Hurricane Harvey Highlights: Need to Assess the Adequacy of Probable Maximum Precipitation Estimation Methods

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Key Points

- Based on NCEP Stage IV QPE, Hurricane Harvey partially exceeded National Weather Service Hydrometeorological Report probable maximum precipitation estimates.
- Statistically significant increasing trends of precipitable water and dew point observations are found along the U.S. Gulf Coast region.
- Improved probable maximum precipitation estimation methodologies are needed to ensure the safety of our critical infrastructures.

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Abstract

Probable maximum precipitation (PMP) is the primary criterion used to design flood protection measures for critical infrastructures such as dams and nuclear power plants. Based on our analysis using the Stage IV (ST4) Quantitative Precipitation Estimates, precipitation associated with Hurricane Harvey near Houston, TX, represents a PMP-scale storm and partially exceeds the Hydrometeorological Report No. 51 (HMR51) 72-h PMP estimates at 5,000-mi^2 (ST4 = 805 mm; HMR51 = 780 mm) and 10,000-mi^2 (ST4 = 686 mm; HMR51 = 673 mm). We also find statistically significant increasing trends since 1949 in the annual maximum total precipitable water and dew point temperature observations along the U.S. Gulf Coast region, suggesting that, if the trend continues, the theoretical upper bound of PMP could be even larger. Our analysis of Hurricane Harvey rainfall data demonstrates that an extremely large PMP-scale storm is physically possible and that PMP estimates should not be considered overly conservative. This case study highlights the need for improved PMP estimation methodologies to account for long-term trends and ensure the safety of our critical infrastructures.

Keywords: Probable maximum precipitation, Hurricane Harvey, Stage IV QPE, infrastructure safety

Introduction

Probable maximum precipitation (PMP) is defined as "*the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year"* (World Meteorological Organization, 2009). It is a deterministic estimate of the upper bound of extreme precipitation with a return period in the range of 10^5 to 10^9 years (National Research Council, 1994). PMP is used as an input parameter to design and protect many highly sensitive facilities such as dams and nuclear power plants (Prasad et al., 2011; US Army Corps of Engineers, 1991) that could result in significant impacts to the environment and to human health, and even loss of life, if they were damaged or failed. Since the exceedance probability of a PMP event is very close to zero, the actual occurrence of a rainfall event approaching or exceeding the PMP should be extremely rare.

A series of U.S. National Weather Service hydrometeorological reports (HMR) published from the 1960s to the 1990s are still used as the official PMP estimates in many parts of the United States (Hansen et al., 1982, 1988, and 1994; Corrigan et al., 1999). For the Houston, TX, area, HMR No. 51 (HMR51; Schreiner et al., 1978) was released in 1978. Among various PMP calculation methods (World Meteorological Organization, 2009; Schreiner et al., 1978; Hershfield, 1961 and 1965; Hansen, 1987; Rakhecha and Singh, 2009), the combined storm moisture maximization, transposition, and envelopment concepts described in the HMRs are the ones most commonly used. For this method, the observed rainfall depth (P_{obs}) from all historical storms that can be reasonably transpositioned to a location of interest is calculated. For each storm, the

observed total precipitable water (PW_{obs}) and its climatological maximum (PW_{max}) at the location of interest are approximated using representative dew point observations from surface weather stations. The ratio of maximum-to-observed precipitable water (PW) depths is then used to estimate the maximum possible precipitation (P_{max}) for that storm through a linear moisture maximization model ($P_{max} = P_{obs} * PW_{max} / PW_{obs}$). The maximized rainfall depths across various storm durations and areas are then identified among all transpositioned storms to form the deterministic upper bound PMP estimates. Although some recent efforts have been made to reevaluate site-specific PMP using updated meteorological observations (with an overall methodology largely consistent with that used in the HMRs), the reevaluations have generally led to smaller PMP depths than those reported in the HMRs (Tomlinson et al., 2008 and 2013; Kappel et al., 2016).

Multiple issues and criticisms have been raised regarding the conventional moisture maximization method used in the HMRs. Papalexiou and Koutsoyiannis (2006) analyzed historical time series of dew point temperatures and maximized rainfall depths and reported no evidence of an upper bound in either atmospheric moisture or maximized precipitation depth. Chen and Bradley (2006 and 2007) pointed out that the 12-h persisting dew point temperature used to calculate PW is subjective and not uniquely defined. Rastogi et al. (2017) showed that the increase of PW is not proportional to the increase in rainfall depth after moisture maximization. Micovic et al. (2015) stated that there is a need to better understand the uncertainty of PMP estimates. Most importantly, the conventional method is observation-driven and intrinsically assumes that there are sufficient “samples” (i.e., historical extreme storms with high rainfall efficiency) to support the estimation of PMP across a wide range of storm durations and areas.

