How Rare Was the August 2016 South-Central Louisiana Heavy Rainfall Event?

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ABSTRACT

This study examines the spatiotemporal characteristics of the historic 10–14 August 2016 south-central Louisiana precipitation event. The storm was the result of a moisture-rich, tropical low pressure system, also known as a tropical easterly wave, that slowly tracked westward along the Gulf Coast from Florida to Texas. Once over south-central Louisiana, the storm was able to take advantage of anomalously high precipitable water, broad low-level instability, and continuous moisture inflow from the Gulf of Mexico to produce historic rainfall. Totals exceeded 254 mm (10 in.) for much of southern Louisiana, while locations adjacent to Baton Rouge and Lafayette received upward of 635 mm (25 in.). One station measured a 48-h rainfall total of 797.3 mm (31.39 in.)—the greatest 48-h total on record for Louisiana. Using calibrated radar data, the Storm Precipitation Analysis System (SPAS) revealed that one location likely received >864 mm (34 in.) of precipitation during the duration of the storm, well over the estimated 1000-yr return interval. A synoptic discussion of the event and analysis of the storm's recurrence interval helps place this storm in a historical context.

1. Introduction

Louisiana is the wettest state in the conterminous United States based on data from the National Centers for Environmental Information (NCEI) (Faiers et al. 1994). The state frequently experiences flood-producing rainfall events, primarily induced by fronts and strong convection (Keim and Muller 1992; Faiers et al. 1994), but tropical systems are also prominent (Keim 1996). For example, the 1-day precipitation record for Louisiana, 558.8 mm (22 in.), was caused by a weak tropical wave on 29 August 1962. Despite a long history of heavy rainfall, Louisiana experienced an event on 10–14 August 2016 that set numerous meteorological and hydrologic records (Table 1). The storm produced a measured 48-h rainfall accumulation of 797.3 mm (31.39 in.; Fig. 1), the greatest 48-h recorded rainfall in Louisiana, surpassing the previous 2-day state record of 739.65 mm (29.12 in.) by 57.7 mm (2.27 in.). The storm also produced a record flood stage of 14.08 m (46.2 ft) on the Amite River at Denham Springs, Louisiana, breaking the previous record of 12.65 m (41.5 ft) by 1.43 m (4.7 ft) that was set during the historic 6–8 April 1983 flood (Muller and Faiers 1984).

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TABLE 1. Rainfall totals (mm) for 1-, 2-, 3-, 7-, and 10-day durations across south-central Louisiana during the August 2016 event. Stations above the blank row are National Weather Service Cooperative Observer Program (COOP) gauges. Below the blank row are Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) gauges. Bold values indicate stations records for their respective period of record (POR). Stations records were not investigated for CoCoRaHS stations because of their short POR.

Station	1 day	2 days	3 days	7 days	10 days
Opelousas	**317.5**	**356.8**	**392.4**	406.2	423.2
Baton Rouge, Concord	**223.5**	**360.7**	390.6	437.9	485.6
Baton Rouge AP	285.5	**377.2**	**435.6**	**586.7**	**658.1**
Baton Rouge Sherwood	242.3	**382.8**	**416.8**	445.8	464.3
Livingston	287.3	**555.2**	**648.2**	**724.9**	**744.2**
Norwood	**285.5**	**543.6**	**568.9**	**617.2**	**635.8**
Abbeville	243.1	416.1	475.5	536.9	545.3
Crowley	303.8	418.6	425.5	465.8	473.9
Jennings	211.8	**399.0**	405.9	**490.7**	532.4
Donaldsonville	172.7	343.7	372.4	423.4	452.9
Jeanerette	222.3	336.6	429.0	**469.9**	482.6
Lafayette	**264.1**	**528.1**	**540.3**	**600.2**	**608.6**
New Iberia	**343.9**	**546.4**	**580.1**	**673.4**	**703.8**
Gonzales	191.1	330.7	356.9	410.2	456.9
Watson	—	797.3	797.3	797.3	797.3
Brownfields	407.7	681.5	708.2	745.2	767.8
Denham Springs	360.4	654.1	701.0	771.4	798.3
Monticello	393.2	610.1	644.9	686.8	716.3
Central	281.9	561.3	587.8	608.1	626.9
Wakefield	372.1	538.5	563.9	585.5	595.6
Jackson	448.3	534.4	574.8	598.2	598.2

The storm system originated near Florida on 3 August 2016 and slowly migrated along the northern Gulf Coast, dissipating nearly two weeks later over Texas. Thirteen people were killed by flooding and an estimated 140 000 structures were inundated (Baton Rouge Area Chamber 2016). Roughly three-quarters of all homes in Livingston Parish and one-third in Ascension Parish received some type of flooding. Of those, nearly 50 000 homes had major flooding [≥457 mm (18 in.) of water within the home]. While the number of housing units in Livingston and Ascension parishes roughly tripled since the historic April 1983 flood, nearly 10 times as many homes had major flooding due to the 2016 storm (Colten 2017).

Louisiana Economic Development (LED) estimated the event caused roughly $8.7 billion in damage, primarily to commercial and residential properties. LED also asserted approximately 278 500 residents of Louisiana were unable to work because of interruptions due to the event, translating to roughly 14% of the Louisiana workforce (Louisiana Economic Development 2016). Analysis from the Louisiana State University (LSU) AgCenter estimated a loss of roughly $110 million to agriculture, with soybeans and rice being the hardest hit commodities (Guidry 2016). The event caused the state of Louisiana to request $4 billion in disaster relief and affected thousands of people across the region. For comparison, the April 1983 flooding event caused an estimated $500 million in 1983 (which equates to roughly $1.2 billion in 2016) but neither event compares to damages incurred by Hurricane Katrina, which totaled approximately $125 billion for Alabama, Florida, Louisiana, and Mississippi (NHC 2018).

The August 2016 south-central Louisiana event is one of many extreme rainfall events in recent years including but not limited to Charleston, South Carolina, in 2015 where >710 mm fell in 4 days (Kappel et al. 2015), Ellicott City, Maryland, in 2016 where 152 mm fell in 2 h, Houston, Texas (Hurricane Harvey) in 2017 where >1552 mm occurred in 5 days (Kappel and Hultstrand 2018; Kappel et al. 2019a), and Elizabethtown, North Carolina in 2018 where >1116 mm fell in 4 days (Kappel et al. 2019b; Brown et al. 2020). This research is part of a growing collection of case studies focusing on heavy and extreme rainfall events across the United States. Previous research examples include Caracena and Fritsch (1983) on the flash floods of 1978 in Texas, Leathers et al. (1998) on the January 1996 floods in north-central Pennsylvania, Keim (1998) on the historic rainfall during the coastal storm in Maine in October of 1996, Changnon and Kunkel (1999) on the July 1996 flooding in Chicago, Durkee et al. (2012) on the 1–2 May 2010 event across Kentucky/Tennessee, Keim et al. (2018) on a high-intensity rainfall event in Nashville, Tennessee, and Wang et al. (2016) and Van der Wiel et al. (2017) who performed attribution studies on the August 2016 event outlined in this paper.

The frequency and intensity of recent rainfall events, combined with the severity of the resulting floods, have raised questions as to whether changes in the global climate have had an impact on the extreme precipitation climatology (Keim et al. 2018). Recent research has attempted to quantify the relationship between changes in the climate and the probability of extreme events (see Van der Wiel et al. 2017; Van Oldenborgh et al. 2017). Van der Wiel et al. (2017), using both observational data and model output, suggested that extreme precipitation events have become more likely in recent years compared to 1900 for the central U.S. Gulf Coast. They also describe that what used to be a precipitation event with a return period of 100 years should now be expected to occur, on average, once every 70 years, or even more frequently. Van Oldenborgh et al. (2017) reached similar conclusions, stating that an event like Hurricane Harvey was made 3 (1.5–5) times more likely by a warming climate. However, research by Kappel (2019) focused on the storms that are controlling of probable

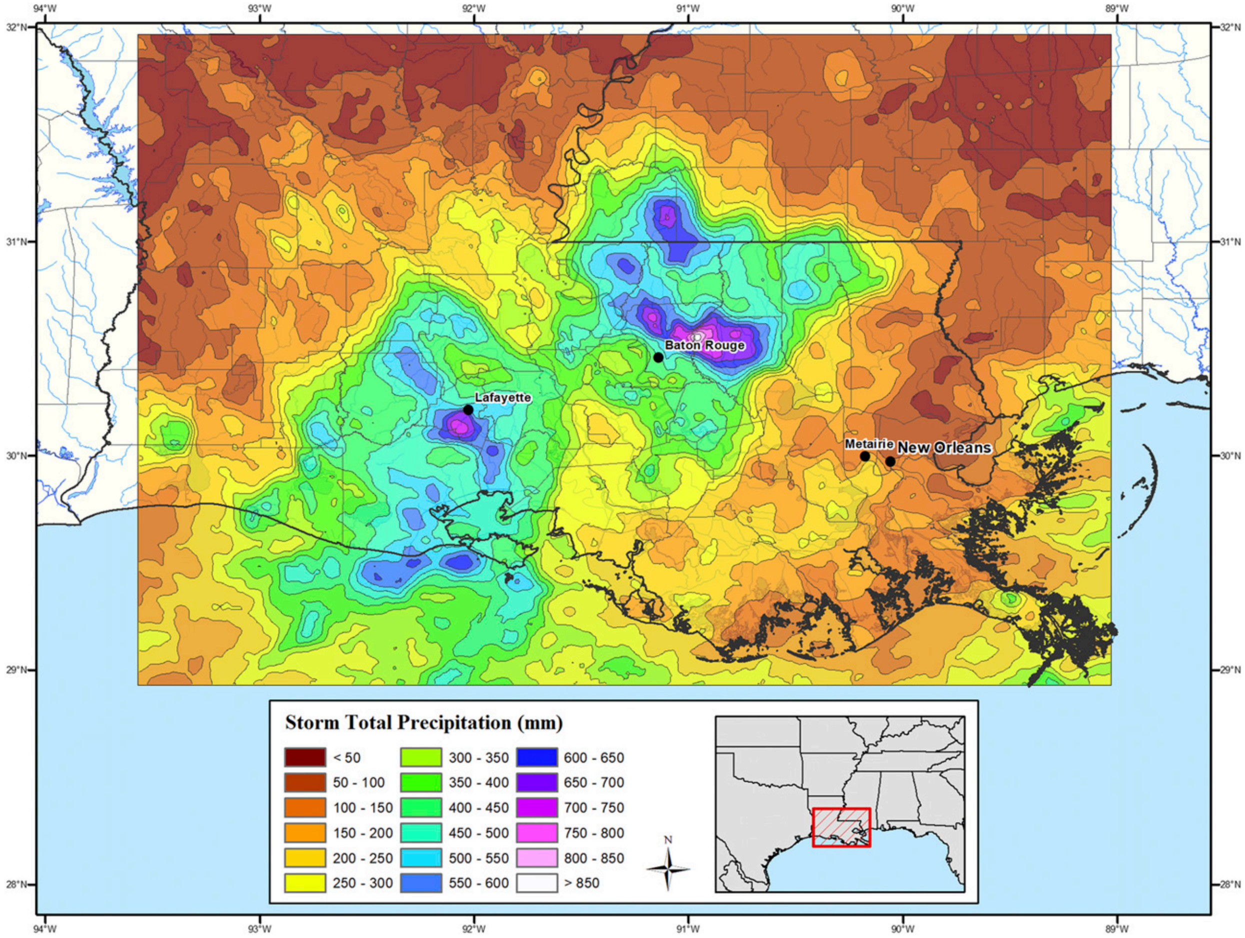

FIG. 1. Total storm rainfall isohyets generated by the Storm Precipitation Analysis System (SPAS) across southern Louisiana during 10–14 Aug 2016.

maximum precipitation (PMP), generally the most extreme of all rainfall events, including the August 2016 rainfall. That analysis, which investigated the date of occurrence of PMP-controlling storms, showed no increasing trend (in frequency) over the past 150 years. Therefore, at least for the most extreme rainfall events, there is uncertainty regarding the effects of climate change on extreme rainfall production.

