation and measured precipitation can vary based on characteristics of the terrain (e.g., size, slope, orientation). A large and steep slope normal to the wind flow generally produces more precipitation compared with a low and gently rising slope. For Los Alamos, Reneau et al. (2003) showed that the annual maximum precipitation amounts increase from east to west across the Pajarito Plateau and eastern Jemez Mountains for 2- to 24-hour time periods and 2- to 100-year return periods. However, their results revealed there is no east to west increase in precipitation for 15- to 30-minute durations.

3.0 METHODOLOGY

3.1 Meteorology Data Source

The meteorology data used for this study comes from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA)-Interim, a third generation reanalysis of the global atmosphere. Available gridded meteorology data includes several surface (e.g., 2 m temperature and 2 m humidity) and upper-level (e.g., wind and ozone) parameters spanning the troposphere and stratosphere. The data are available since 1979 and continuing in real time. ERA-Interim provides analyses at 6-hour intervals (0, 6, 12, and 18 Universal Time Coordinated [UTC]) on 37 pressure levels from 1000-hPa to 0.1-hPa (Berrisford et al. 2011; Dee et al. 2011). This study focuses on 750-hPa, the approximate elevation of the study area, and 500-hPa, the middle atmosphere. The atmospheric pressure decreases exponentially with height such that for a standard atmosphere, 750-hPa corresponds to ~8,091 ft (2,466 m) and 500-hPa corresponds to ~18,000 ft (5,500 m).

3.2 Meteorology Data

The meteorology data used for this study include geopotential heights at 500-hPa to understand the height of this pressure level, relative humidity at 750-hPa to detect the maximum moisture, and the wind field at 750-hPa. In addition, the integrated water vapor in a vertical column of the atmosphere over a location, known as PW, was used to identify the available moisture in the troposphere. PW indicates the depth of water at the surface if all of the water vapor in a vertical column precipitated. For thunderstorms, rainfall measurements typically exceed the PW as a result of the entrainment of water vapor from nearby areas. Thus, PW is not a tool to forecast precipitation amounts but is generally correlated with precipitation. Generally, PW is at a minimum during the winter and increases in the summer as the capacity of the atmosphere to hold moisture increases and coupled with the advection of moisture from the Gulf of Mexico to the southwest states. According to the NWS Storm Prediction Center, the climatological median moving average of PW for Albuquerque ranges from a minimum of 0.22 inches (5.59 mm) in the winter to a maximum of 0.81 inches (20.6 mm) in the summer.

The observed daily precipitation data is developed by the NWS Advanced Hydrologic Prediction Service with a spatial resolution of 4 km × 4 km. The data represents a 24-hour precipitation total ending at 12 UTC (6 A.M. MDT or 5 A.M. MST), signifying the end of a hydrologic day. For example, precipitation valid on 12 UTC 11 September represents the amount of precipitation that occurred in the previous 24 hours since 12 UTC 10 September.

Precipitation measurements around the town of Los Alamos and at LANL have been taken since 1910 as part of the NWS Cooperative Observer Program (COOP). Over the course of 105 years, the Los Alamos precipitation measurement station location has moved eight times with little change in altitude. Since 1990, the Los Alamos station has been located at the Technical Area (TA) 06 meteorology tower (Dewart and Boggs 2014). Currently, there are five meteorology observation towers (Fig. 3) across the Pajarito Plateau and Mortandad Canyon that measure meteorological variables including temperature, insolation, wind speed and direction, vertical wind speed, relative humidity, and precipitation. Precipitation is measured with tipping bucket rain gauges at 0.01 inch increments. Precipitation data at the meteorology tower sites were obtained online from the LANL Weather Machine at http://weather.lanl.gov. In addition to the LANL network, precipitation data is obtained from storm water rain gauges within and around LANL, and the Precipitation Emergency Notification System located west of LANL.

Monthly normal precipitation data is available from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group spanning 30 years from 1981 to 2010. PRISM estimates the climate spatial patterns through the use of point measurements and a digital elevation model for mid-latitude regions. PRISM datasets include meteorological parameters such as precipitation, maximum and minimum temperature, dew point, and maximum and minimum vapor pressure deficit (Daly et al. 1994).

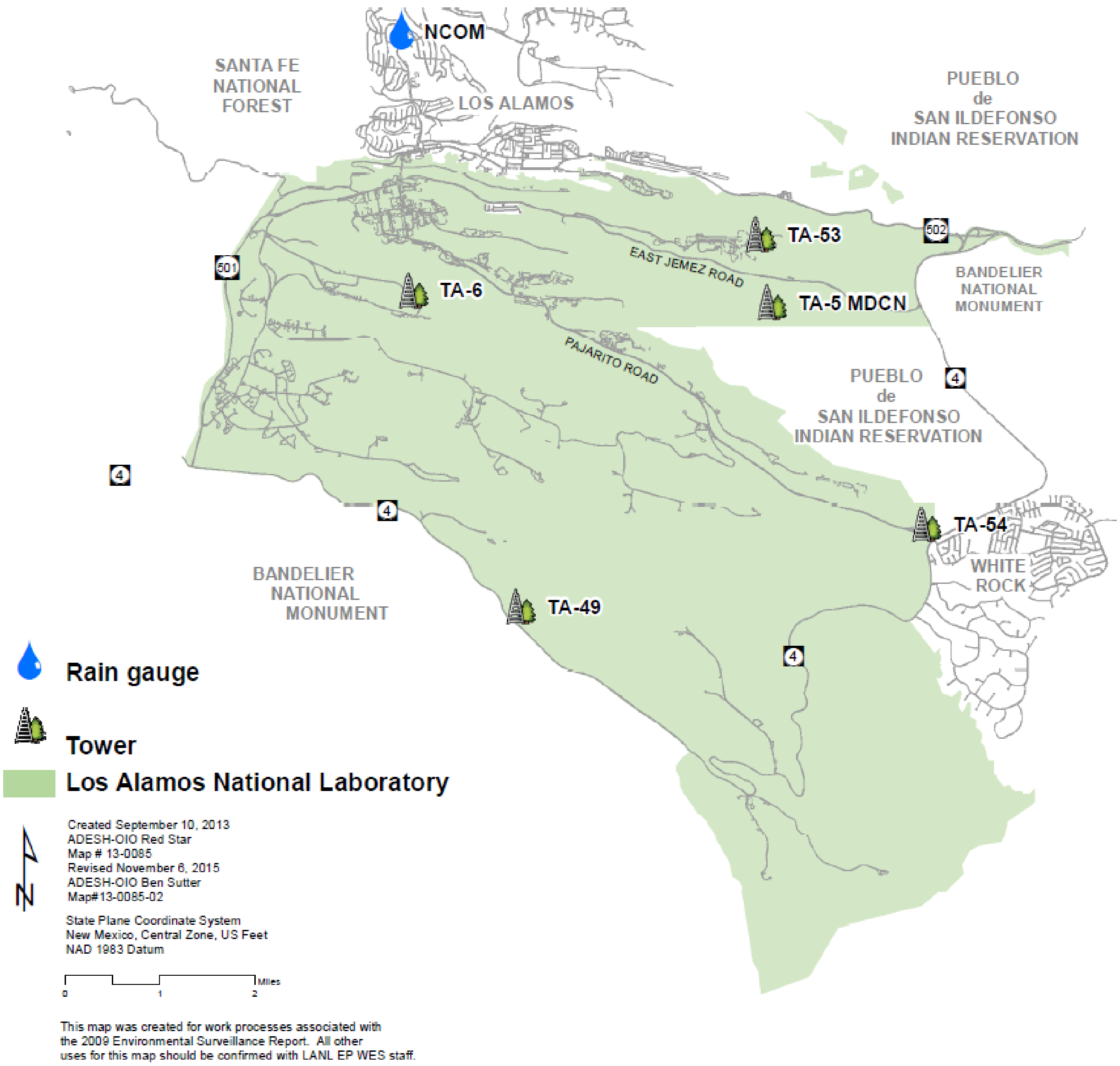


Fig. 3: Meteorological monitoring towers

4.0 EVENT OVERVIEW

4.1 Synoptic Perspective

The torrential rainfall across New Mexico was primarily from 10–18 September 2013. Gochis et al. (2015) showed a cutoff low in the southwest and a blocking ridge over the Canadian Rockies from 10–16 September that helped to sustain the position of the cutoff low for multiple days. Warm and moist air advection from the eastern Pacific and Gulf of Mexico can help develop stronger thunderstorms. The large-scale atmospheric pattern on 10 September shows an upper-level trough axis in the desert southwest (Fig. 4a). The upper-level trough and associated surface low pressure causes a cyclonic (counterclockwise) circulation which results in southwesterly flow from the eastern Pacific to the desert southwest. The lack of station observations in Mexico and varying wind direction in the southwest (Fig. 4a) fail to show a southwesterly flow at the surface. At 500-hPa, strong southwesterly flow is shown across Arizona and New Mexico and an upper-level trough extending to western Mexico (Fig. 4b). Southeasterly flow near the surface from the Gulf of Mexico and southwesterly flow aloft from the eastern Pacific allowed strong moisture advection to New Mexico (Fig. 4).

Los Alamos experienced the heaviest rainfall on 13 September. A synoptic analysis from 0–18 UTC 13 September 2013 is shown in Fig. 5. Figure 5a reveals the upper-level cutoff low over Nevada and Utah, and a ridge across the south central and Midwest regions of the country. The cyclonic flow around the cutoff low at 750-hPa does not extend into Arizona and New Mexico, but stronger southwesterly flow occurred over the southwest at 500-hPa (not shown). The ridge shows anticyclonic (clockwise) flow centered near Oklahoma which caused winds from the southeast for New Mexico. The maximum relative humidity is located near the Rocky Mountains and extends south and southeast toward the Gulf of Mexico. By 6 UTC (Fig. 5b), the cutoff low weakened and New Mexico experienced an increase in relative humidity nearing saturation. The cyclonic circulation nearly dissipated by 12 UTC (Fig. 5c), but a strong southerly wind and maximum relative humidity occurred for most of northern New Mexico. After 18 UTC (Fig. 5d), relative humidity significantly decreased across the state as the storm propagated to the north. The northern and western portions of the state experienced the largest relative humidity during this event predominantly at 6 and 12 UTC.