Evaluations of some recent extreme storms such as Hurricanes Floyd of 1999 and Fran of 1996 (Caldwell et al., 2011) reported that their moisture-maximized rainfall depths exceeded the HMR PMP. Despite these concerns, and the potential serious impacts of underestimating PMP, there has not been a focused federal effort since the development of the HMRs to improve our understanding of the physics controlling these extreme events and the methodologies to estimate PMP.

During flooding along the Gulf Coast resulting from Hurricane Harvey, reports of record-breaking rainfall were issued. Considering the significant impacts of this storm on Texas and Louisiana, a focused evaluation is needed to understand how the precipitation associated with Hurricane Harvey compares with current PMP estimates. In particular, since conventional PMP estimation methods are based on historical rainfall events, there is a need to know whether Hurricane Harvey rainfall should be used to update the current PMP estimates and if existing infrastructure protection requirements are adequate. Because PMP is considered a static upper bound of the precipitation that could occur during extreme storms, with no consideration of long-term climatological trends, there is also a need to assess trends in extreme precipitation indicators related to Hurricane Harvey to determine if changes in PMP-producing measurements are occurring, which may suggest even greater rainfall events in the future.

To demonstrate the important implications of Hurricane Harvey for the concept and practice of conventional PMP, we analyzed the areal rainfall depth and PW related to Hurricane Harvey in this case study. Using the National Center for Environmental Prediction (NCEP) Stage IV Quantitative Precipitation Estimate (QPE) data set (ST4; Lin, 2011), we summarize the depth-area-duration (DAD) relationship of Hurricane

Harvey and compare it with existing PMP estimates near Houston, TX. We further analyze the trends of PW and dew point temperature in the Gulf Coast region and discuss their potential influence on the estimation of PMP. Given the use of PMP estimates for dam and nuclear power plant design, these findings highlight the need to improve current PMP estimation methodologies to protect the communities and environments at risk from the failure of such facilities.

Methods

Data collection and processing

Three publicly available data sets were used in this study, including (1) the NCEP ST4 (Lin, 2011), (2) total PW from the 6-h NCEP Reanalysis data set (Kalnay et al., 1996), and (3) hourly surface dew point temperature observations from the National Centers for Environmental Information (NCEI) Integrated Surface Database (ISD; Smith et al., 2011).

NCEP ST4 is one novel operational rainfall product that dynamically assimilates both radar and gauge observations in real time to support river flood forecasting, numerical weather model verification, climatological studies, and other applications (e.g., Luitel et al., 2018; Gagnon et al., 2012; Nelson et al., 2016; Prat and Nelson, 2015; Pavlovic et al., 2016). It is based on radar-driven precipitation estimates with further corrections by rain gauges and quality control by National Weather Service River Forecast Centers. ST4 is available in 4 km spatial resolution from 2002 to the present, and it features spatial rainfall distributions detected by weather radar that cannot be measured by conventional gauge networks. We used the most recent ST4 data release to conduct the assessment in this study. Readers are referred to Gourley et al. (2010) for

further description of the ST4 process and its intercomparison with gauge observations and other precipitation products.

The NCEP Reanalysis is a widely used meteorological data set that provides sub-daily model-observation assimilated meteorological records from 1948 to the present. We analyzed the 6-h total PW estimates from 18 grid points in the U.S. Gulf Coast region (27.5°N–32.5°N, 85°W–97.5°W). Focusing on August 11th to September 10th annually (i.e., approximately 2 weeks before/after the timing of Hurricane Harvey), we identified the maximum annual 72-h average PW at each grid, calculated the maximum gridded PW in each zone, analyzed the trend through linear fitting, and detected the significance of the trend at a 5% significance level. Despite the expected model bias in estimating PW (e.g., Zhao et al., 2015), reanalysis is able to capture the observed climatology and interannual variations and hence is suitable for the purpose of this study.

For further verification of the potential PW trends, surface dew point temperature observations were obtained from the NCEI TD3505 ISD. Using the same spatial and temporal searching domains used in our PW analysis, we selected 15 stations that have the most complete dew point temperature observations from 1949 to the present. During data processing, if a station lacked more than 20% of its dew point temperature records during the period from August 11th to September 10th, that entire year was discarded. The trend at each station was analyzed and detected via the same approach used in the PW analysis. Surface dew point temperature observations are widely used in conventional PMP studies to help estimate the representative PW of each analyzed storm.