The purpose of this case study is to examine the August 2016 event from both a meteorological and climatological perspective and is guided by three main objectives:

1) to examine the synoptic setting of the event,
2) to assess the spatiotemporal pattern of precipitation, and
3) to place this storm in a historical context using average return intervals (ARIs) and annual exceedance probabilities (AEPs).

The following sections describe the data and methods, a discussion of the synoptic characteristics of the event, the spatiotemporal pattern of rainfall, and resulting flooding that places this storm in a historical context.

2. Data and methods

To assess the spatiotemporal patterns of rainfall, point rainfall totals (observed gauge) and the Storm Precipitation Analysis System (SPAS; Parzybok and Tomlinson 2006; Hultstrand and Kappel 2017) were used. Point rainfall totals were examined from 14 National Weather Service (NWS) Cooperative Observer Program (COOP) and 7 Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) rainfall gauges (Table 1). Since the CoCoRaHS network is relatively new, most stations have a short period of record. Nonetheless, CoCoRaHS stations recorded some of the highest rainfall totals during the event and the inclusion of these data provide clarity on the spatiotemporal variability of rainfall.

To place the rainfall in a historical context, observed point precipitation values are compared with National

Oceanic and Atmospheric Administration's (NOAA) Atlas 14 (Perica et al. 2013) point precipitation average recurrence intervals (ARI; or average return period). ARI's indicate the average time between events of a given magnitude when averaged over a long period (Lincoln 2014; Lincoln et al. 2017) and are frequently calculated for an event for a range of different durations, typically from hours to days (i.e., Keim 1998). NOAA Atlas 14 contains rainfall durations extending from 5 min to 60 days with recurrence intervals ranging from 1 to 1000 years. Partial duration series (PDS)-based rainfall frequency estimates are an expressed value reported with their corresponding 90% confidence intervals. As the duration and average recurrence intervals increase, the confidence interval widths increase as well, resulting from variability in precipitation and the rare nature of extreme events. The annual exceedance probability (AEP), the probability that an event of the given magnitude will occur within any given year (one divided by ARI), is more commonly used to describe the rare nature of an event to the public (Lincoln et al. 2017). Recent studies (Parzybok et al. 2011; Parzybok and Shaw 2012; Keim et al. 2018) have described rainfall totals in terms of both ARI and AEP to better define the historical nature of a storm.

To provide additional detail on the spatial pattern of rainfall, the storm is further examined using SPAS (Parzybok and Tomlinson 2006; Hultstrand and Kappel 2017). SPAS is a gridded rainfall analysis software package that combines all available rainfall data, including rain gauge (subhourly, hourly, and daily), supplemental/bucket survey rainfall, dynamically calibrated NEXRAD weather radar data, and climatological base maps. The combination of these sources produces a high resolution, spatially continuous gridded analysis of rainfall totals. Rainfall values are produced at time intervals as short as 5 min, and at spatial scales as fine as 1 km^2 (Parzybok and Tomlinson 2006; Hultstrand and Kappel 2017). The system is designed to produce a precise representation of accumulated rainfall in both space and time across the event domain. Additional information on the SPAS system is available in Parzybok and Tomlinson (2006), Hultstrand and Kappel (2017), and Keim et al. (2018). Here we use SPAS to generate maximum 6-, 24-, 48-, and 72-h precipitation, as well as AEP, at each gridded location for the duration of the August 2016 event.

To quantify the magnitude and extent of the precipitation, depth–area–duration (DAD) tables and mass curves were generated, using SPAS, for two separate zones (Fig. 2) impacted by the storm. This type of analysis is important for evaluating hydrological impacts because it provides an estimate of the volume of rainfall that fell over various area sizes during the storm. Two zones were delineated because there were two distinct precipitation maximums produced by the storm that varied in time and location. Zone 1 encompasses Baton Rouge, Watson, and other areas that were impacted by the storm 12–24 h earlier than locations in zone 2 like Lafayette and Abbeville. Producing one DAD table for the entire storm would have cojoined the two distinct precipitation maxima, creating an unrealistic characterization of the spatial extent of the heaviest rainfall.

3. Results

a. Synoptic summary

1) THE INITIAL DISTURBANCE

The following section outlines antecedent upper air conditions (Fig. 3), observed rainfall totals (Fig. 4), meteorological setting (Fig. 5), and skew-*T* information (Fig. 6) of the storm. From 3 to 9 August 2016, a disturbance near the northeast Gulf of Mexico coast, associated with an upper-level low, slowly propagated along the panhandle of Florida. On 5 August 2016, the Weather Prediction Center (WPC) and National Hurricane Center (NHC) issued discussions concerning a slow-moving, moisture-rich trough (tropical wave) over the west-central Florida coast and eastern Florida panhandle. Surface maps first identified an elongated area of low pressure (trough) on 5 August. The NHC assigned a 20% chance of tropical development and noted that although the disturbance was embedded in tropical moisture, it lacked a low-level wind field and well-defined center of circulation, thus disqualifying it at as a tropical depression (Van der Wiel et al. 2017). At 0000 UTC 6 August 2016, the disturbance at 500 hPa was located south of Apalachicola, Florida. The disturbance was vertically stacked, or located similarly at all levels of the atmosphere, at 500 and 850 hPa but was not present at the surface or above 500 hPa. By 0600 UTC 7 August 2016, a surface low pressure developed.

2) WESTWARD MOVEMENT TO MOBILE BAY AREA

The NHC continued to monitor the area of low pressure, but determined it was too weak for tropical cyclone formation and removed it from the discussion on 7 August 2016. From 7 to 9 August, the system continued to slowly [$\leq \sim 5.5$ kt (1 kt ≈ 0.51 m s^{-1})] move west-northwestward. Upper-level airflow across the Gulf Coast was cut off from the westerlies that were present over the majority of the United States (Fig. 3), allowing the system to migrate west-northwestward into a conducive environment for further development and enhanced instability. The weak upper-level winds (low-shear) allowed

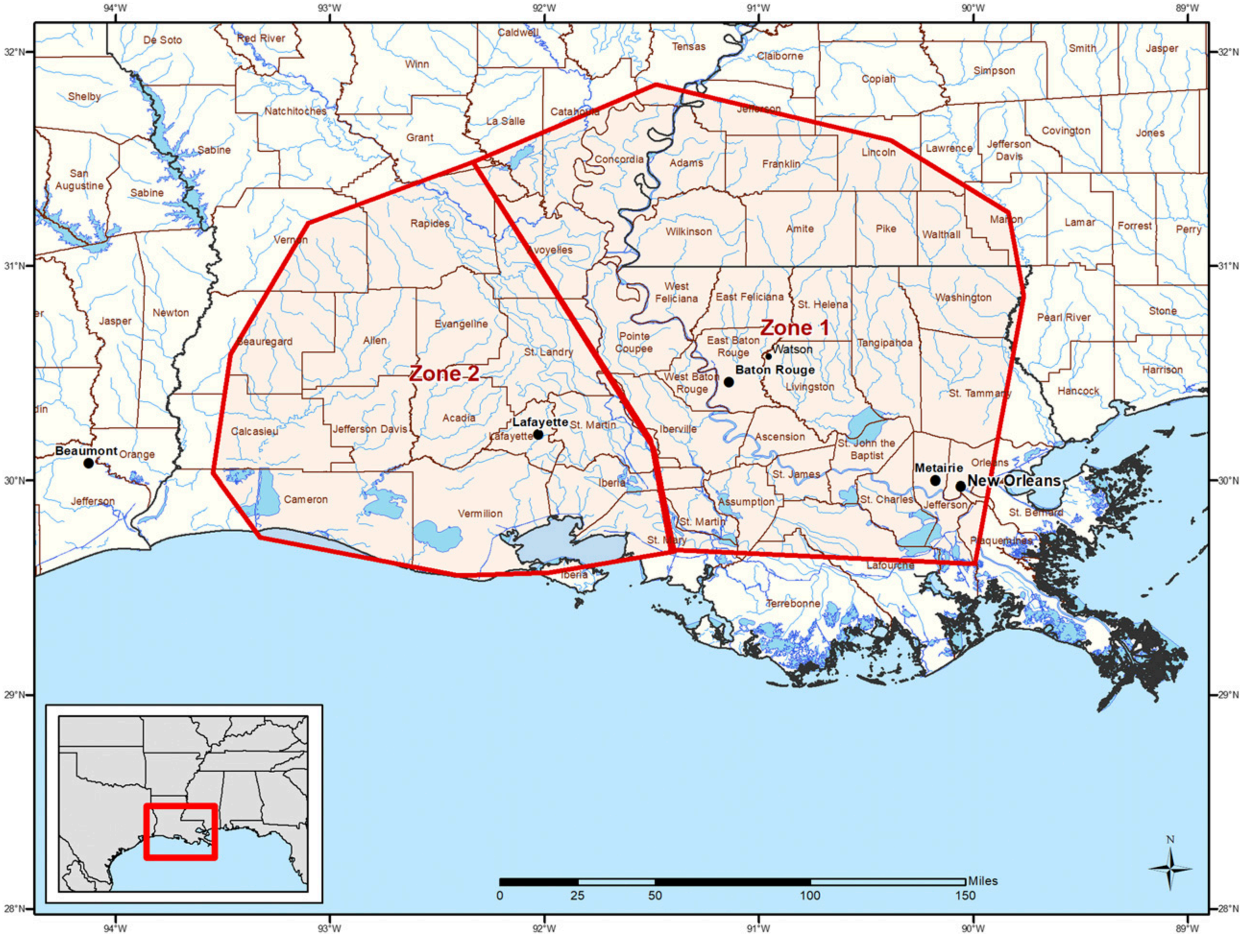

FIG. 2. Delineated SPAS zones used for DAD tables and mass curves. The storm center in zone 1 is located at Watson, LA (30.555°N, 90.965°W) and the storm center in zone 2 is located near Lafayette, LA (30.145°N, 92.085°W). Watson, Louisiana, the gauge that recorded 797.3 mm (31.39 in.) in 48 h can be seen to the northeast of Baton Rouge, LA, located beneath the "Zone 1" label.

the disorganized system to sustain itself and slowly drift into an upper-level shortwave (Fig. 3) where supergeostrophic winds were present, enhancing instability and moisture convergence focused on southern Louisiana. For more information on this interaction, see Wang et al. (2016).

The NHC again highlighted the disturbance on 9 August 2016 and monitored it until 11 August 2016. Remarks from the Tropical Weather Outlook (9–11 August; archive available at https://www.nhc.noaa.gov/data/) described a broad area of low pressure situated at the southern Mississippi–Alabama border moving west-northwestward and inland, with little to no chance for development, but indicated the potential for locally heavy rainfall along the Gulf Coast. Rainfall totals associated with the disturbance, across coastal Florida, west of Gainesville, for the 24-h period from 1200 UTC 8 August to 1200 UTC 9 August were in the 76.2–152.4 mm (3–6 in.) range (Fig. 4a).