Figure 6 focuses on New Mexico. At 0 UTC (Fig. 6a), the central counties have the highest relative humidity with >80% and generally winds from the southeast across the state. By 6 UTC (Fig. 6b), the maximum relative humidity shifts toward the north and away from the southeast as the winds become more southerly. A peak in relative humidity and strong southerly winds occurs at 12 UTC (Fig. 6c) for most of the north and western counties. The majority of New Mexico dries out by 18 UTC (Fig. 6d), except for some local areas in the north and west.

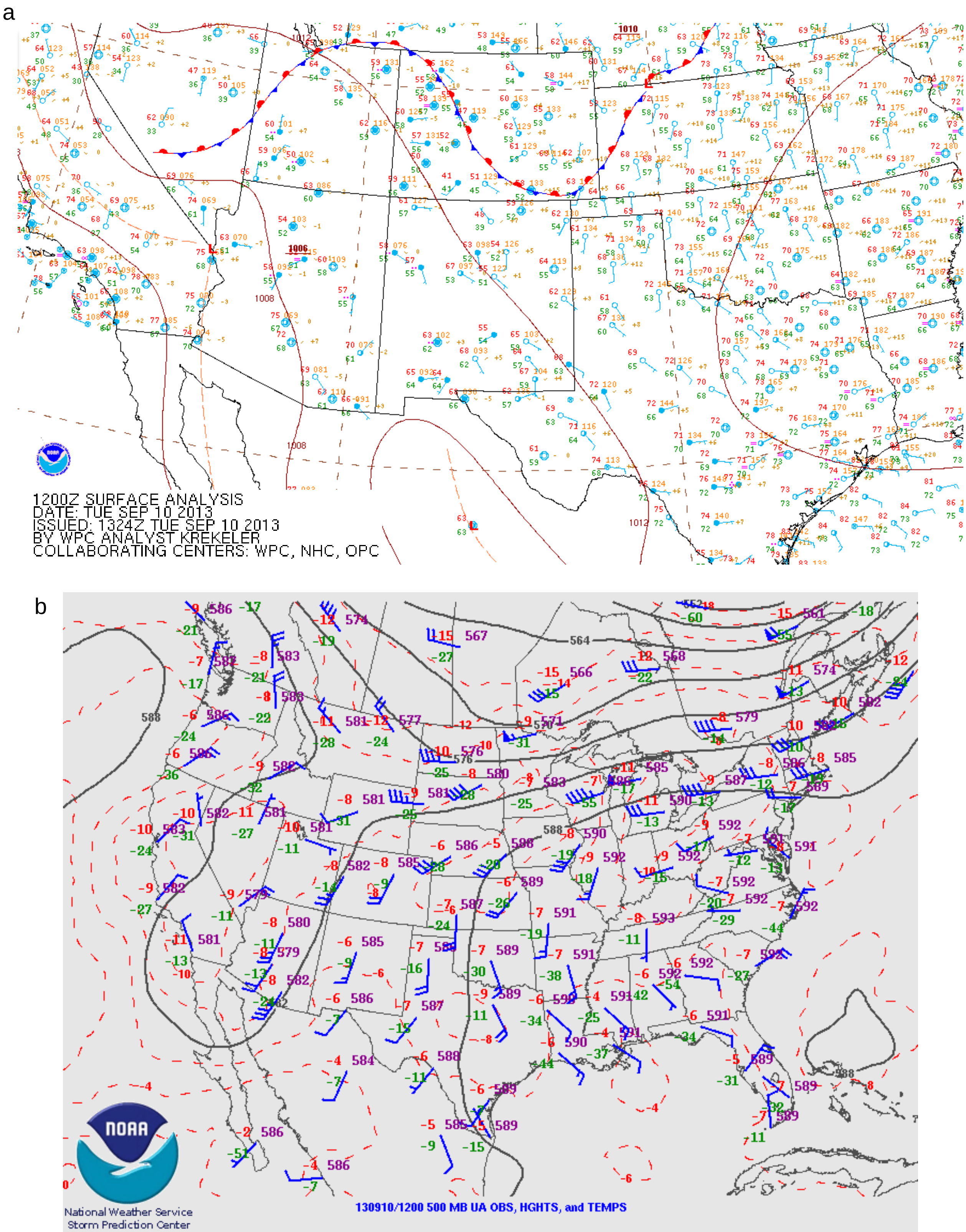


Fig. 4: (a) Surface analysis map with surface pressure in hPa (solid contours), upper-level trough (long dashed brown line) and (b) 500-hPa upper-air map with geopotential heights (solid contours), temperatures (dashed contours), and observations valid 12 UTC 10 September 2013

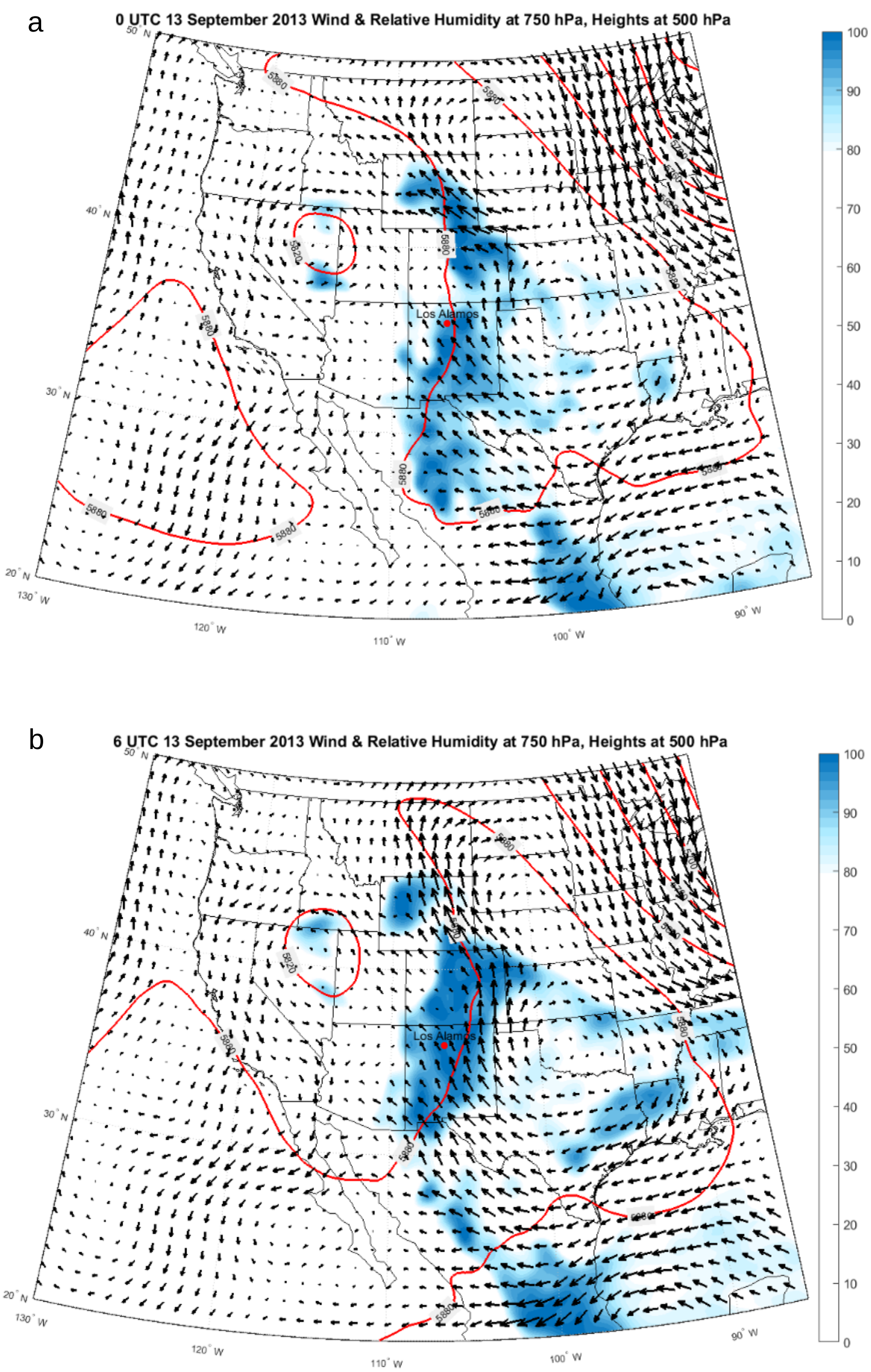
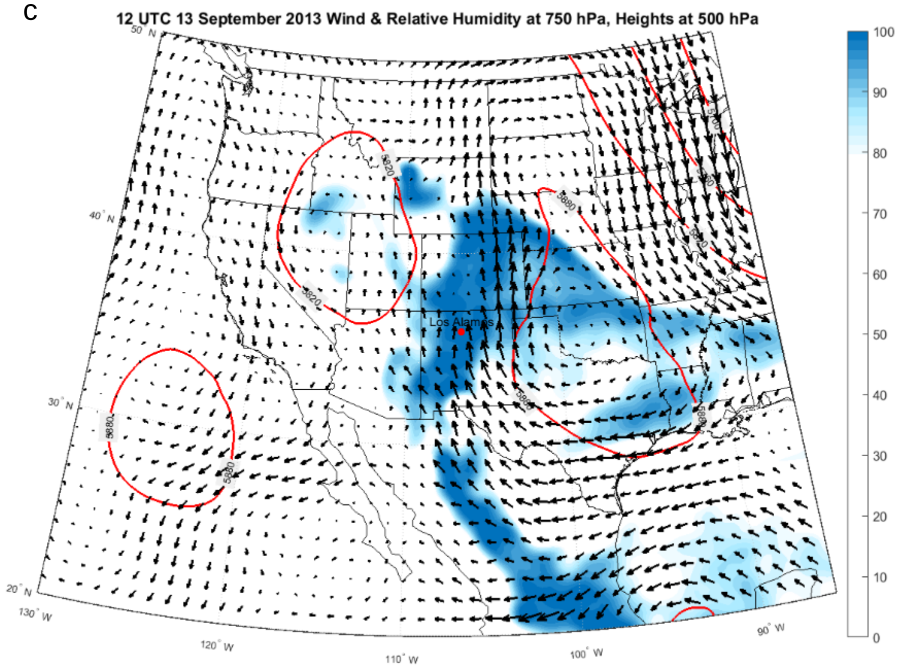