Maximum rainfall depth searching

We used elliptical moving windows with different combinations of eccentricity and orientation to thoroughly search the maximum rainfall observed during 2017/08/24/13Z–2017/08/31/12Z within the domain of 27°N–35°N and 90°W–100°W under 6-, 12-, 24-, 48-, and 72-h storm durations and 10-, 200-, 1,000-, 5,000-, 10,000-, and 20,000-mi^2 (25.9-, 518-, 2,590-, 12,900-, 25,900-, and 51,800-km^2) storm areas. The searching method was designed to mimic the shapes of synthetic storms generated by HMR52 (Hansen et al., 1982) and was used by Rastogi et al. (2017) in summarizing the DAD relationship from gridded precipitation. Since the spatial resolution of ST4 is 4 km, the 10-mi^2 DAD calculated herein would be less accurate than that for other storm areas and should be interpreted with caution.

Results

Hurricane Harvey rainfall analysis

Based on our analysis using NCEP ST4, Hurricane Harvey, which brought overwhelming rainfall to the Houston, TX, region during August 25–30, 2017, has joined the list of storms approaching or exceeding the current HMR PMPs. Recent studies on Hurricane Harvey (e.g., Emanuel, 2017; Risser and Wehner, 2017; van Oldenborgh et al., 2017) also confirm its rare strength and magnitude. Hurricane Harvey was the eighth named storm and third hurricane of the 2017 Atlantic hurricane season. It formed near the east Lesser Antilles on August 17 and reached its maximum Category 4 intensity on August 25 before making landfall near Rockport, TX. As a result of the weak prevailing winds and strong subtropical high-pressure system over part of the United States at the time, Hurricane Harvey moved very slowly across the Houston region (Beven II, 2017; Risser and Wehner, 2017) while being supplied continuous moisture from the Gulf of

Mexico. The result was stalled and prolonged heavy precipitation (i.e., very close to the theorized PMP forming conditions). Rainfall from this hurricane exceeded historical records not only for the Houston area but also for the continental United States (National Weather Service, 2017; Weather Prediction Center, 2017). The heavy rainfall resulted in significant flooding in one of the country's largest metropolitan areas and affected the safe operation of multiple critical dams upstream of the Houston area. The recent study by van Oldenborgh et al. (2017) suggested the return period of the highest observed 3-day precipitation amount of Hurricane Harvey to be greater than 9000 years.

Using the 4-km spatial resolution ST4, we identified the maximum 6-, 12-, 24-, 48-, and 72-h accumulated rainfall depths across 10-, 200-, 1,000-, 5,000-, 10,000-, and 20,000-mi^2 (25.9-, 518-, 2,590-, 12,950-, 25,900-, and 51,800-km^2) areas near Houston during Hurricane Harvey and compared them with HMR51 (i.e., the HMR applicable for Houston) in Table 1. Hurricane Harvey rainfall depths were proportionally smaller compared with HMR51 at shorter durations (less than 70% PMP for 6 and 12 h) but proportionally larger at longer durations (greater than 80% of PMP for 48 and 72 h). At 72 h and 5,000 and 10,000 mi^2 (12,950 and 25,900 km^2), Hurricane Harvey ST4 rainfall depths exceeded HMR PMP values by 103% and 102%, respectively. The four combinations of area and duration with the largest ST4/HMR51 ratios are shown in Figure 1, and plots for all durations and areas analyzed are provided in Supplementary Information [SI] Figures S1–S5. We also conducted further validation using the average hourly rainfall data from 153 Harris County rain gauges (Figure S6), and the results suggested high R^2 values between rain gauge observations and the corresponding final ST4 values. Despite the unavoidable estimation bias of ST4, an evaluation performed by

Gourley et al. (2010) also suggested that ST4 has the highest correlation coefficient to gauge observations among various rainfall products.

[Table 1]

[Figure 1]

The volume and duration of precipitation associated with this storm that stalled directly over the Houston region explain why it produced so much rainfall and support our finding from the NCEP analysis that Hurricane Harvey was a rare event. The comparison with HMR PMP suggests that, although more intense storms have been observed at shorter durations and smaller areas, there have been very few historical storms with comparable strength to Hurricane Harvey at longer durations and larger areas. Because the 72-h PMP precipitation depths were exceeded during Hurricane Harvey, and they are the main input used to calculate the controlling probable maximum flood (PMF) hydraulic design event (Prasad et al., 2011; US Army Corps of Engineers, 1991), it is not surprising that multiple dams and reservoirs received record high inflow and emergency releases were required to maintain the safety of these structures (Cephus, 2017). Other hydraulic structures (e.g., levees, water retention areas, storm water drainage systems) that are designed to handle only a smaller hydraulic event (e.g., a 200-year return level flow) would fail to function during a precipitation and flooding event of this magnitude.