At 0000 UTC 10 August 2016, the system was located south of Mobile, Alabama, at 500 hPa (Fig. 5a). The system was also present at 850 hPa (Fig. 5b), northeast of its 500-hPa location. At the surface, the system was located almost directly below the 850-hPa low (Fig. 5c). The system exhibited a weak slope with height toward the Gulf of Mexico rather than a vertically "stacked" structure typical of a tropical cyclone; this slope with height increased in subsequent days. As with most warm-core systems, there was little reflection of the disturbance at 200 hPa (not shown); the presence of an upper-level ridge over northern Alabama provided northeast winds. Rain showers related to the system, from 1200 UTC 9 August to 1200 UTC 10 August, were prevalent along the Florida panhandle and had shifted farther west from the previous period (Fig. 4b).

3) WESTWARD MOTION TO GRAND ISLE

The first mesoscale precipitation discussion was issued for Louisiana 1500 UTC 11 August 2016, when the system was northeast of Louisiana's southern border.

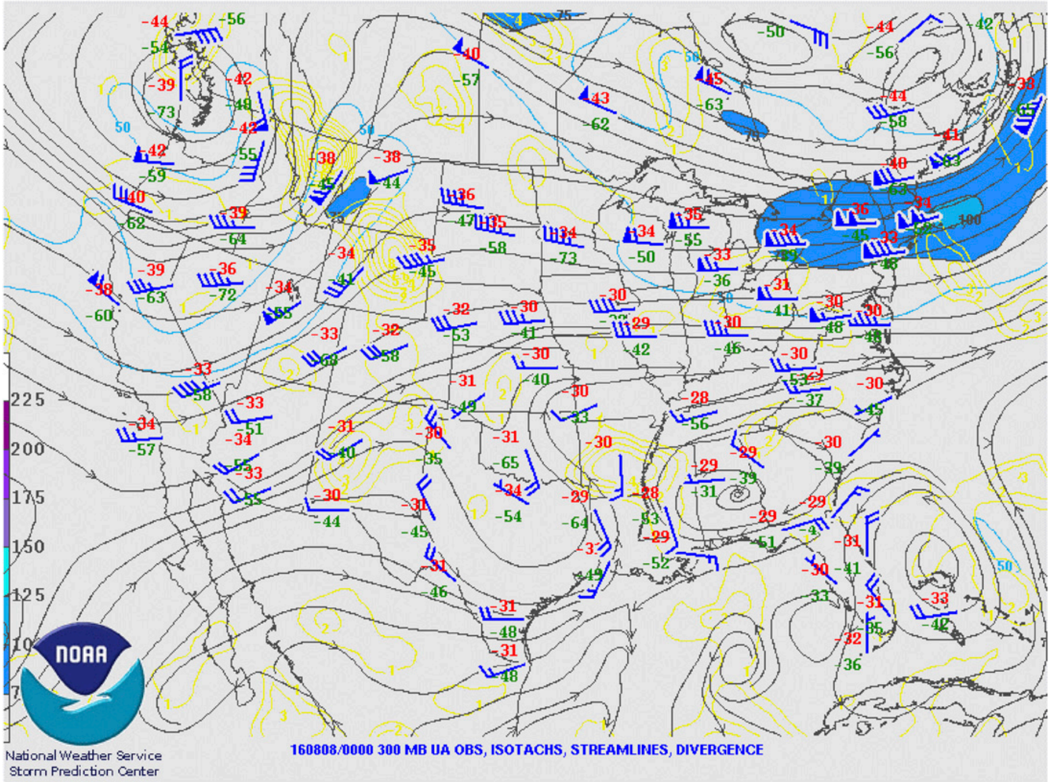

FIG. 3. The flow at 300 hPa for 0000 UTC 8 Aug 2016. From the National Weather Service Storm Prediction Center's archive found at https://www.spc.noaa.gov/obswx/maps/.

The system, which organized and was now being called a "storm," behaved similarly to an inland tropical depression; however, it exhibited weak surface winds due to a near-uniform horizontal pressure gradient. By 0000 UTC 12 August 2016, the upper-level low at 500 hPa was located on the southeast Louisiana coast near Grand Isle (Fig. 5d). At 850 hPa, the system was present in southern Mississippi, between Jackson, Mississippi, and New Orleans, Louisiana (Fig. 5e), with the surface low located near Jackson, Mississippi (Fig. 5f), indicating a large slope with height toward the Gulf of Mexico. Northerly anticyclonic flow was present around 200 hPa (not shown) with a height maximum located over northeast Texas. Rainfall totals across southern Louisiana (from 1200 UTC 11 August to 1200 UTC 12 August) increased significantly in both magnitude and spatial extent from the previous 24-h period (Figs. 4c,d).

At Slidell, Louisiana, roughly 40 km northeast of New Orleans, Louisiana, on the northeast side of Lake Pontchartrain, a radiosonde observation showed a precipitable water value of 71.22 mm (2.80 in.) at 0000 UTC 12 August 2016. By 1200 UTC, this value increased to 73.62 mm (2.90 in.), higher than the previous record at Slidell of 73.15 mm (2.88 in.) and much higher than the climatological average (see https://www.spc.noaa.gov/exper/soundingclimo/). Moderate instability was present for both soundings with CAPE of 897.1 J kg^{-1} at 0000 UTC and 848.4 J kg^{-1} at 1200 UTC. Comparing the 0000 UTC 18 August 2005 sounding at Slidell for Hurricane Katrina to this event's soundings further highlights the similarity between this storm and other tropical cyclones. Both soundings showed similar tropopause height, moisture inflow, thickness, lifted condensation levels, and above-average precipitable water values (see Fig. 6) that extend throughout the depth of the atmosphere. The most notable difference between the storms can be seen in the wind profiles. The August 2016 storm was a tropical wave without a substantial low-level wind field, while Hurricane Katrina reached category 5 status during its life cycle.

As the storm moved farther into Louisiana, the counterclockwise motion combined with its westward movement along the coast induced a southerly flow of deep moisture between 850 and 500 hPa that increased precipitable water, dewpoints, instability, and fed bands of heavy rainfall. Some of the heaviest periods of rainfall occurred between 1200 UTC 12 August and 1200 UTC 13 August (Fig. 4e). Wang et al. (2016) discussed how the presence of an upper-level trough (short-wave trough)

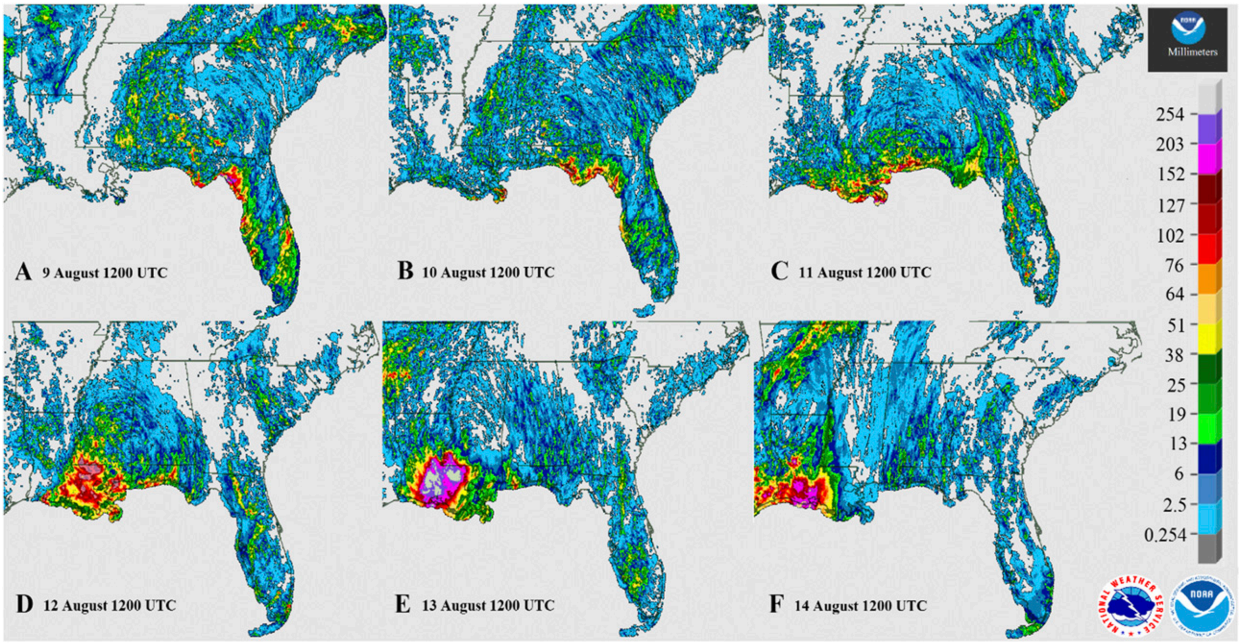

FIG. 4. National Weather Service's Advanced Hydrologic Prediction Service daily estimated precipitation for 1200 UTC (a) 9, (b) 10, (c) 11, (d) 12, (e) 13, and (f) 14 Aug. Totals (mm) represent 24-h accumulations starting the previous day at 1200 UTC. For example, (a) represents the estimated accumulation starting at 1200 UTC 8 Aug and ending at 1200 UTC 9 Aug. Available at https://water.weather.gov/precip/.

and westward migrating surface cyclone across the northern plains aided a tropical–midlatitude interaction that strengthened moisture pooling and helped the storm generate hours of heavy rainfall; however, this particular synoptic model is only applicable to this particular precipitation event in south-central Louisiana.

The lack of steering flow present in the atmosphere caused some locations to receive hours of continuous rainfall. By 0000 UTC 13 August 2016, the 500-hPa low (Fig. 5g) had moved inland of the central Louisiana coast and continued to exhibit the same slope with height toward the Gulf of Mexico. At 850 hPa (Fig. 5h) the storm was located over north-central Louisiana, with the surface low to the north and west over eastern Texas (Fig. 5i). Precipitable water values at Slidell, Louisiana, remained elevated at 64.20 mm (2.52 in.), with continued strong inflow from the Gulf (up to 250 hPa) that helped fuel moisture convergence, leading to unprecedented rainfall totals on 12–13 August (Figs. 4e,f).