Fig. 5: Synoptic-scale analysis of relative humidity (color shading in %) and wind at 750-hPa (vectors), and geopotential heights at 500-hPa (red contours) at (a) 0, (b) 6, (c) 12, and (d) 18 UTC 13 September 2013

c



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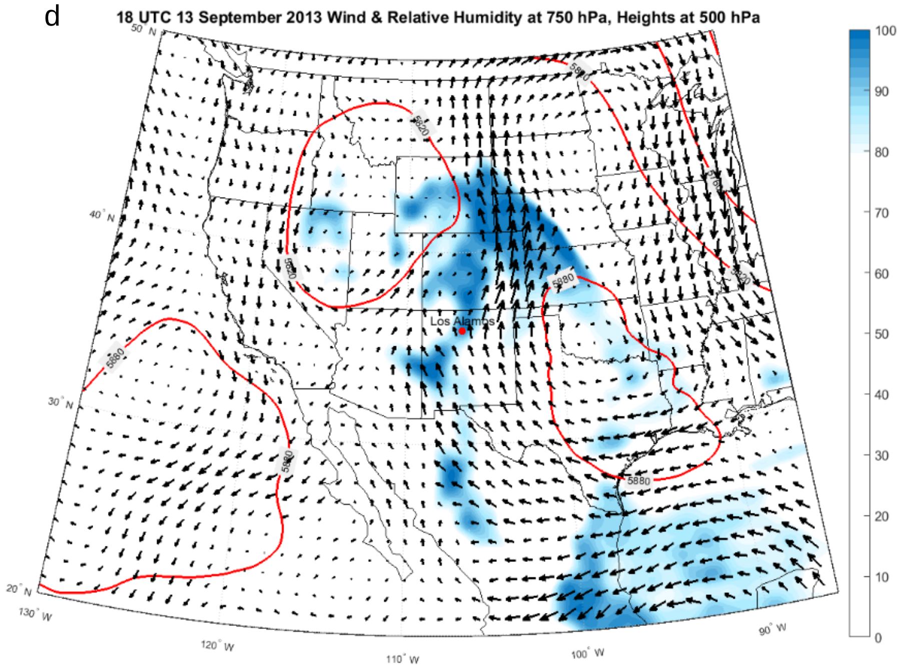
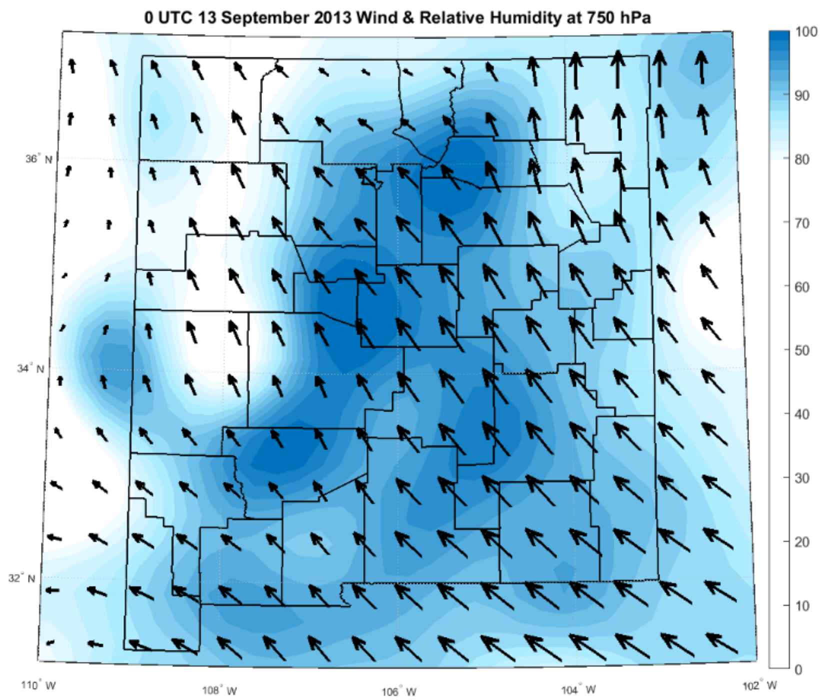


Fig. 5: (continued)

a



b

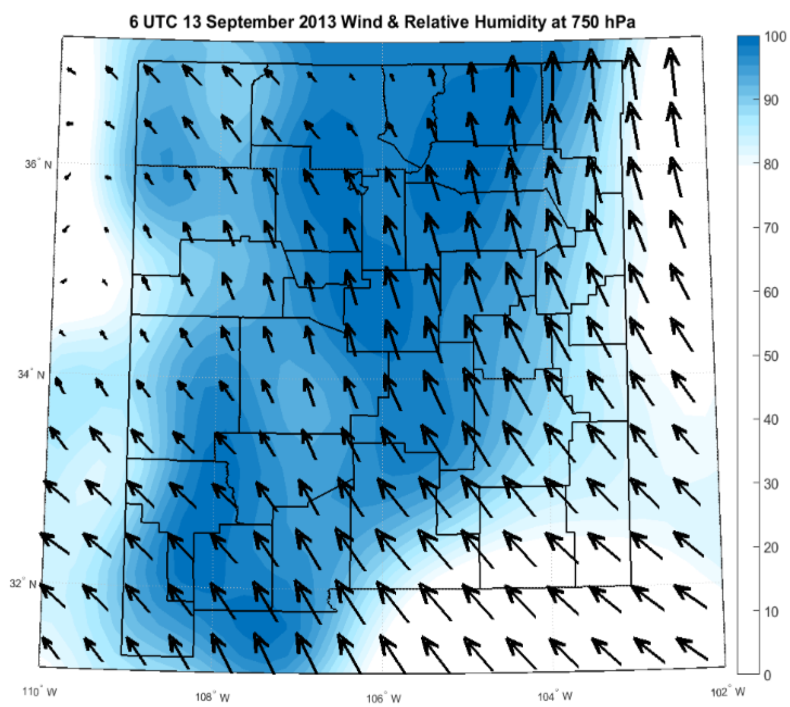
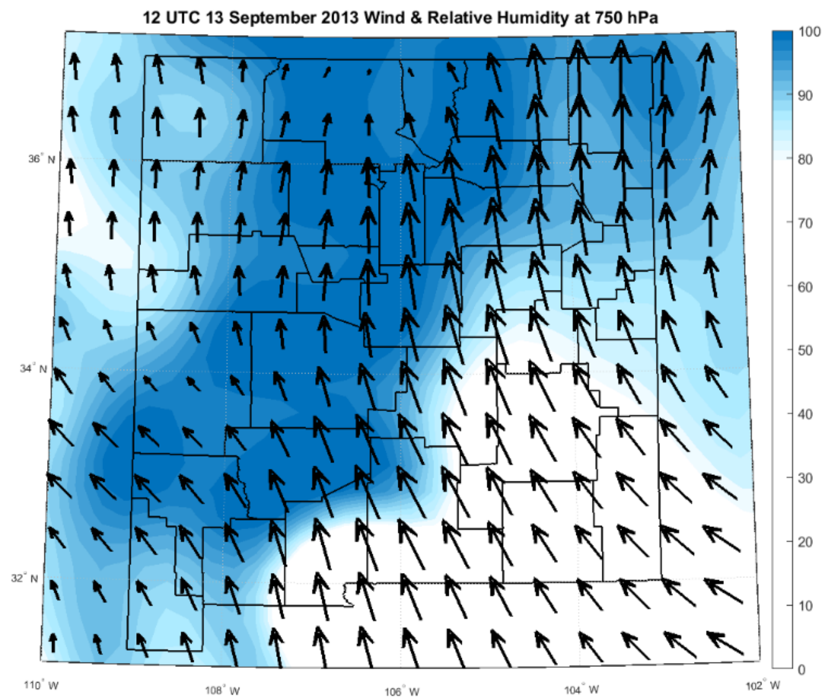


Fig. 6: Similar to Fig. 5 but focused on New Mexico

c



d

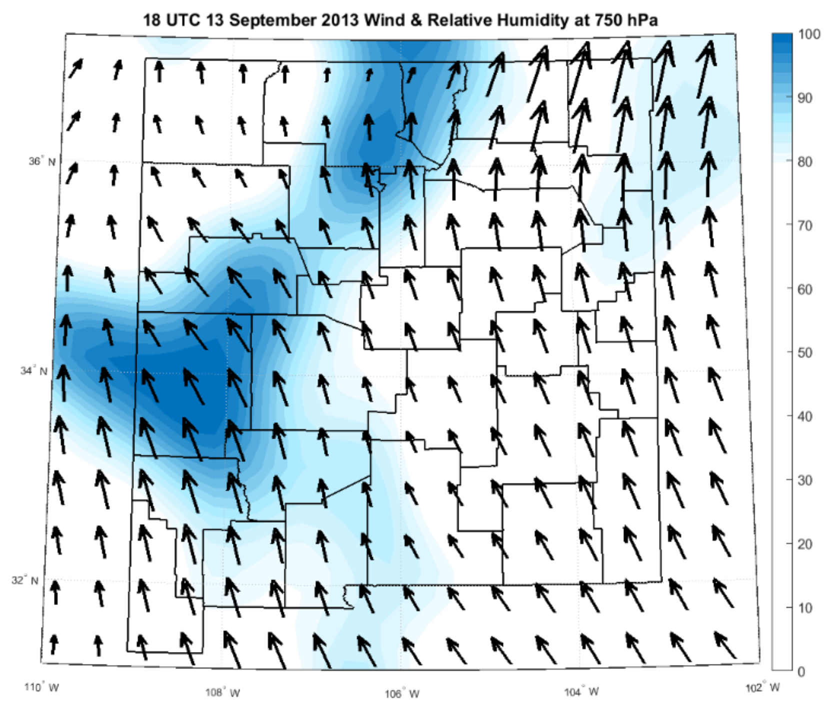


Fig. 6: (continued)

4.2 New Mexico Precipitation

Figure 7 shows the temporal and spatial variation in 24-hour total observed precipitation for New Mexico valid from 11–18 September 2013. Southern and eastern New Mexico received the heaviest precipitation from 10–12 September (Figs. 7a–c) and then the central and western regions of the state were impacted from 13–15 September (Figs. 7d–f). After this time, the heavy rain was more scattered and localized (Figs. 7g, 7h). The most intense precipitation for Los Alamos was an estimated 2+ inches ending at 12 UTC 14 September (Fig. 7d). Flooding became prevalent by the end of the event particularly in the northern and central regions of New Mexico. Table 1 shows the maximum reported precipitation for each northern and central New Mexico counties from 10–18 September 2013. The maximum precipitation during the event occurred in Whitewater Creek measuring 10.09 inches. The maximum precipitation received in Los Alamos County for the 9-day event was measured at Bandelier National Monument recording 7.93 inches.