Precipitable water trend analysis

Considering that Hurricane Harvey exceeded some HMR51 PMP values, a key question is whether Hurricane Harvey will further elevate PMP estimates after moisture maximization adjustments are made. The moisture maximization and resulting PMP

depend primarily upon two factors: (1) the representative PW_{obs} of Hurricane Harvey and (2) the climatological maximum PW_{max} at a similar annual timing. To assess these factors, we evaluated 1949–2017 PW estimates from the NCEP Reanalysis (Figure 2). Note that we chose the NCEP Reanalysis because it calculates total PW from 3-dimensional atmospheric fields and should be more reliable than estimating PW_{obs} from only a single surface dew point temperature observation (i.e., the HMR approach). In addition, NCEP Reanalysis provides the longest period of data coverage (compared to other reanalysis data products) which is important to better support the trend analysis. Focusing on a 72-h duration and the annual 8/11–9/10 time frame (i.e., approximately 2 weeks before/after Hurricane Harvey), we identified annual maximum PW grid values from three zones in the region, including (1) Zone A: the grid closest to Houston, TX, (2) Zone B: grids surrounding Houston, TX, and (3) Zone C: grids along the U.S. Gulf Coast region. In each plot, a statistically significant increasing trend was found, with PW increasing by about +1.6 to +2% per decade. Results for other durations are provided in SI Figure S7.

[Figure 2]

The 2017 maximum PW associated with Hurricane Harvey represents the highest value in Zone A (64.6 kg/m^2) but is slightly lower than the highest value from 2008 in Zones B and C (64.7 kg/m^2). Therefore, the PW_{obs} associated with Hurricane Harvey would be very near the climatological maximum PW_{max} observed throughout the entire NCEP Reanalysis period (1949–2017) along the Gulf Coast of the United States. Following the conventional PMP approach, the rainfall depth (P_{obs}) from Hurricane Harvey would be adjusted slightly or not at all in revising PMP estimates to determine a

P_{max}. This may be reasonable—given Hurricane Harvey's rare strength and occurrence, one would expect there to be very limited capacity for the rainfall associated with Hurricane Harvey to be further enhanced. However, the real concerning factor is the increasing trend of PW_{max}. Currently, the World Meteorological Organization (2009) specifically defines PMP "*with no allowance made for long-term climatic trends*," so trends in PW are not considered. However, if the statistically significant upward trend in Figure 2 continues, PW_{max} will increase at a rate of approximately +2% per decade in the Gulf Coast region; and future P_{max} (i.e., analyzed with updated PW values in the future) will increase at the same rate following the linear maximization assumption. In other words, the Hurricane Harvey DAD reported in Table 1(a) will be scaled up by the value of PW_{max}/PW_{obs} (which is expected to be higher in the future) and hence lead to even larger PMP. These results bring into question the assumption that PMP has a static upper bound. This is a concern because current PMPs used to design and operate critical and costly infrastructure over extended time frames may increase as a result of climatological changes and become obsolete during the period of operation.

The average age of the 90,580 dams in the United States is 56 years (American Society of Civil Engineers, 2017), but the cost of replacement will force many of them to operate for many more decades. Forty-five of the 90 nuclear power reactors in the United States are over 40 years old, and some estimates suggest that many of them may continue to operate for another 50 or more years (US Nuclear Regulatory Commission, 2017; Voosen, 2017). Assuming that some of our most critical infrastructure may be operational over a 100-year lifespan, it is imperative that these facilities be designed to withstand PMPs that could occur during this extended time frame and not just the PMP that was

predicted to occur when the facility was constructed. If PW increases at a rate of 1.6–2.0% per decade, PMP estimated in the future (using an increased PW_{max} from expanded PW measures and the same set of storm DADs) could increase at this rate as well. The HMR51 72-h 5,000-mi^2 (12,950 km^2) PMP estimate for the Houston area is 780 mm (Table 1) and was published in 1978. Under the assumption that PW_{max} near Houston is increasing by 1.6–2.0% per decade, the PMP estimate would be 828 to 841 mm when calculated in 2017, and 894 to 924 mm when calculated in 2070. With Hurricane Harvey having already achieved a depth of 805 mm, this magnitude of PMP estimate no longer appears to be overly conservative.