4) NORTHWARD MOTION AND THE DEMISE OF THE SYSTEM

At 0000 UTC August 14, rains began to subside as the 500-hPa low moved into northern Louisiana. The surface low remained nearly stationary over eastern Texas in the previous 24 h, resulting in more of a vertically stacked meteorological environment as the 500-hPa low moved over the region. Precipitable water values at Slidell declined to 51.94 mm (2.04 in.), but southerly inflow from the Gulf of Mexico was still impressive up to 350 hPa. At 0000 UTC 15 August, precipitable water at Slidell was 57.05 mm (2.25 in.) with strong inflow from the Gulf of Mexico. However, the majority of precipitation had ended across the area of major flooding north and east of Baton Rouge. At 500 hPa, the low had weakened as it continued its northward motion into Arkansas. At the surface, the low had moved into Arkansas and became embedded along a stationary front, thus ending the deluge across Louisiana.

b. *Assessment of rainfall*

1) HOURLY RAINFALL: POINT PRECIPITATION

Reliable hourly rainfall data were investigated at three stations within the area of the event—Lafayette, Baton Rouge, and New Iberia. Observations from those stations, including traces, were examined from 10 to 14 August. The heaviest hourly rainfall observation between the three stations was 84.33 mm (3.32 in.), recorded in New Iberia at 1200 UTC 12 August 2016. This hourly observation is less than (but within the 90% confidence interval of) the mean estimated 25-yr ARI from NOAA Atlas 14, which is not particularly rare considering the overall extreme nature of this storm. Other stations across Louisiana reported similar tendencies in

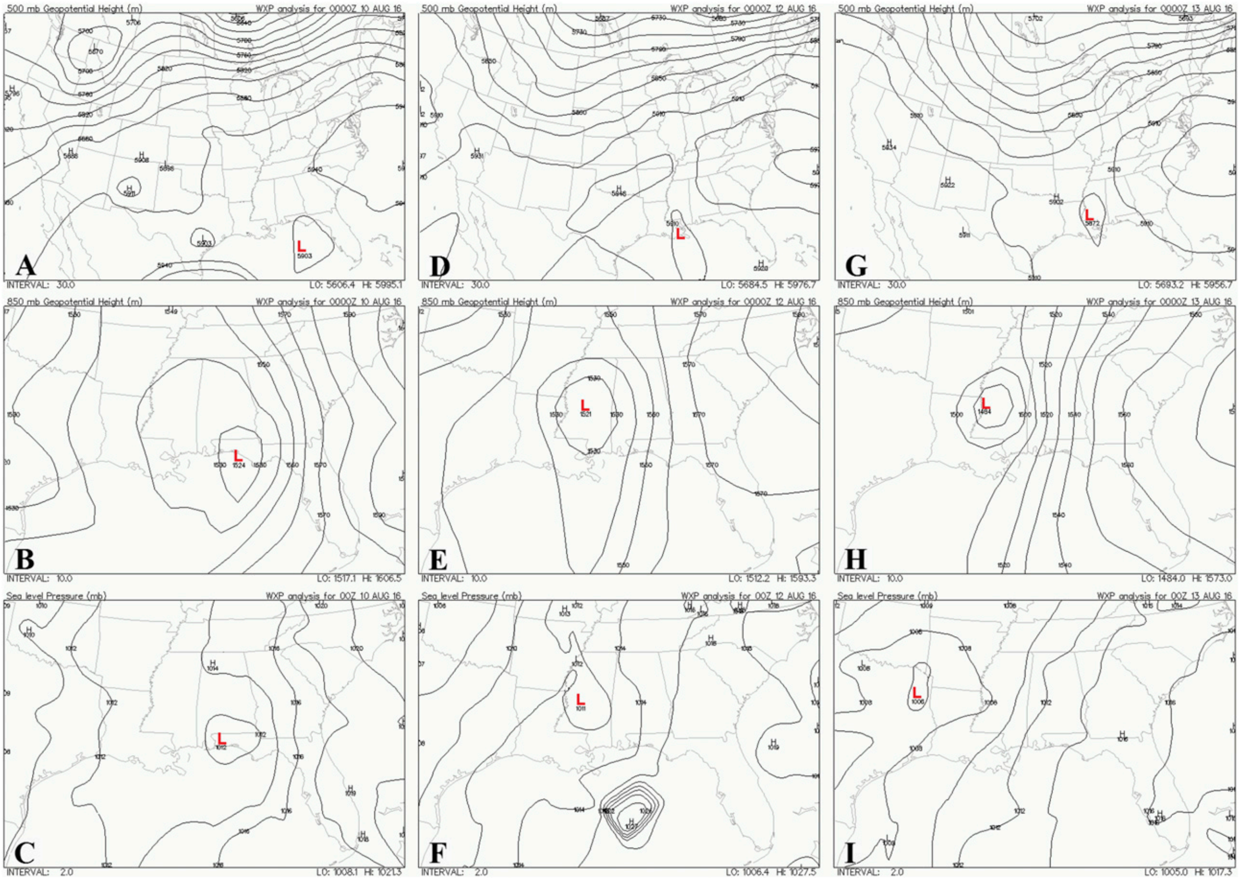

FIG. 5. Analysis of (top) 500 hPa, (middle) 850 hPa, and (bottom) the surface at 0000 UTC (a)–(c) 10, (d)–(f) 12, and (g)–(i) 13 Aug 2016. Red L's represent the low pressure area of interest and were enhanced in size for visualization purposes. Panels were generated via Plymouth State University's Department of Meteorology Weather Center Data Archive found at https://vortex.plymouth.edu/myo/.

hourly precipitation, with no particular hour producing an extreme quantity of rainfall; however, the storm and resulting flood were the result of consecutive days (and hours) of intense unrelenting rainfall (Wang et al. 2016). For example, at the Lafayette Airport, there were 51 consecutive hours of rainfall from 0900 UTC 12 August 2016 to 1100 UTC 14 August 2016. At the Baton Rouge Airport, 55 consecutive hours of rainfall from 1800 UTC 11 August 2016 to 0000 UTC 13 August 2016 were observed. New Iberia also had 55 consecutive hours of rainfall but from the period 0700 UTC 12 August 2016 to 1300 UTC 14 August 2016. These precipitation durations are comparable to records found by Brown et al. (2019a, 2020) for Louisiana; however, their analysis did not include hourly trace values.

2) HOURLY RAINFALL: GRIDDED OBSERVATIONS (SPAS)

The mass curves for zone 1 (located near Watson, Louisiana; Fig. 7a) and zone 2 (located near Lafayette, Louisiana; Fig. 7b) represent the single highest estimated precipitation total in each respective zone along with estimated hourly accumulations between 0700 UTC 10 August and 0600 UTC 14 August. The maximum average depth of precipitation at differing temporal scales was computed for area sizes up to 41 634 km^2 (16 075 mi^2) in zone 1 (Table 2) and 30 034 km^2 (11 596 mi^2) in zone 2 (Table 3) around each storm center.

Based on the mass curve for zone 1 (Fig. 7a), the largest estimated hourly rainfall total was 63.96 mm (2.52 in.), recorded at 1200 UTC 12 August. This location experienced only 4 h with rainfall rates over 50.8 mm (2 in.). On average, the estimated rainfall rate per hour at the storm center in zone 1 was 9.14 mm (0.36 in.). In 5 h, from 1100 to 1500 UTC 12 August, it was estimated the storm center received 254 mm (10 in.) of rainfall, an average rainfall rate of 50.8 mm h^{-1} (2 in. h^{-1}). In the 10-h period between 0700 and 1600 UTC 12 August, the location of maximum rainfall received an estimated 381 mm (15 in.) of rainfall, an average hourly rainfall rate of 38.1 mm h^{-1} (1.5 in. h^{-1}) per hour. SPAS estimated at this location, roughly half (453 mm) of the total

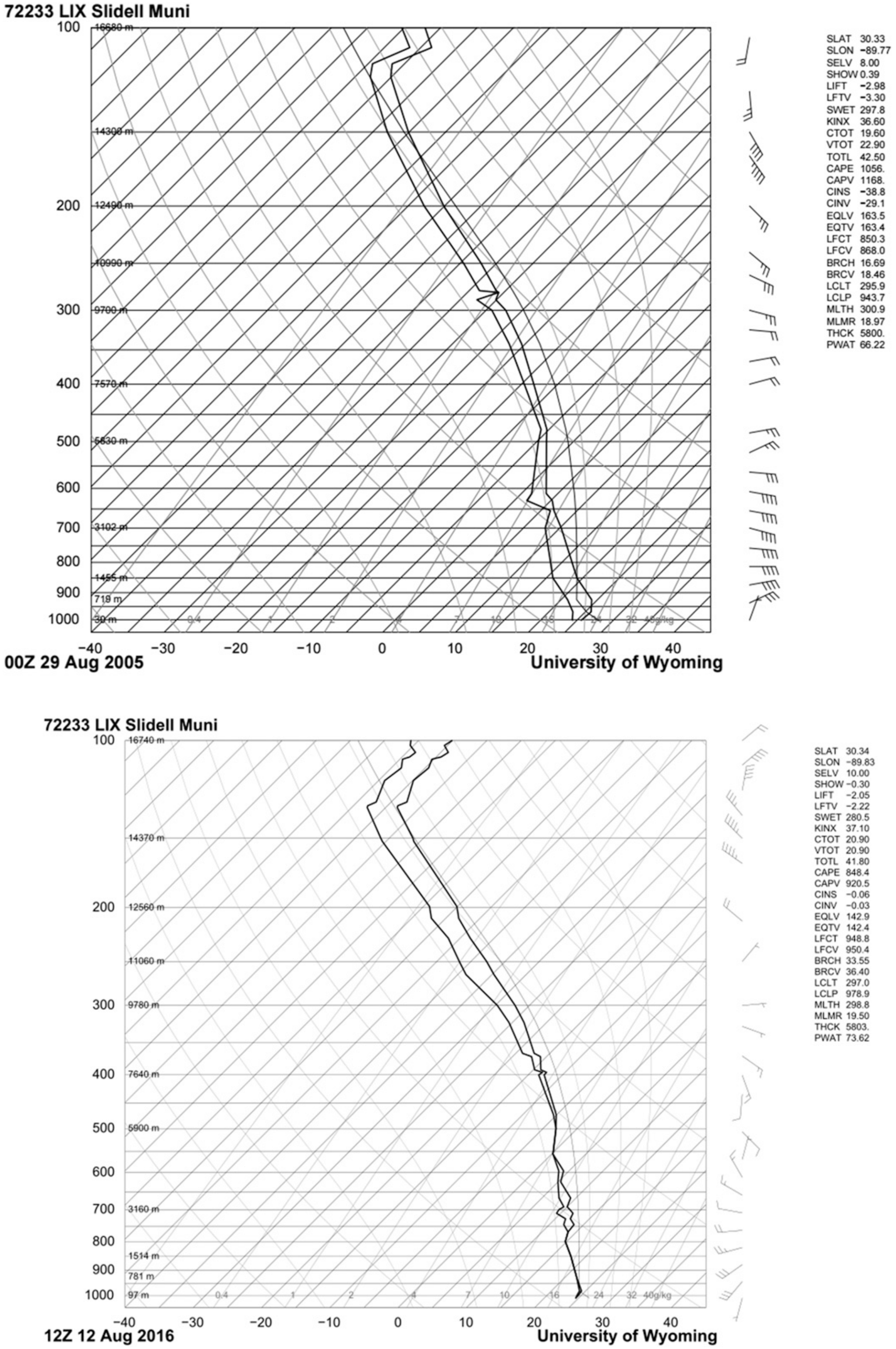

FIG. 6. Skew-*T* from Slidell (LIX) (top) at 0000 UTC 29 Aug 2005 during Hurricane Katrina and (bottom) for the August 2016 event. Source: University of Wyoming College of Engineering, Department of Atmospheric Science. Available at http://weather.uwyo.edu/upperair/sounding.html.