The normal September precipitation for New Mexico calculated from data spanning 1981–2010 is shown in Fig. 8a. For most of the state, the average precipitation for September is less than 3 inches except for various regions at higher elevation. Based on the Los Alamos station data, the September average precipitation for Los Alamos is 2.01 inches. The September 2013 event caused above average precipitation for the majority of New Mexico by 2+ inches, with several areas exceeding the average by 5+ inches, including Los Alamos (Fig. 8b). Only a few counties experienced below average precipitation for the month (e.g., Lea, Hidalgo, Mora).

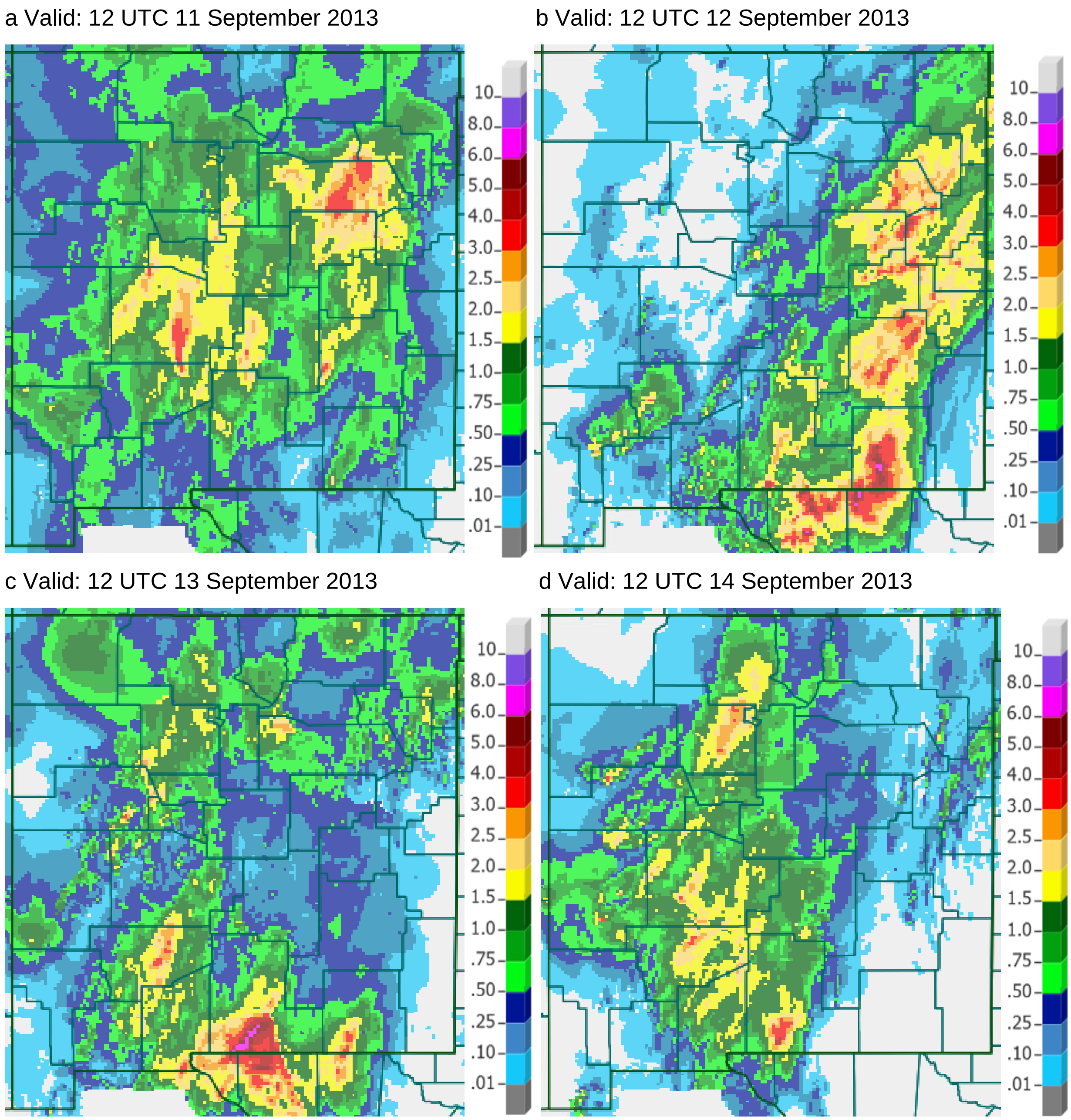
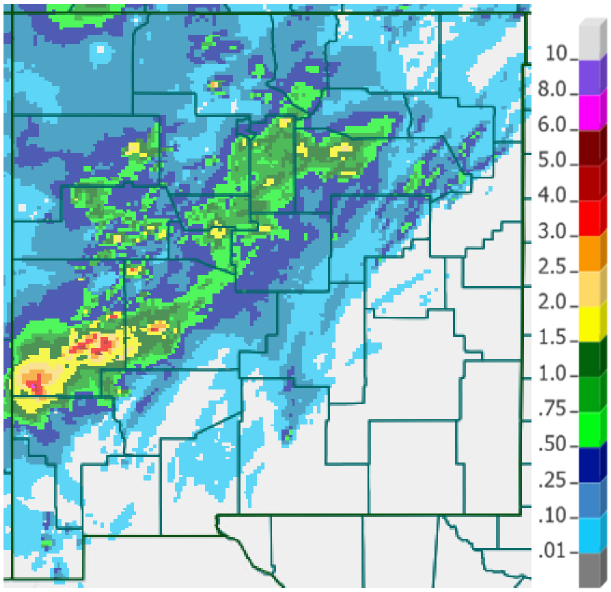
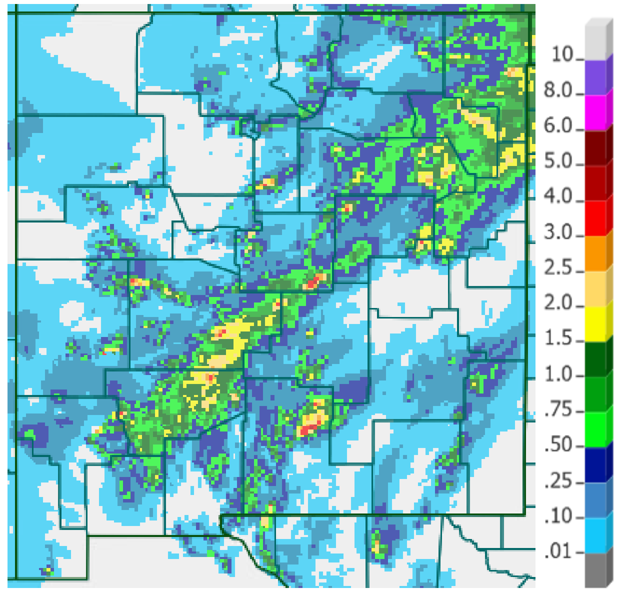


Fig. 7: Daily observed precipitation (inches) valid: (a) 11, (b) 12, (c) 13, (d) 14, (e) 15, (f) 16, (g) 17, (h) 18 September 2013

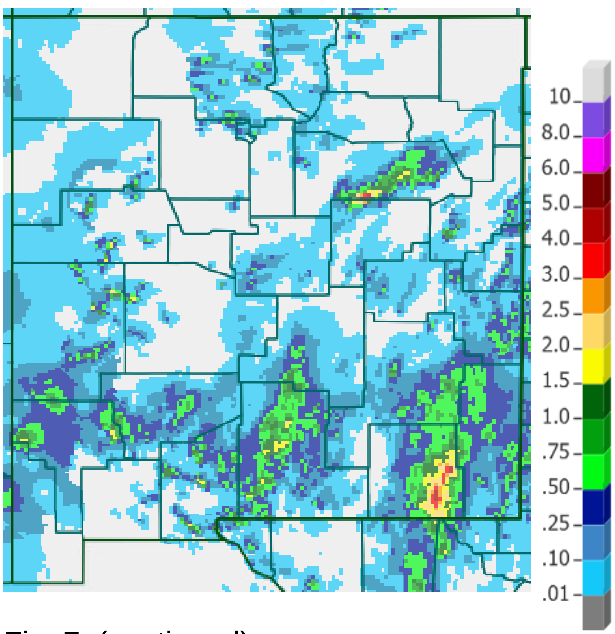
e Valid: 12 UTC 15 September 2013



f Valid: 12 UTC 16 September 2013



g Valid: 12 UTC 17 September 2013



h Valid: 12 UTC 18 September 2013

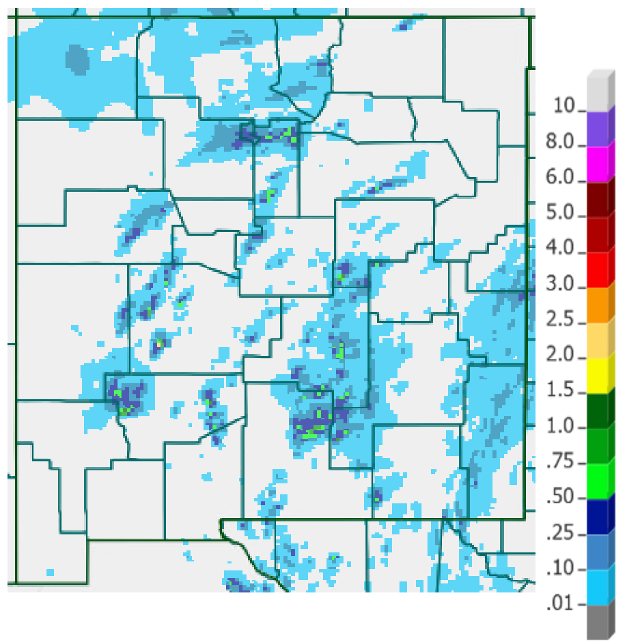


Fig. 7: (continued)

Table 1: Maximum Precipitation Reports for Northern and Central New Mexico Counties during 10–18 September 2013

Location	Source	County	Precipitation Total (inches)
Whitewater Creek	HADS	Catron	10.09
Las Vegas 8.4 NW	CoCoRaHS	San Miguel	9.78
Skyview Bonito Lake 2 S	HADS	Lincoln	8.34
Sumner Dam	COOP	De Baca	8.33
Bandelier National Monument	HCN	Los Alamos	7.93
Angel Fire 10.2 SSE	CoCoRaHS	Colfax	7.40
Los Posos	DRI	Sandoval	7.33
Bitterlakes	COOP	Chaves	6.47
House 0.1 S	CoCoRaHS	Quay	5.74
Socorro 9.9 SSE	CoCoRaHS	Socorro	5.72
Tijeras 5 E	CoCoRaHS	Bernalillo	5.49
Pasamonte	COOP	Union	5.37
Melrose Range	RAWS	Roosevelt	5.33
Edgewood 3.4 NW	CoCoRaHS	Santa Fe	5.23
Edgewood 7.0 SSW	CoCoRaHS	Torrance	4.54
Abiquiu 7.5 WNW	CoCoRaHS	Rio Arriba	4.38
Brushy Mountain	RAWS	Cibola	4.05
Melrose	COOP	Curry	4.03
Rosebud 7 NW	COOP	Harding	3.90
Valdez 1.5 NNW	CoCoRaHS	Taos	3.75
Mesa Chivato	RAWS	McKinley	3.73
Aztec Ruins	COOP	San Juan	2.68
Belen 9.3 SE	CoCoRaHS	Valencia	2.59
Vaughn	HCN	Guadalupe	2.55

HADS = Hydrometeorological Automated Data System; CoCoRaHS = Community Collaborative Rain, Hail, and Snow Network; HCN = Historical Climate Network; DRI = Desert Research Institute; RAWS = Remote Automated Weather Stations

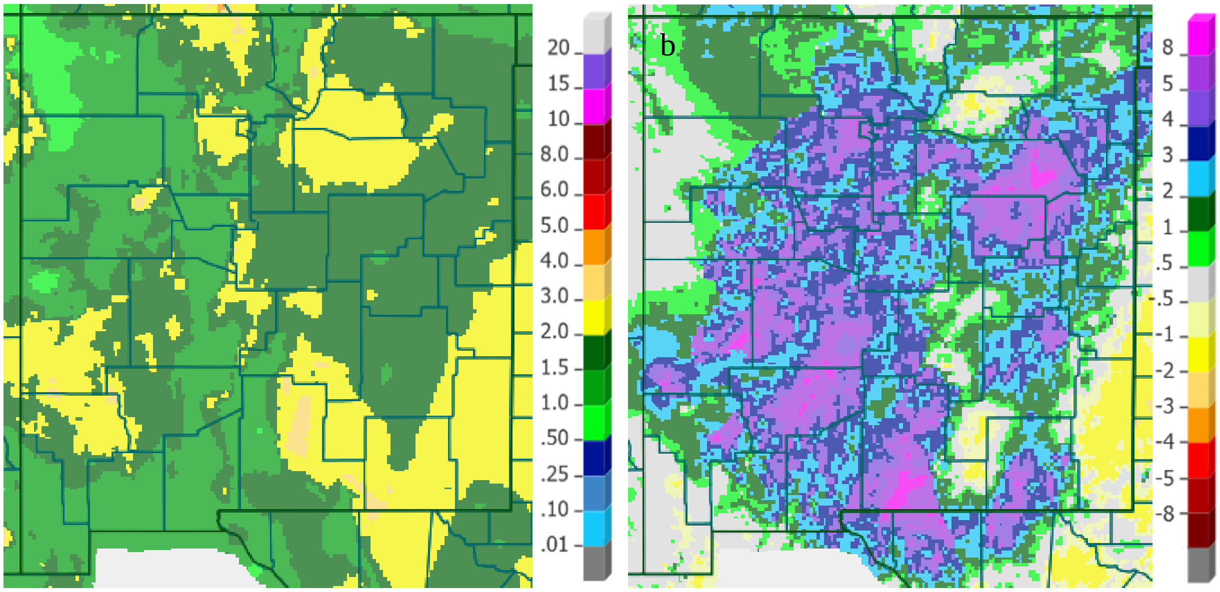


Fig. 8: (a) September normal precipitation (inches) and (b) departure from normal (inches) for September 2013

4.3 Los Alamos Precipitation

The meteorology towers across Los Alamos captured the intense rainfall in September 2013 (Table 2). The total precipitation at the Los Alamos station from 10–18 September was 7.66 inches. The heaviest precipitation during the event occurred on 13 September measuring 3.52 inches at TA-06, which broke the record for highest daily precipitation from 5 October 1911 that recorded 3.48 inches. The most intense 15-minute rainfall on 13 September occurred at 1415 UTC (8:15 A.M. MDT) with 0.73 inches. A trace occurring on 17 September indicates less than 0.01 inches. September 2013 was the wettest September on record for Los Alamos and the third wettest month on record behind August 1952 and 1923.

Table 2: Los Alamos 24-hour Precipitation (inches) from 10–18 September 2013

Date	TA-06	TA-49	TA-53	TA-54
10 Sep	1.35	1.40	1.21	1.37
11 Sep	0.10	0.08	0.05	0.02
12 Sep	1.72	1.18	1.14	1.79
13 Sep	3.52	2.90	2.58	2.49
14 Sep	0.33	1.77	0.45	0.90
15 Sep	0.03	0.08	0.04	0.12
16 Sep	0.00	0.00	0.00	0.00
17 Sep	Trace	0.00	0.00	0.00
18 Sep	0.61	0.02	0.36	0.11
Total:	**7.66**	**7.43**	**5.83**	**6.80**

The variation in precipitation across Los Alamos from 10–15 September 2013 with respect to elevation is shown in Fig. 9. In the case of the September 2013 event for Los Alamos, the higher elevations received substantially more precipitation compared with lower elevations. The total precipitation increases from LANL in the east to the Jemez Mountains in the west. Across LANL, the measured precipitation was ~6 inches with little variability. Thus, the measurement at TA-06 adequately represents the precipitation across LANL for this storm. Precipitation measurements significantly increase at higher elevations (above ~8000 ft) recording ~17 inches. The maximum measured precipitation was 18.3 inches and the minimum was 4.78 inches. The storms most likely developed over the Jemez Mountains and drifted to the east over Los Alamos as a result of the southwesterly flow at 500-hPa.

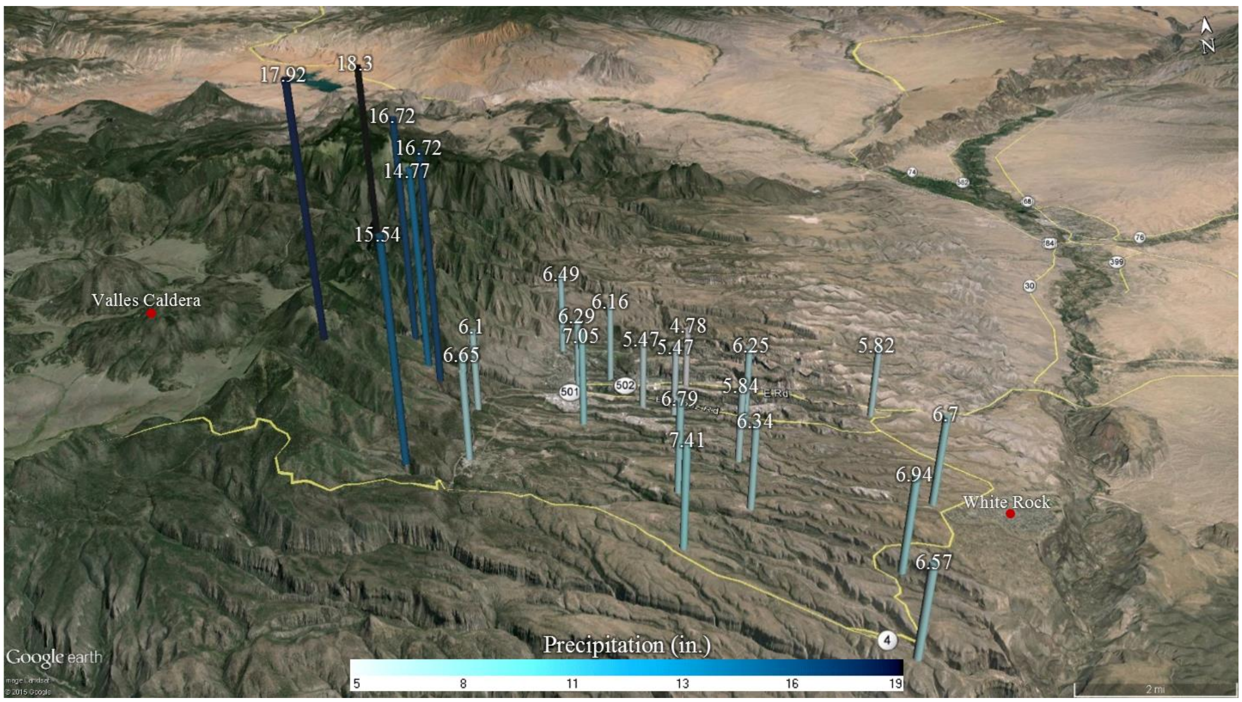


Fig. 9: Precipitation measurements across Los Alamos from 10–15 September 2013

The heavy rainfall measurements shown in Fig. 9 can be compared with PW to understand the available moisture over Los Alamos. Figure 10 shows the PW across New Mexico on 13 September 2013. The climatological median moving average of PW in Albuquerque on 13 September is 0.66 inches (18.3 mm). Southern and eastern New Mexico exceeded 40 mm at 0 UTC (Fig. 10a), significantly above average for the region. From 0–12 UTC (Figs. 10a–c), the PW over Los Alamos remained nearly constant of <30 mm. By 18 UTC (Fig. 10d), the PW across the state decreases as the atmospheric moisture was most likely precipitating out of the atmosphere. The measured precipitation on 13 September exceeded the available PW directly over Los Alamos. The heavy rainfall for Los Alamos on 13 September was most likely the result of the entrainment of moisture from the southeast in order to achieve such heavy precipitation measurements.