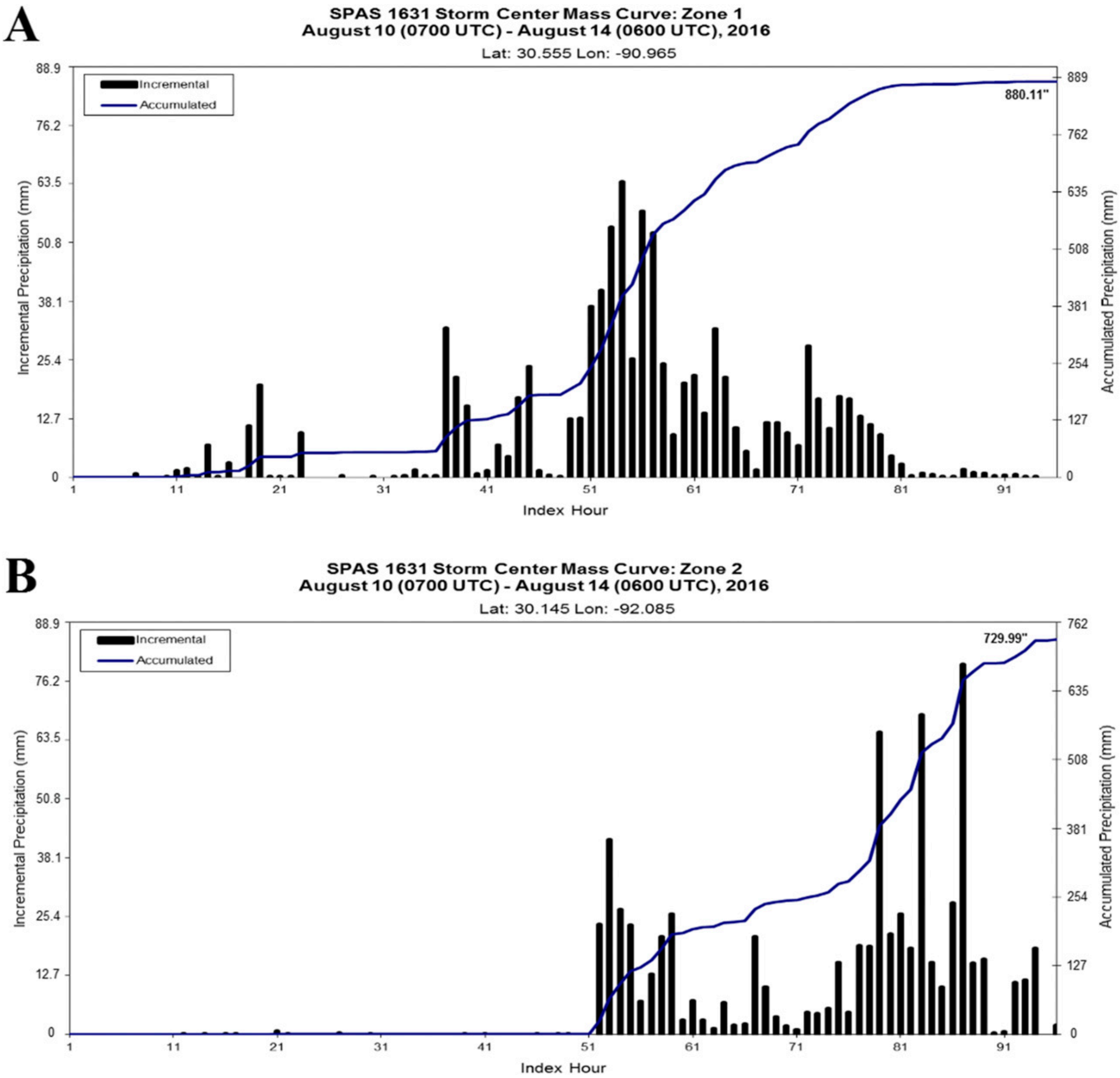

FIG. 7. Hourly accumulations and incremental rainfall from 0700 UTC 10 Aug to 0600 UTC 14 Aug for (a) the storm center for zone 1 located near Watson, LA (30.555°N, 90.965°W), and (b) the storm center for zone 2 located near Lafayette, LA (30.145°N, 92.085°W), from SPAS analysis.

accumulation from the entire event (880 mm) fell in 13 h, from 0900 to 2100 UTC 12 August.

In zone 2 (Fig. 7b), the highest estimated hourly accumulation was 79.65 mm (3.14 in.), recorded at 2100 UTC 13 August, with only 3 h having rainfall totals over 50.8 mm (2 in.). The estimated hourly rainfall total in zone 2 was 7.59 mm (0.29 in.), slightly less than observed in zone 1. Over the 5-h period from 1700 to 2100 UTC 13 August, 202 mm (7.9 in.) of precipitation was estimated, occurring more than 24 h later than the 5-h maximum observed in zone 1. In the 10-h period from 1200 to 2100 UTC 13 August, 352 mm (13.87 in.) of precipitation fell, with an average rainfall rate per hour of 35 mm (1.38 in.). SPAS estimated approximately half (370 mm) of the total storm accumulation (730 mm) at the storm center fell in 11 h, from 1100 to 2100 UTC 13 August.

3) 6-h rainfall: Gridded observations (SPAS)

Each hourly maximum rainfall map calculated by SPAS (e.g., 6, 24, 48, and 72 h) represents the greatest

TABLE 2. Depth–area–duration (DAD) table for the eastern zone (zone 1) of the August 2016 precipitation event (0700 UTC 10 Aug–0600 UTC 14 Aug) in south-central Louisiana (latitude: 30.555°N, longitude: 90.965°W).

	Maximum average depth of precipitation (mm)													
	Duration (h)													
Area (km^2)	1	2	3	4	5	6	12	18	24	36	48	72	96	Total
1	107.95	162.31	183.9	221.23	256.79	295.66	421.39	517.14	590.55	724.66	817.12	872.49	880.11	880.11
3	107.19	161.04	182.63	219.71	255.52	293.12	417.32	512.57	585.47	718.57	810.26	865.12	872.49	872.49
26	105.16	154.18	179.32	215.9	252.22	282.45	404.37	492.25	562.36	692.15	781.56	831.6	840.23	840.23
65	104.39	146.05	173.99	211.33	249.68	276.35	394.46	473.2	544.58	665.23	748.54	794	803.15	803.15
130	101.6	137.16	168.15	202.69	241.81	267.21	383.54	458.98	538.23	640.84	719.07	760.48	770.64	770.64
259	97.54	128.27	161.29	191.26	226.06	253.24	369.57	443.48	524.26	613.92	687.07	728.47	740.16	740.16
389	92.71	122.94	156.21	184.66	213.36	243.84	361.19	429.51	510.54	598.42	668.27	710.44	723.65	723.65
518	87.38	118.36	150.88	179.32	207.26	237.49	353.06	418.34	497.84	587.76	655.32	696.47	712.47	712.47
777	76.2	110.24	139.45	170.69	197.87	228.09	341.12	402.08	479.3	570.74	637.03	676.4	693.42	693.42
1036	65.53	102.36	131.57	164.08	191.77	221.23	331.98	390.65	466.09	558.55	624.08	660.91	677.93	677.93
1295	57.4	96.01	127.51	158.75	186.69	215.9	323.6	382.27	454.91	547.37	611.63	648.21	662.69	662.69
2590	45.47	82.55	113.28	141.73	168.66	194.56	296.16	354.33	419.1	504.19	566.67	602.49	617.47	617.47
5180	35.81	67.82	93.47	120.4	146.05	167.64	262.38	320.8	376.43	452.37	509.78	543.31	557.53	557.53
9065	29.21	54.36	74.93	96.77	117.6	135.89	226.57	282.45	330.45	401.07	455.68	488.95	503.68	503.68
12 950	24.64	44.96	63.25	81.79	98.81	114.55	195.83	245.87	287.27	358.9	411.73	450.6	464.82	464.82
19 425	19.56	35.81	50.8	65.28	78.49	91.19	157.48	201.68	238.76	304.04	353.31	393.45	406.15	406.15
25 900	15.49	28.96	41.91	54.36	65.79	76.71	132.84	170.94	201.93	260.86	307.34	346.96	357.89	357.89
38 850	10.92	21.08	30.23	39.12	48.01	55.88	97.79	128.27	151.38	198.12	239.01	271.53	280.16	280.16
41 634	10.41	19.81	28.19	36.58	44.7	52.07	91.69	121.67	143.76	188.21	227.33	258.06	266.7	266.7

rainfall total for that particular interval during the duration of the storm (0700 UTC 10 August–0600 UTC 14 August). For example, Fig. 8a shows the greatest 6-h rainfall accumulation across the selected region from 0700 UTC 10 August to 0600 UTC 14 August. The SPAS system also generates AEP's for selected durations (i.e., 6 h; Fig. 8b), similar to the point estimates obtained from NOAA Atlas 14.

Roughly 55 km north of Baton Rouge, on the border of Louisiana and Mississippi, and roughly 70 km northeast of Baton Rouge, two pockets of extreme 6-h rainfall totals are found (Fig. 8a). In 6 h, these locations received

TABLE 3. Depth–area–duration (DAD) table for the western zone (zone 2) of the August 2016 precipitation event (0700 UTC 10 Aug–0600 UTC 14 Aug) in south-central Louisiana (latitude: 30.145°N, longitude: 92.085°W).

	Maximum average depth of precipitation (mm)													
	Duration (h)													
Area (km2)	1	2	3	4	5	6	12	18	24	36	48	72	96	Total
1	88.39	136.35	190.75	239.01	249.17	255.78	388.62	450.34	486.66	653.54	728.47	728.98	730	730
3	87.63	135.64	189.48	237.49	247.14	254	386.84	447.04	483.11	650.24	724.41	725.17	726.19	726.19
26	85.85	132.84	186.18	233.17	241.55	247.14	382.78	438.15	473.96	642.11	714.25	715.52	716.28	716.28
65	83.57	129.29	180.09	225.81	233.43	242.82	380.24	431.8	469.65	638.81	704.6	705.61	707.14	707.14
129	79.76	123.19	172.21	215.9	223.27	239.52	363.98	423.67	466.09	624.08	683.77	685.04	687.83	687.83
259	73.91	115.32	162.05	202.69	208.28	234.44	343.66	410.21	456.44	592.07	644.65	647.7	653.29	653.29
388	68.83	109.22	153.16	191.01	195.33	230.63	336.8	401.83	449.33	573.28	619.51	625.6	632.97	632.97
518	66.55	104.14	145.29	180.34	191.77	227.08	330.96	394.97	442.98	560.32	602.74	610.36	619.25	619.25
777	62.99	96.52	133.1	164.08	186.44	219.2	321.31	383.79	432.31	542.8	580.64	590.3	600.46	600.46
1036	59.69	91.19	124.71	152.4	181.61	210.82	313.18	374.9	423.16	529.59	565.15	576.58	587.76	587.76
1295	57.91	87.12	118.36	143.76	177.29	203.45	306.58	367.28	414.53	519.18	552.96	566.17	577.85	577.85
2590	50.55	76.2	105.66	130.3	161.29	183.13	283.97	341.63	387.86	485.14	516.64	534.16	546.61	546.61
5180	40.89	66.04	94.23	117.09	139.45	160.78	258.83	315.98	361.19	451.87	479.04	498.09	513.33	513.33
9065	32	55.88	81.53	103.12	123.19	139.7	231.65	290.07	329.95	418.34	448.31	464.82	480.06	480.06
12 950	25.91	48.26	71.88	91.69	111.51	127	211.84	264.41	303.02	389.13	416.56	434.34	452.37	452.37
19 425	20.07	38.61	57.66	75.18	92.96	106.93	177.04	222.25	256.29	328.17	354.08	371.6	390.91	390.91
25 900	15.75	30.48	45.47	59.69	74.93	88.14	145.54	185.67	217.42	272.8	300.99	316.48	335.03	335.03
30 034	13.72	26.42	39.88	52.32	65.79	77.22	127.51	163.58	195.58	243.59	271.53	285.75	303.02	303.02