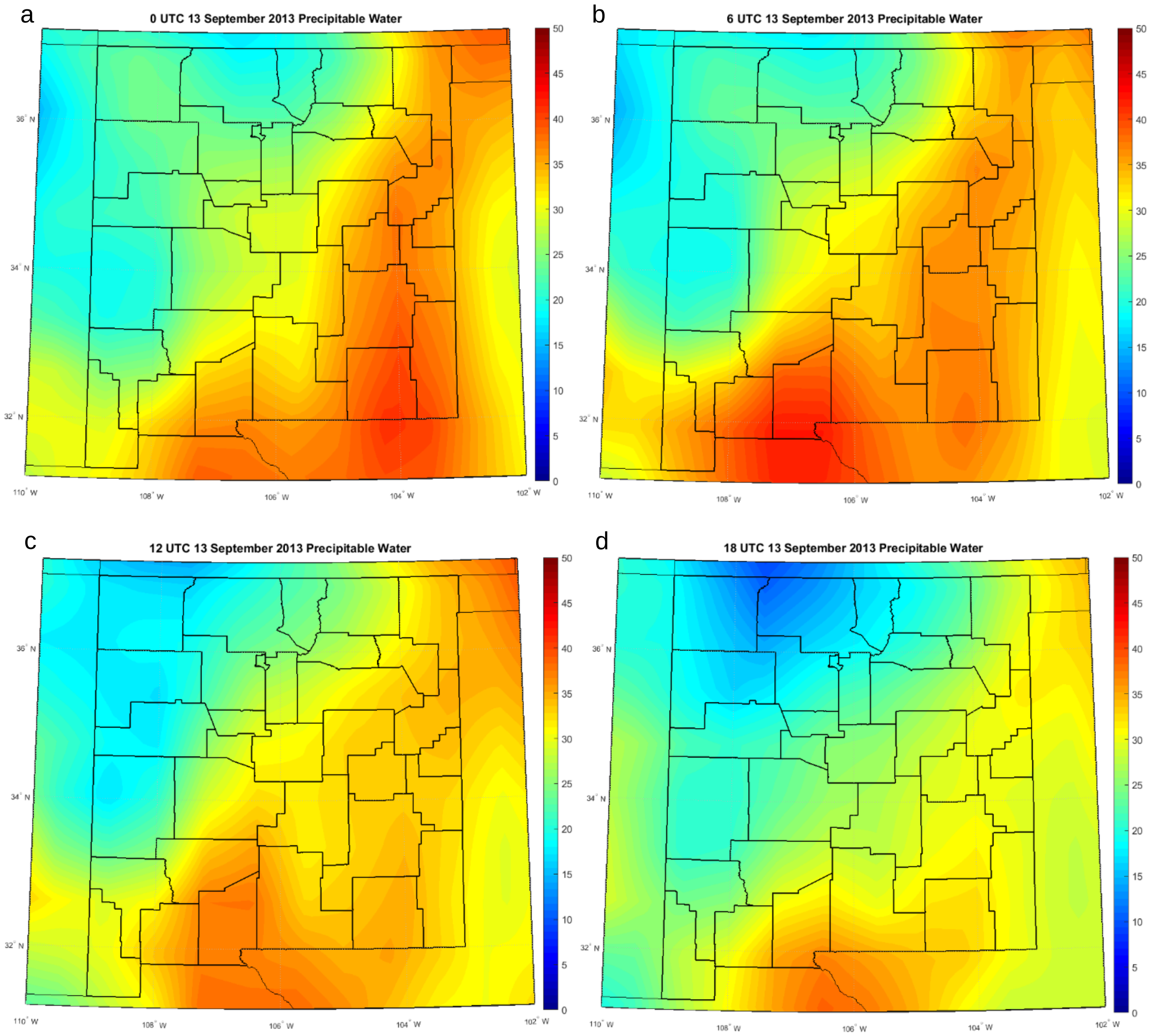


Fig. 10: PW (color shading in mm) across New Mexico at (a) 0, (b) 6, (c) 12, and (d) 18 UTC 13 September 2013

4.4 Topographic Forcing

The topographic forcing during the heaviest precipitation for Los Alamos on 13 September is shown in Fig. 11. The wind from the southeast caused upslope flow as the air ascended the Jemez and Sangre de Cristo Mountains (Fig. 10a). The winds traveling on the leeward side of the mountains flowed downslope and caused evaporation. By 6 UTC (Fig. 10b), the slight shift in wind direction closer to southerly causes stronger upslope flow for both mountain ranges. A maximum in southerly wind at 12 UTC (Fig. 10c) causes a maximum in topographic forcing for the Jemez and Sangre de Cristo Mountains. The strongest forcing covered most of the Jemez Mountains at this time to create significant uplift over the mountains. This maximum in topographic forcing occurred 2 hours prior to the heaviest 15-minute precipitation measured by TA-06 at 1415 UTC. The substantial upslope flow at 12 UTC helped to force moisture-laden air (Figs. 5c, 6c) deep into the atmosphere and contribute to the heavy precipitation measured at TA-06. After 18 UTC (Fig. 10d), the winds weaken and shift back to a southeasterly wind to cause weaker topographic forcing. The topographic forcing was an important factor in the heavy rainfall for Los Alamos during the September 2013 event.

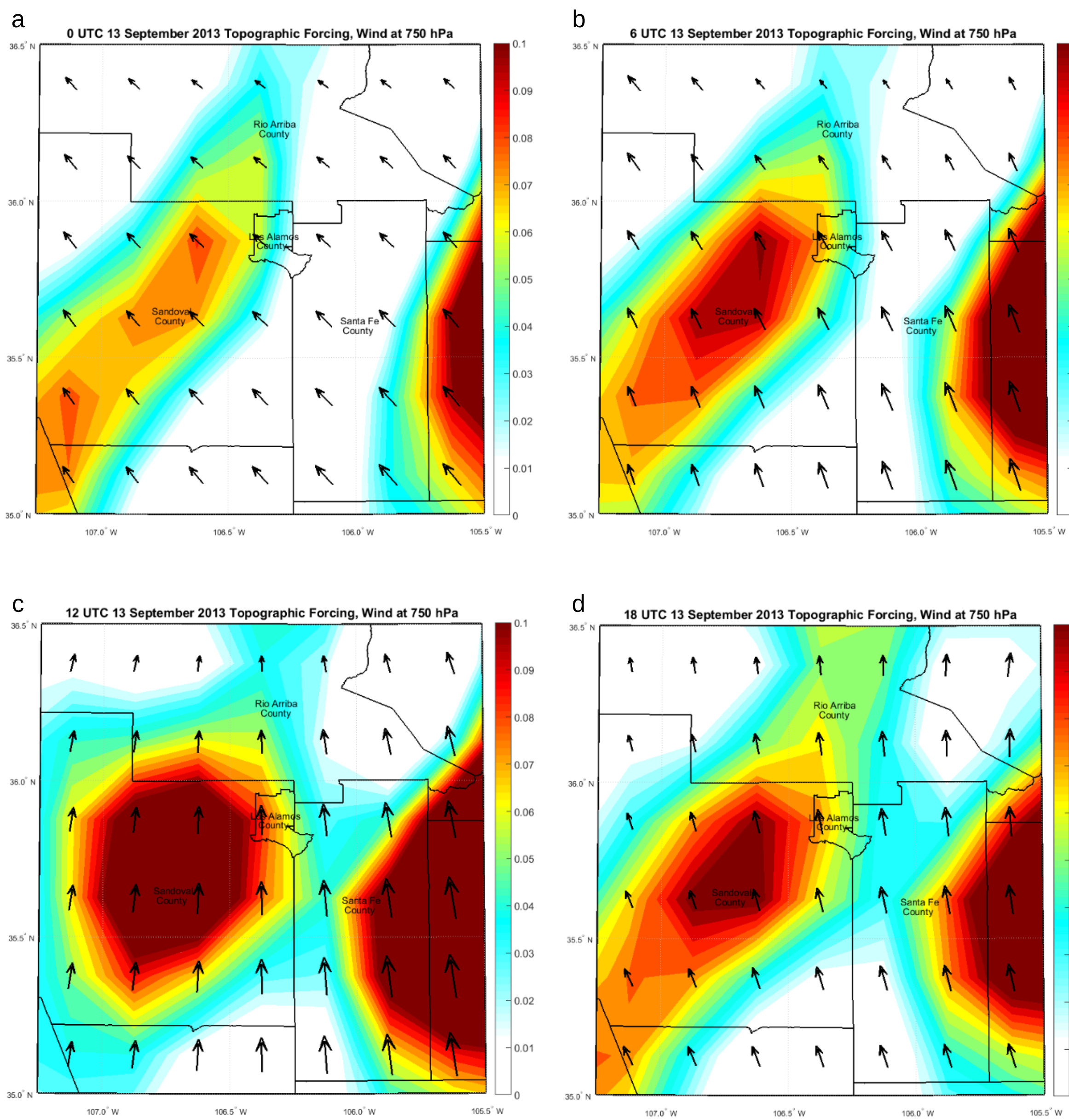


Fig. 11: Topographic forcing (color shading) and winds at 750-hPa (vectors) during the most intense precipitation at (a) 0, (b) 6, (c) 12, and (d) 18 UTC 13 September 2013

5.0 COMPOSITE OF SUMMERTIME HEAVY RAINFALL EVENTS

5.1 Selected Precipitation Events

As shown in the September 2013 event, the favorable wind direction, ample moisture, and topographic forcing helped to cause the record rainfall for Los Alamos. A goal of this study was to understand the summertime meteorological conditions that cause heavy rainfall events for Los Alamos. An evaluation of the synoptic meteorology and topographic forcing during historically significant rainfall events helps to achieve this goal. The strongest daily rain events previously observed in Los Alamos since 1910 are shown in Table 3.