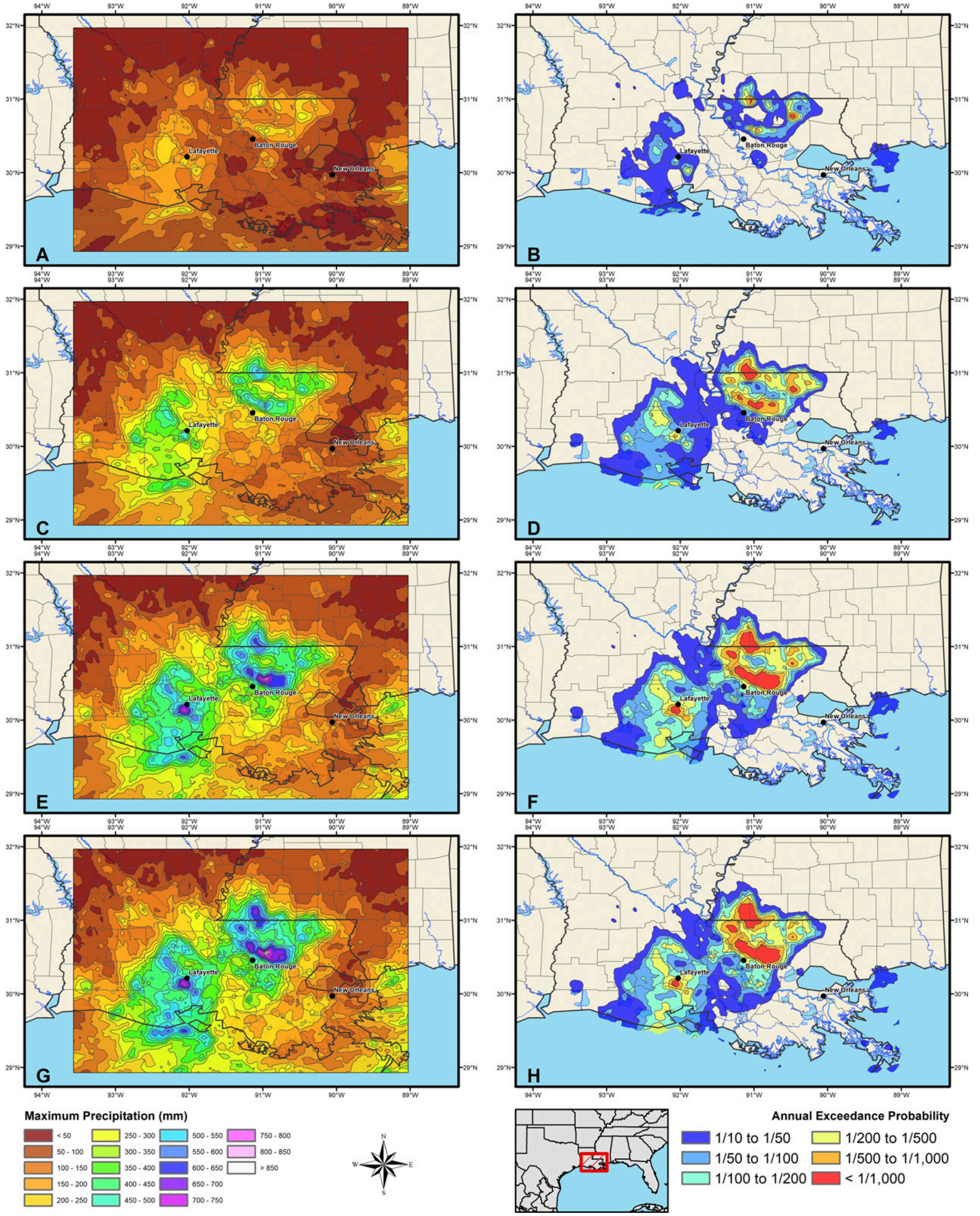

FIG. 8. (a) 6-h maximum rainfall, (b) 6-h annual exceedance probability, (c) 24-h maximum rainfall, (d) 24-h annual exceedance probability, (e) 48-h maximum rainfall, (f) 48-h annual exceedance probability, (g) 72-h maximum rainfall, and (h) 72-h annual exceedance probability for 10–14 Aug 2016 from SPAS.

approximately 254–305 mm (10–12 in.) of rainfall, corresponding to greater than a 1000-yr event (Fig. 8b). Areas only a few kilometers north-northeast of Baton Rouge also received notable 6-h maximum rainfall totals, ranging from 152 to 254 mm (6–10 in.) with isolated pockets receiving 254–305 mm (10–12 in.). These accumulations amount to between an estimated 500- and 1000-yr event.

4) 24-H PRECIPITATION

Roughly the entire southern portion of Louisiana experienced a minimum of between 50 and 102 mm (2–4 in.) of rainfall during the 24-h maximum period, with half of that area experiencing at least 152 mm (6 in.) (Fig. 8c). The 24-h maximum rainfall map shows two areas across southern Louisiana, slightly north of Baton Rouge and southwest of Lafayette, that received roughly 254–457 mm (10–18 in.) of rainfall, equivalent to a 200–500-yr AEP (Fig. 8d). Embedded areas north and northeast of Baton Rouge received between 457 and 508 mm (18–20 in.) of rain in 24 h, greater than an estimated 1000-yr event (Fig. 8d). The rainfall that produced these totals primarily transpired on 12–13 August.

Observed data from the Baton Rouge Municipal Airport on 12 August 2016 showed 285.5 mm (11.24 in.) of rainfall, short of the all-time record (at the airport) set on 14 April 1967 of 304.55 mm (11.99 in.). Norwood (NWS COOP gauge), located south of the Mississippi and Louisiana border, also recorded 285.5 mm (11.24 in.) of rainfall but on 13 August. Livingston, another point observation, experienced 287.27 mm (11.31 in.) of precipitation on 13 August 2016.

The NWS COOP gauge at Lafayette recorded 264.16 mm (10.4 in.) of rainfall on 13 August 2016, breaking the previous 1-day record set on 16 May 1980 of 263.65 mm (10.38 in.). In fact, the previous day (12 August 2016) the gauge at Lafayette recorded 263.91 (10.39 in.), making that total a record for the station by 0.254 mm (0.01 in.) until the following day, when it was again surpassed. Accumulations around Lafayette during the maximum 24-h period were of the 50–200-yr AEP, with isolated areas exceeding a 200-yr event.

ARI's were investigated using daily gauge-based precipitation from 21 stations and NOAA Atlas 14 (Fig. 9a). No station exceeded a daily 1000-yr event, but the Jackson gauge recorded over an estimated 500-yr event. Four other stations (Brownfields, Denham Springs, Monticello, Wakefield) surpassed the mean estimated 200-yr event and one station (New Iberia) the mean estimated 100-yr event. The other 15 stations did not record a 1-day precipitation total over NOAA Atlas 14's mean estimated 100-yr event.

5) 48-H PRECIPITATION

Figures 8e and 8f show the maximum 48-h rainfall totals and corresponding AEP's ranging from 1/10 (10%) to smaller than 1/1000 (0.1%). Two distinct areas were hit hardest: Baton Rouge and points north and east of the city, and Lafayette and areas immediately south of the city, where some locations recorded >508 mm (>20 in.) of rainfall. In the Baton Rouge area, according to observed gauge measurements, Watson recorded a 48-h observation of 797.3 mm (31.39 in.), the largest 48-h rainfall total on record in Louisiana. At Brownfields and Denham Springs, 2-day rainfall totals were 681.5 mm (26.83 in.) and 654.1 mm (25.75 in.), respectively. At the Baton Rouge Airport 377.19 mm (14.85 in.) of precipitation was recorded between 12 and 13 August 2016, while 555.24 mm (21.86 in.) was recorded at Livingston over the same two days, both setting all time 2-day precipitation records for their respective locations.

The observed 2-day maximum rainfall total in Lafayette was 528.06 mm (20.79 in.), surpassing the previous 2-day record by 249.17 mm (9.81 in.). In Crowley, located west of Lafayette, the observed 2-day rainfall total was 418.6 mm (16.48 in.) which outpaced the second highest value record by 71.12 mm (2.80 in.). The 48-h maximum rainfall map from SPAS revealed a small region south of Lafayette that received between 660.4 and 762 mm (26–30 in.) of rain, far greater than the estimated 1000-yr ARI. Nine stations (Jackson, Wakefield, Central, Monticello, Denham Springs, Brownfields, Watson, Norwood, and Livingston) recorded greater than an estimated 1000-yr 2-day rainfall event (Fig. 9b). Other stations, such as New Iberia and Lafayette, experienced larger than 500- and 200-yr events, respectively. Five other stations (Baton Rouge Concord, Baton Rouge Airport, Baton Rouge Sherwood, Abbeville, and Crowley) recorded 2-day events larger than the estimated 100-yr event.

6) 72-H PRECIPITATION

The 72-h maximum rainfall map (Fig. 8g) generated by SPAS estimated a small area northeast of Baton Rouge (near Watson, Louisiana) received >850 mm (33.5 in.) of rainfall. This is in proximity to the Watson rainfall gauge which recorded 797.3 mm (31.39 in.) in 48 h. The 72-h rainfall and annual exceedance probability (Fig. 8h) only differ slightly from the 48-h rainfall/AEP maps. This is because the majority of the storm was focused into 48-h. Of the 21 stations, 15 recorded at least a 100-yr 3-day event, while 12 stations recorded at least a 200-yr 3-day event (Fig. 9c). Similar to the 2-day observed precipitation, nine stations (Jackson, Wakefield, Central, Monticello, Denham Springs, Brownfields, Watson, Norwood, and Livingston) exceeded the 3-day

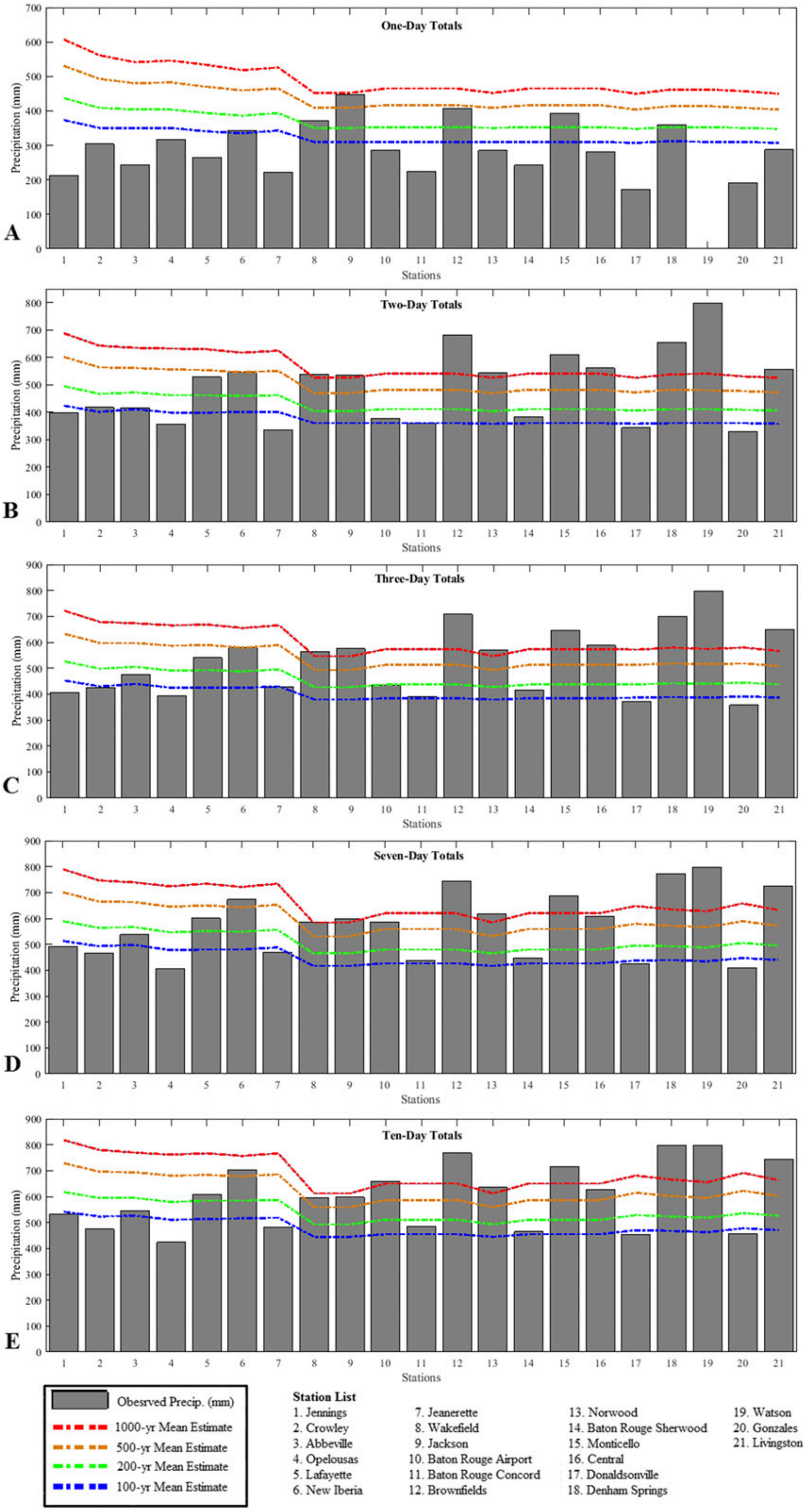

FIG. 9. (a) One-, (b) two-, (c) three-, (d) seven-, and (e) 10-day max rainfall totals (mm; bars) and estimated mean recurrence frequency (mm; lines) from NOAA Atlas 14. Blue (100 yr), green (200 yr), orange (500 yr), and red (1000 yr) lines represent the mean estimated precipitation totals for the respective station and duration from NOAA Atlas 14.

estimated 1000-yr event. New Iberia recorded a 3-day rainfall total of 580.14 mm (22.84 in.), slightly greater than the estimated 500-yr 3-day event of 579.12 mm (22.8 in.).

7) STORM TOTAL

The mass curves produced by the SPAS analysis also provide the estimated total accumulation at the storm center for each zone. At the center of zone 1 near Watson, Louisiana, the 4-day estimated maximum accumulation was 880 mm (34.65 in.), 82.8 mm (3.26 in.) above the observed total recorded at Watson. In zone 2, the estimated 4-day maximum accumulation was 730 mm (28.74 in.) southwest of Lafayette, 187 mm (7.39 in.) above the observation at Lafayette Regional Airport (roughly 16 km away). The values estimated by SPAS for zones 1 and 2 would rank as the wettest and second wettest 4-day periods ever recorded in Louisiana respectively, ranking ahead of the rainfall accumulations measured at Denham Springs and Brownfields for the event, and highlighting the historic and unprecedented nature of this storm.

As previously stated, the maximum average depth of precipitation at differing temporal scales was computed for area sizes up to 41 634 km^2 (16 075 mi^2) in zone 1 (Table 2) and 30 034 km^2 (11 596 mi^2) in zone 2 (Table 3) around each zone's storm center. In zone 1 the maximum DAD analysis reveals that an average of 266.7 mm (10.50 in.) of precipitation fell across an area of 41 634 km^2 (16 075 mi^2), roughly the size of the states of Vermont and New Hampshire combined, over a 96-h period. In fact, it is estimated that a 12 950 km^2 (5000 mi^2) area, roughly the size of Connecticut, received 465 mm (18.3 in.) of precipitation in 96 h. In zone two, 303 mm (11.93 in.) of precipitation fell over an area roughly 30 033 km^2 (11 596 mi^2). An estimated 452 mm (17.81 in.) fell over an area roughly 12 950 km^2 (5000 mi^2) and 546.35 mm (21.51 in.) over 2590 km^2 (1000 mi^2).

8) 7- AND 10-DAY PRECIPITATION TOTALS

This storm primarily transpired from 10 to 14 August 2016, but precipitation fell in southern Louisiana on the days prior to and after 10–14 August 2016, adding to longer duration rainfall totals. In many cases, these longer-duration rainfall totals also exceeded many 7- and 10-day estimates for 500- and 1000-yr events (Figs. 9d,e). A specific example can be seen in the Hydrometeorological Design Studies Center's August 2016 report that shows the maximum observed rainfall amounts compared to precipitation frequency estimates for AEPs up to 1/1000 for durations extending to 60 days for an automated rain gauge near Zachary, Louisiana (see https://www.nws.noaa.gov/oh/hdsc/aep_storm_analysis/). The report shows the 48-h observed rainfall totals at this gauge have probabilities ≤ 1/1000 for daily durations up to roughly 10 days. If this same graphic was made for the gauge at Watson, which is located roughly 19 km to the southeast of the Zachary gauge and recorded 797.3 mm (31.39 in.), the 48-h total would have probabilities less than or equal to 1/1000 for daily durations up to roughly 20 days.

Eight stations (Jackson, Wakefield, Monticello, Denham Springs, Brownfields, Watson, Norwood, and Livingston) observed precipitation totals that exceeded the estimated 1000-yr event for the 7-day duration (Fig. 9d). Three stations (New Iberia, Central, and Baton Rouge Airport) exceeded the 7-day 500-yr estimate, while Lafayette's 7-day observed rainfall exceeded the 200-yr estimate. At the 10-day duration, again, 15 stations recorded a 10-day precipitation total that was greater than at least the 100-yr precipitation estimate. Seven stations (Monticello, Denham Springs, Brownfields, Watson, Norwood, Livingston, and Baton Rouge Airport) recorded a 10-day precipitation total greater than the 1000-yr 10-day estimate (Fig. 9e).

9) RIVER IMPACTS

This storm was able to efficiently tap an extremely saturated atmosphere, dumping an estimated 26.49 quadrillion liters (7 trillion gallons) of rainwater in Louisiana from 8 to 14 August. The maximum recordable stage by several automated stream gauges was exceeded. Stream gauge observations and estimates indicate that at least 28 locations set new stage records, with over 50% of these locations having a period of record longer than 50 years. The extreme nature of this rainfall caused numerous locations to break the previous flood record (1983).

The two rivers that drain a majority of the Baton Rouge area, the Amite and Comite, have relatively low gradients resulting in slow drainage of their basins and a tendency for both rivers to quickly flood after excessive rainfall (see Muller and Faiers 1984). Urbanization in these basins, as well their subbasins, has exacerbated localized flooding. As a result of the August deluge, the Amite River (at Magnolia) crested at 17.79 m (58.36 ft), 3.16 m (10.36 ft) above flood stage and 1.98 m (6.49 ft) above the previous historical record. Downriver in Denham Springs, the Amite River crested at 14.07 m (46.2 ft), 2.2 m (7.2 ft) above major flood stage and 1.4 m (4.7 ft) above the previous record flood for the site (https://www.usgs.gov/news/usgs-records-historic-flooding-south-louisiana). During the event, the Amite river rose from an already elevated 10.66 m (35 ft) to an astonishing 14.08 m (46.2 ft) in approximately 24 h, spurring widespread flooding, particularly in Denham Springs where a majority of homes were flooded. Preliminary reports by the United States Geological Survey (USGS) showed 30 sites within the stream gauge network (261 sites total) were above flood stage (water surface exceeds natural banks and begins to create a hazard) and 50 were overtopped by floodwaters (Burton and Demas 2016; Van der Wiel et al. 2017). The speed at which the flood waters encroached, with two stream gauges showing rises of roughly 9.1 m (30 ft) in 48–72 h (Burton and Demas 2016), caught people off guard, leaving them stranded on the little high ground they could find as the flood waters rose (Colten 2017).

4. Discussion and conclusions

The precipitation event of 10–14 August 2016 was not caused by a tropical cyclone or a frontal system but rather by a slow-moving, moisture-rich tropical wave. Tropically induced flood events across Louisiana are generally caused by named tropical storms or hurricanes (e.g., Hurricane Gustav and Tropical Storm Allison) that have clear tropical origins and characteristics. A possible worst-case flooding scenario for southern Louisiana is a slow-moving hurricane (similar to Hurricane Harvey) that produces extreme rainfall and drives storm surge into Lakes Pontchartrain and Maurepas, forcing water levels in the lakes to rise, blocking rainfall-induced flood flows from the rivers that drain southeast Louisiana. In contrast, while the August 2016 storm had tropical origins, it lacked a closed circulation and a well-defined center needed to be classified as a tropical depression or tropical storm (Van der Wiel et al. 2017).

Despite not being classified as a tropical system, this storm produced historic rainfall totals across southern Louisiana, where many daily and multiday records were surpassed. Large swaths of southern Louisiana recorded at least 254 mm (10 in.) of rainfall, while some areas, such as Baton Rouge, Denham Springs, and Lafayette, received greater than a 1000-yr event in roughly 48 h, with many totals exceeding the NOAA Atlas 14 estimates by 203 mm (8 in.) or more. In Watson, Louisiana, a record accumulation of 797.3 mm (31.39 in.) was observed—the greatest 48-h rainfall total on record in Louisiana.

Estimates from SPAS revealed some locations may have received accumulations 82.8 mm (3.26 in.) higher than observed in Watson, Louisiana, demonstrating the ability of tools like SPAS to better quantify spatiotemporal characteristics of extreme rainfall events. For this reason, it is hoped that future case studies will implement tools such as SPAS to provide information that observations alone cannot provide. The incredible rainfall totals and subsequent flooding produced by the storm altered existing knowledge of precipitation in Louisiana and has significant implications for future hydrologic design and PMP studies across the region.

Most heavy rainfall events are concentrated in periods of less than 24 h (Belville and Stewart 1983; Keim and Muller 1992; Brown et al. 2019b); however, this storm (and Hurricane Harvey rains in 2017) proved to be an exception. Precipitation intensity relates to risks of flooding, especially when sustained over many hours, and the amount of precipitation relates to energy available in the environment (Trenberth and Zhang 2018). The alignment of multiple variables, such as warm Gulf of Mexico sea surface temperatures (SSTs), high precipitable water, an upper-level trough that aided moisture pooling, slow movement speed, and associated energy created this historic event. Some of these same atmospheric characteristics have been key contributors to other extreme rainfall events such as Hurricane Harvey and are consistent with expectations of a warming climate (Van der Wiel et al. 2017; Van Oldenborgh et al. 2017).

Extreme precipitation events, such as the one outlined here, may become more frequent due to increasing surface air temperatures (Van der Wiel et al. 2017). Precipitation intensity, defined as the average amount of precipitation per unit time conditional on precipitation falling (Trenberth et al. 2003), should increase by roughly 7% for each degree Celsius of temperature increase, as shown by the Clausius–Clapeyron relationship, due to increased atmospheric moisture (Trenberth et al. 2003; Trenberth 2011; USGCRP 2017). As global temperatures rise, the moisture-holding capacity of the atmosphere increases, contributing to moisture convergence (Tebaldi et al. 2006) and providing abundant moisture for storms to use in a given atmospheric column (Allan and Soden 2008; Scoccimarro et al. 2013). However, other factors related to thermodynamics and the atmosphere's ability to convert this increased moisture into precipitation on the ground are also altered in a changing climate. This may result in more frequent, but less extreme rainfall or other rainfall accumulation characteristics that are not yet fully understood or quantified (Kappel 2019).

There is also a strong relationship between total column water vapor, SSTs, and ocean heat content (Trenberth et al. 2005). As oceans and global temperatures warm, and models project a continued increase in ocean heat content, SST (Cheng et al. 2019), and air temperatures (IPCC 2014; USGCRP 2017), more moisture could become available and advected into storm systems. The resulting moisture convergence in a highly saturated atmospheric column can lead to extreme precipitation events (Trenberth et al. 2003).