Table 3: Strongest Daily Rain Events in Los Alamos Recorded History

Date	Precipitation Total (inches)
13 Sep 2013	3.52
05 Oct 1911	3.48
10 Jun 1913	2.51
31 Jul 1968	2.47
01 Aug 1951	2.26
22 Sep 1929	2.21
17 Oct 1944	2.20
07 Jun 1987	2.16
19 Oct 1957	2.06
10 Aug 1925	2.05
10 Jun 1988	2.05
25 Aug 2006	2.02
14 Jul 1930	1.98
14 Oct 1994	1.97
20 Aug 1952	1.92
21 Aug 2011	1.89

Included in this study are all storms that occurred since 1979 to accommodate data availability from the ERA-Interim. Another selection criteria included the elimination of storms if there were tropical storms near New Mexico in the eastern Pacific and Mexico. The events chosen for this study include the storms in 1987, 1988, 2006, 2011, and 2013.

A composite of the heavy rainfall events provide an average of the meteorological conditions. The initial analysis time (T = 0) was defined as the time of heaviest precipitation for each event. The composite calculations range from 12 hours before (T - 12) and 12 hours after (T + 12) the initial analysis time at 6-hour intervals. For example, the heaviest precipitation during the September 2013 storm occurred at ~14 UTC 13 September. Thus, the nearest model data at 12 UTC refers to T = 0, 0 UTC 13 September to T – 12, and 0 UTC 14 September to T + 12.

5.2 Composite Synoptic Perspective

The composite large-scale atmospheric flow is shown in Fig. 12. The synoptic composite shows similar characteristics to Fig. 5 during the September 2013 event. An upper-level trough is approaching from the west coast and a ridge is to the east of New Mexico at T – 12 (Fig. 12a) with winds from the southeast. As the trough propagates to the east, the associated winds from the south and southwest approach New Mexico by T = 0 (Figs. 12b, 12c). At T = 0, the relative humidity for northern New Mexico is near 60%, significantly less than the moisture during the September 2013 event. The maximum moisture is from the south and east with southerly winds that advect the moisture to New Mexico. The southwesterly winds continue at T + 6 (Fig. 12d) and shift back to southerly winds by T + 12 (Fig. 12e). Interestingly, the maximum moisture for northern New Mexico occurs at T + 12.

5.3 Composite Topographic Forcing

The composite topographic forcing near Los Alamos is shown in Fig. 13. Compared with the September 2013 event, the topographic forcing and wind speeds were less for the composite. Wind directions varied from southeasterly at T – 12 (Fig. 13a) to southwesterly by T = 0 (Fig. 13c). The lower topographic forcing for the composite was a result of the weaker wind speeds at 750-hPa. The topographic forcing for the Jemez Mountains remained nearly constant throughout the period as the wind speeds did not vary. The composite topographic forcing varied from 13 September 2013 as the strongest forcing was predominantly over the southwest region of the Jemez Mountains, where winds from the south and southwest would significantly contribute to upslope flow. Nevertheless, the varying southerly winds caused upslope flow during the previous storms and this contributed to lifting moist air deep into the atmosphere. For previous heavy rainfall events in Los Alamos, topographic forcing played an important role in forcing air aloft.

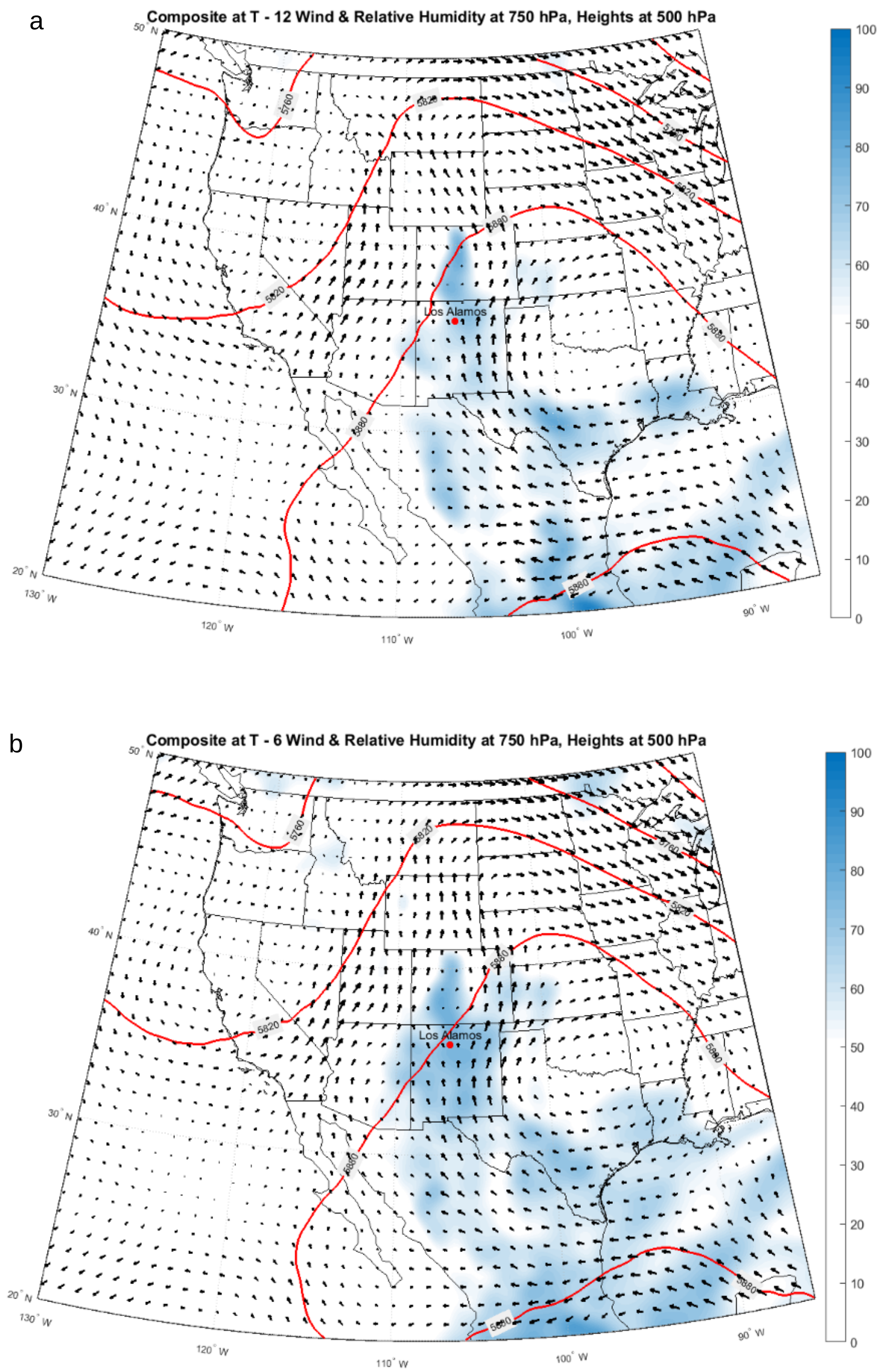
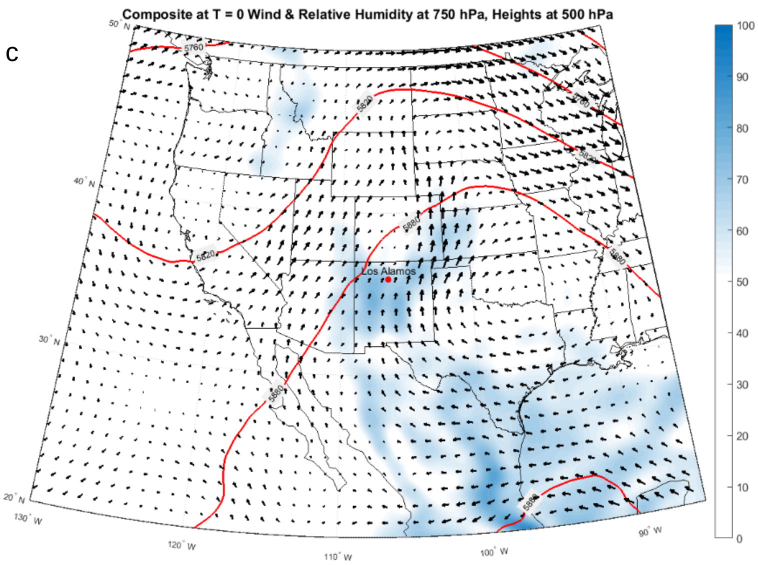
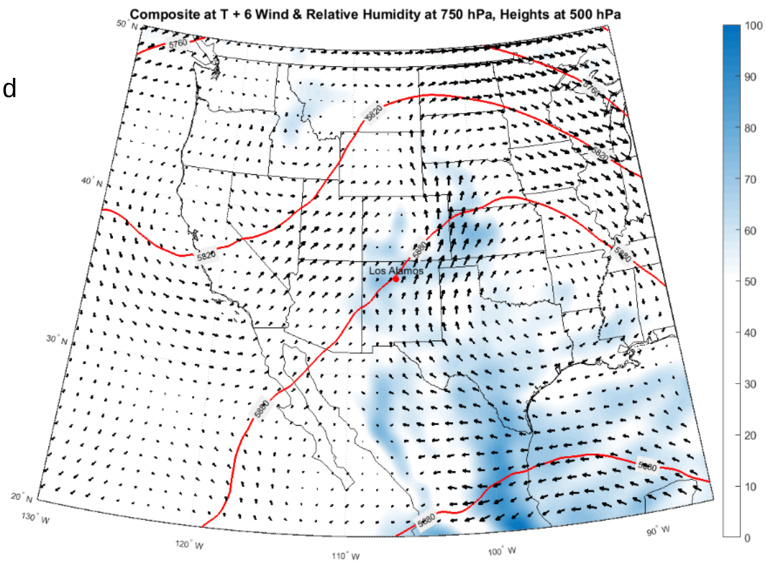


Fig. 12: Composite of relative humidity (color shading in %), geopotential heights (m), and winds (vectors) for heavy rainfall events at (a) T – 12, (b) T – 6, (c) T = 0, (d) T + 6, and (e) T + 12

c



d



e

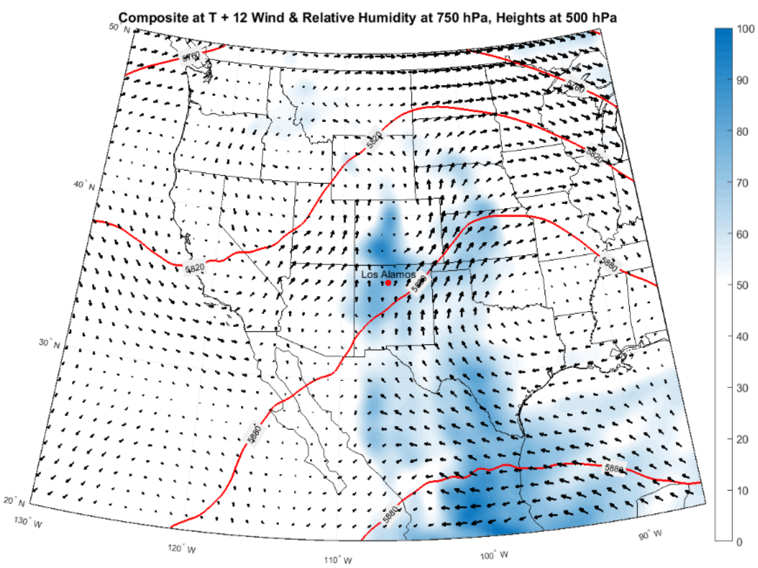


Fig. 12: (continued)

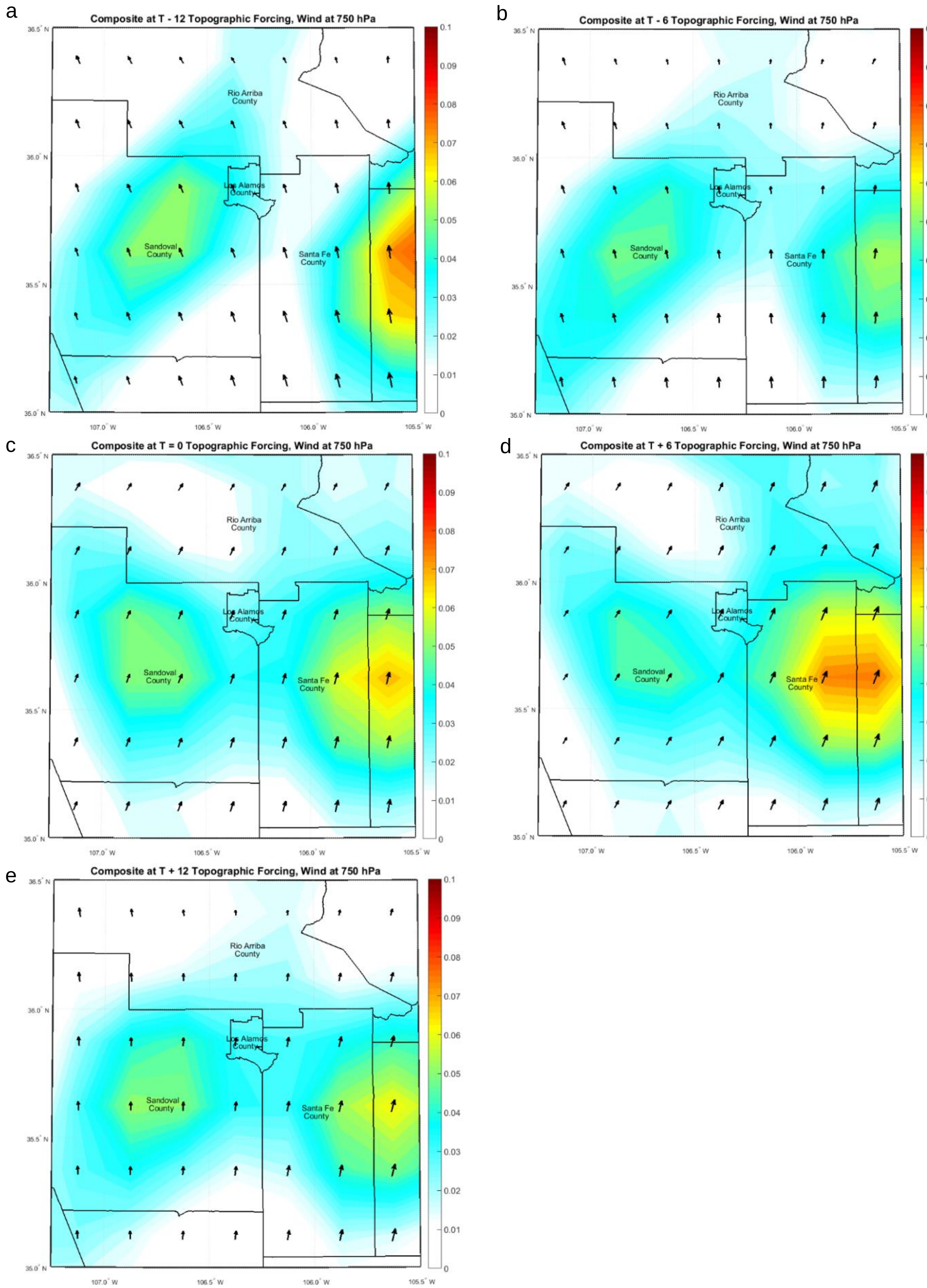


Fig. 13: Composite topographic forcing (color shading) and winds (vectors) at (a) T – 12, (b) T – 6, (c) T = 0, (d) T + 6, and (e) T + 12

6.0 DISCUSSION AND CONCLUSIONS

The historic rainfall event for Colorado and New Mexico during September 2013 caused devastating flooding for several areas. For Los Alamos, the most intense rainfall occurred on 13 September with a record daily precipitation of 3.52 inches. This study focused on the potential causes for such a strong event. A cutoff low over Utah and Nevada coupled with a high pressure system over the south central states helped to draw moisture from the south and east (Fig. 5). The southerly winds advected moisture from the Gulf of Mexico to the desert southwest. The moist air was then forced to interact with the complex terrain of New Mexico. For Los Alamos, the influence of the terrain forced the moist air deeper into the atmosphere and produced showers over the Jemez Mountains. The southwesterly flow at 500-hPa then transported the storms to the east toward Los Alamos. Various measurements across Los Alamos from 10–15 September recorded more precipitation over higher elevations of the eastern Jemez Mountains compared with the lower elevations of the Pajarito Plateau (Fig. 9). The Sangre de Cristo Mountains do not have as many station observations as Los Alamos, but the ample moisture (Figs. 5, 6) and strong topographic forcing (Fig. 11) caused heavy precipitation over the mountains. The record daily precipitation on 13 September measured in Los Alamos most likely was a result of strong moisture advection from the south and east, strong topographic forcing, and the entrainment of significantly above average PW to the southeast (Fig. 10).

A composite of summertime heavy rainfall events for Los Alamos showed similar results to the September 2013 event. New Mexico was between an upper-level trough and cyclonic circulation to the west, and an upper-level ridge and anticyclonic circulation to the east (Fig. 12). These circulations helped draw moisture from the south toward New Mexico. This moist air interacted with the complex terrain and was forced aloft. The composite of topographic forcing was not as strong as the September 2013 event, but was still significant in lifting moist air into the atmosphere to cause precipitation (Fig. 13). Therefore, it can be concluded that Los Alamos typically receives heavy rainfall during the summer as a result of southerly winds that advect moisture from the south, the moist air is forced aloft due to the Jemez Mountains, and the precipitation is subsequently transported toward Los Alamos. Compared with previous storms in the composite, the magnitude of wind speed, relative humidity, and topographic forcing during the September 2013 event was significantly higher and contributed to the record rainfall.

An uncertainty in the topographic forcing calculations is the result of the resolution used for the topography. The resolution of the meteorology data and topography are equal such that the high resolution shown in Fig. 2, that includes valleys and canyons, is not the resolution used for this study. Therefore, the topographic forcing in this study represents the general forcing by the Jemez and Sangre de Cristo Mountains at coarse resolution.

The availability of past meteorological observations hinders the composite calculations. The composite plots were developed from five strong rainfall events since 1979. However, Los Alamos has experienced several heavy rainfall events that occurred prior to 1979, including eight storms in the top 10 daily precipitation events (Table 3). Thus, the composite represents a general synoptic setting of summertime heavy rainfall events for Los Alamos based on recent storms. The addition of future heavy rainfall events to the five storms included in the composite will help improve our understanding of the factors that produce the significant rainfall for Los Alamos. Future studies will evaluate the meteorological conditions for heavy precipitation events occurring in the winter months.

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