As a result, locations around the globe could observe increases in precipitation intensity and extremes even if changes in mean precipitation are negligible (Trenberth et al. 2003; Chou et al. 2009). As such, it is important to analyze these events to understand the meteorological conditions that produce them and the characteristics of the precipitation that they produce.

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REFERENCES

Allan, R. P., and B. J. Soden, 2008: Atmospheric warming and the amplification of precipitation extremes. *Science*, **321**, 1481–1484, https://doi.org/10.1126/science.1160787.

Baton Rouge Area Chamber, 2016: BRAC's preliminary analysis of potential magnitude of flooding's impact on the Baton Rouge region. Baton Rouge Area Chamber, accessed 26 August 2016, 3 pp., https://bloximages.newyork1.vip.townnews.com/theadvocate.com/content/tncms/assets/v3/editorial/8/b5/8b5eec1c-662d-11e6-ae3d-7b8d8a55b473/57b739d469a16.pdf.pdf.

Belville, J. D., and N. O. Stewart, 1983: Extreme rainfall events in Louisiana: The New Orleans type. Preprints, *Fifth Conf. on Hydrometeorology*, Tulsa, OK, Amer. Meteor. Soc., 284–290.

Brown, V. M., A. W. Black, and B. D. Keim, 2019a: Hourly rainfall climatology of Louisiana. *Theor. Appl. Climatol.*, **137**, 2011–2027, https://doi.org/10.1007/s00704-018-2718-8.

——, B. D. Keim, and A. W. Black, 2019b: Climatology and trends in hourly, precipitation for the Southeast United States. *J. Hydrometeor.*, **20**, 1737–1755, https://doi.org/10.1175/JHM-D-19-0004.1.

——, ——, and ——, 2020: Trend analysis of multiple extreme hourly precipitation time series in the southeastern United States. *J. Appl. Meteor. Climatol.*, **59**, 427–442, https://doi.org/10.1175/JAMC-D-19-0119.1.

Burton, J., and A. Demas, 2016: USGS records historic flooding in South Louisiana. United States Geological Survey, accessed 19 October 2019, https://www.usgs.gov/news/usgs-records-historic-flooding-south-louisiana.

Caracena, F., and J. M. Fritsch, 1983: Focusing mechanisms in the Texas Hill Country flash floods of 1978. *Mon. Wea. Rev.*, **111**, 2319–2332, https://doi.org/10.1175/1520-0493(1983)111<2319:FMITTH>2.0.CO;2.

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

Cheng, L., J. Abraham, Z. Hausfather, and K. E. Trenberth, 2019: How fast are the oceans warming? *Science*, **363**, 128–129, https://doi.org/10.1126/science.aav7619.

Chou, C., J. D. Neelin, C. A. Chen, and J. Y. Tu, 2009: Evaluating the "rich-get-richer" mechanism in tropical precipitation change under global warming. *J. Climate*, **22**, 1982–2005, https://doi.org/10.1175/2008JCLI2471.1.

Colten, C., 2017: Floods collide with sprawl in Louisiana's Amite River basin. *Focus Geogr.*, **60**, https://doi.org/10.21690/fogeo/2017.60.2f.

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

Faiers, G. E., B. D. Keim, and K. K. Hirschboeck, 1994: A synoptic evaluation of frequencies and intensities of extreme three-and 24-hour rainfall in Louisiana. *Prof. Geogr.*, **46**, 156–163, https://doi.org/10.1111/j.0033-0124.1994.00156.x.

Guidry, K., 2016: Preliminary estimate of impacts to agriculture from August 2016 excessive rains and flooding. LSU AgCenter, accessed 24 August 2016, http://gov.louisiana.gov/assets/docs/RestoreLA/SupportingDocs/Meeting-9-28-16/2016-August-Flood-Economic-Impact-Report_09-01-16.pdf.

Hultstrand, D. M., and W. D. Kappel, 2017: The Storm Precipitation Analysis System (SPAS) report. Nuclear Regulatory Commission (NRC) Inspection Rep. 99901474/2016-201, Enercon Services, Inc., 95 pp.

IPCC, 2014: *Climate Change 2014: Synthesis Report*. R. K. Pachauri et al., Eds., IPCC, 151 pp., http://www.ipcc.ch/report/ar5/syr/.

Kappel, W. D., 2019: Are storms changing and how does this effect PMP. *Dam Safety 2019*, Orlando, FL, ASDSO, https://damsafety.org/basic-page/dam-safety-2019-opening-general-session.

——, and D. M. Hultstrand, 2018: Hurricane Harvey. *J. Dam Safety*, **16**, 25–34.

——, ——, J. T. Rodel, G. A. Muhlestein, K. Steinhilber, D. McGlone, J. Rodel, and B. Lawrence, 2015: Statewide probable maximum precipitation for Virginia. Virginia Department of Conservation and Recreation Rep., 129 pp., https://www.dcr.virginia.gov/dam-safety-and-floodplains/document/pmp-final-report.pdf.

——, ——, G. A. Muhlestein, K. Steinhilber, and B. Lawrence, 2019a: Regional probable maximum precipitation for the states of Oklahoma, Arkansas, Louisiana, and Mississippi. Tech. Rep., 104 pp., http://www.owrb.ok.gov/damsafety/pdf/2019RegionalPMPStudy.pdf.

——, ——, J. T. Rodel, G. A. Muhlestein, K. Steinhilber, D. McGlone, and B. Lawrence, 2019b: Statewide probable maximum precipitation for Pennsylvania. Pennsylvania Department of Environmental Protection Rep., 125 pp., https://www.dep.pa.gov/Business/Water/Waterways/DamSafety/Pages/Probable-Maximum-Precipitation-Study-.aspx.

Keim, B. D., 1996: Spatial, synoptic, and seasonal patterns of heavy rainfall in the southeastern United States. *Phys. Geogr.*, **17**, 313–328, https://doi.org/10.1080/02723646.1996.10642588.

——, 1998: Record precipitation totals from the coastal New England rainstorm of 20–21 October 1996. *Bull. Amer. Meteor. Soc.*, **79**, 1061–1067, https://doi.org/10.1175/1520-0477(1998)079<1061:RPTFTC>2.0.CO;2.

——, and R. A. Muller, 1992: Temporal fluctuations of heavy rainfall magnitude in New Orleans, Louisiana: 1871–1991. *J. Amer. Water Resour. Assoc.*, **28**, 721–730, https://doi.org/10.1111/j.1752-1688.1992.tb01494.x.

——, W. D. Kappel, G. A. Muhlestein, D. M. Hultstrand, T. W. Parzybok, A. B. Lewis, E. M. Tomlinson, and A. W. Black, 2018: Assessment of the extreme rainfall event at Nashville, TN and the surrounding region on May 1–3, 2010. *J. Amer. Water Resour. Assoc.*, **54**, 1001–1010, https://doi.org/10.1111/1752-1688.12657.

Leathers, D. J., D. R. Kluck, and S. Kroczynski, 1998: The severe flooding event of January 1996 across north-central Pennsylvania.

Bull. Amer. Meteor. Soc., **79**, 785–797, https://doi.org/10.1175/1520-0477(1998)079<0785:TSFEOJ>2.0.CO;2.

Lincoln, W. S., 2014: Analysis of the 15 June 2013 isolated extreme rainfall event in Springfield, Missouri. *J. Operat. Meteor.*, **2**, 233–245, https://doi.org/10.15191/nwajom.2014.0219.

——, R. F. Thomason, M. Stackhouse, and D. S. Schlotzhauer, 2017: Utilizing crowd-sourced rainfall and flood impact information to improve the analysis of the North Central Gulf Coast flood event of April 2014. *J. Operat. Meteor.*, **5**, 26–41, https://doi.org/10.15191/nwajom.2017.0503.

Louisiana Economic Development, 2016: The economic impact of the August 2016 floods on the state of Louisiana. Louisiana Economic Development Rep., 22 pp., http://gov.louisiana.gov/assets/docs/RestoreLA/SupportingDocs/Meeting-9-28-16/2016-August-Flood-Economic-Impact-Report_09-01-16.pdf.

Muller, R. A., and G. E. Faiers, 1984: A Climatic perspective on Louisiana floods 1982-1983. Department of Geography and Anthropology, Louisiana State University, 48 pp.

National Hurricane Center, 2018: Costliest U.S tropical cyclones. National Oceanic and Atmospheric Administration, https://www.nhc.noaa.gov/news/UpdatedCostliest.pdf.

Parzybok, T. W., and E. M. Tomlinson, 2006: A new system for analyzing precipitation from storms. Hydro Review, Vol. 25 (3), 58–65.

——, and B. L. Shaw, 2012: Forecast average recurrence interval precipitation maps for the United States: A new way of communicating the location and magnitude of high impact precipitation events. *26th Conf. on Hydrology*, New Orleans, LA, Amer. Meteor. Soc., 5.1, https://ams.confex.com/ams/92Annual/webprogram/Paper196778.html.

——, B. Clarke, and D. M. Hultstrand, 2011: Average recurrence interval of extreme rainfall in real-time. Earthzine, https://earthzine.org/average-recurrence-interval-of-extreme-rainfall-in-real-time.

Perica, S., and Coauthors, 2013: Version 2.0: Southeastern States (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi). Vol. 9, Precipitation-Frequency Atlas of the United States, NOAA Atlas 14, 163 pp., http://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume9.pdf.

Scoccimarro, E., S. Gualdi, A. Bellucci, M. Zampieri, and A. Navarra, 2013: Heavy precipitation events in a warmer climate: Results from CMIP5 models. *J. Climate*, **26**, 7902–7911, https://doi.org/10.1175/JCLI-D-12-00850.1.

Tebaldi, C., K. Hayhoe, J. M. Arblaster, and G. A. Meehl, 2006: Going to the extremes. *Climatic Change*, **79**, 185–211, https://doi.org/10.1007/s10584-006-9051-4.

Trenberth, K. E., 2011: Changes in precipitation with climate change. *Climate Res.*, **47**, 123–138, https://doi.org/10.3354/cr00953.

——, and Y. Zhang, 2018: How often does it really rain? *Bull. Amer. Meteor. Soc.*, **99**, 289–298, https://doi.org/10.1175/BAMS-D-17-0107.1.

——, A. Dai, R. M. Rasmussen, and D. B. Parsons, 2003: The changing character of precipitation. *Bull. Amer. Meteor. Soc.*, **84**, 1205–1218, https://doi.org/10.1175/BAMS-84-9-1205.

——, J. Fasullo, and L. Smith, 2005: Trends and variability in column-integrated atmospheric water vapor. *Climate Dyn.*, **24**, 741–758, https://doi.org/10.1007/s00382-005-0017-4.

USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment*, D. J. Wuebbles et al., Eds., Vol. 1, U.S. Global Change Research Program, 470 pp., https://doi.org/10.7930/J0J964J6.

Van der Wiel, K., and Coauthors, 2017: Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. *Hydrol. Earth Syst. Sci.*, **21**, 897–921, https://doi.org/10.5194/hess-21-897-2017.

Van Oldenborgh, G. J., and Coauthors, 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environ. Res. Lett.*, **12**, 124009, https://doi.org/10.1088/1748-9326/aa9ef2.

Wang, S. Y. S., L. Zhao, and R. R. Gillies, 2016: Synoptic and quantitative attributions of the extreme precipitation leading to the August 2016 Louisiana flood. *Geophys. Res. Lett.*, **43**, 11 805–11 814, https://doi.org/10.1002/2016GL071460.