Station-based dew point temperature trend analysis

To determine if observed historic dew point temperature records also suggest that PW is increasing, we analyzed annual maximum dew point temperatures to determine long-term trends. In the conventional HMR procedure, surface dew point temperature measured at representative stations along the pathway of air moisture inflow trajectory is used as a proxy to estimate PW_{obs} under hydrostatic and pseudo-adiabatic assumptions (Chen and Bradley, 2006 and 2007). The climatological maximum dew point temperature in the same location and at similar timing is then used to estimate PW_{max}. Although the function between dew point temperature and PW is not strictly linear, both the annual maximum dew point temperature and PW should follow similar regional and temporal trends.

[Figure 3]

The annual maximum 72-h average dew point temperature from surface weather stations is illustrated in Figure 3. From the same U.S. Gulf Coast region, we identified 15

surface weather stations from the NCEI ISD that have the most complete hourly dew point temperature observation records from 8/11 to 9/10 during 1949–2017. Increasing trends in dew point temperature were found in all stations across the region, with most trends being statistically significant at the 5% significance level. Similar findings were also found for the 6-, 12-, 24-, and 48-h durations (SI Figures S8–S11), suggesting a high likelihood that, regionally, PW and dew point temperature are increasing. Our results are consistent with Robinson's (2000) finding that the observed hourly dew point temperature from 178 stations in the conterminous United States increased by approximately +1°C per century (i.e., +0.1°C/decade) during 1951–1990. Under hydrostatic and pseudo-adiabatic assumptions, a +0.1°C per decade rate of increase in dew point temperature would contribute to an approximately +0.8% per decade rate in PW_{max}. Although the rate estimated by Robinson (2000) is only half the NCEP PW_{max} rate estimated for Zone A, it would still result in measurable increases in PMP over the long term. For example, a +0.8% per decade increase to HMR51's 1978 72-h 5,000-mi^2 (12,950 km^2) estimate would result in PMP estimates near Houston increasing to approximately 804 mm by 2017 and 825 mm by 2050.

Discussion and Recommendation

Our analysis of the Hurricane Harvey rainfall data and trends in PW indicates two primary areas of concern regarding the adequacy of the current PMP estimation methodologies: the observation-based nature of the conventional method and the increasing trend in maximum total PW.

- **Sufficiency of historic observations:** The conventional HMR method intrinsically assumes that a sufficient number of historical extreme storm events have been

observed to support PMP estimation. However, such an assumption has never been tested or verified. From an information theory point of view, if there are sufficient samples to support the identification of a statistical maximum, removing any single sample should not result in a major reduction in PMP. However, the conventional PMP estimate is usually controlled by a few exceptionally large storms and is therefore not supported by this theory. From a physical perspective, within a fixed period of time, one would expect to observe more short-duration and smaller-area extreme storms (with high rainfall efficiency) and fewer storms with longer duration and larger areas. Therefore, the PMP estimates for longer durations and larger areas would have more uncertainty. The data sufficiency of PMP is also questioned by Emanuel (2017) in a recent analysis for Hurricane Harvey. Although over a century of extreme storm records exists in the United States, given the extreme nature and rarity of PMP events, one may not confidently conclude whether a sufficient number of extreme storms has been observed in this time frame to calculate PMP. Hurricane Harvey's exceedance of HMR51 at long duration and over large areas highlights this challenge.

- **Increasing trend of total precipitable water:** Although there is no direct evidence to associate the occurrence of the Hurricane Harvey extreme rainfall event with atmospheric warming, studies have suggested a high likelihood of PW_{max} and PMP enhancement as climatic conditions change. Risser and Wehner (2017) suggested human-induced climate change likely increased the chances of precipitation accumulation during Hurricane Harvey (similar to the conclusions by van Oldenborgh et al., 2017). Using the Coupled Model Intercomparison Project phase-5 data, Kunkel

et al. (2013) showed that PW_{max} is projected to increase in the various global climate models tested and inferred that PMP is likely to increase accordingly. Beauchamp et al. (2013), Rousseau et al. (2014), and Rouhani and Leconte (2016) followed HMR methods to estimate PMP for watersheds in Quebec, Canada, using downscaled climate projection data; and they suggest a likely increase in PMP due to increasing PW. This view is also shared by Stratz and Hossain (2014), Klein et al. (2016), Rastogi et al. (2017), and Gangrade et al. (2018) for various other watersheds. Although further exploration is needed for different types of geographical/meteorological locations at refined spatial resolution, future increases in PMP are generally projected by these models. Our post–Hurricane Harvey analyses of annual maximum PW and dew point along the Gulf Coast are consistent with these model projections.

Moving forward, there is a need to improve the methodology of PMP estimation. Compared with the time frame in which the HMRs were developed, more extensive rainfall observations recorded through various sensor techniques are now available to support more refined PMP analysis. With highly improved computing capabilities, researchers have started to explore approaches to reevaluating PMP using numerical weather prediction models that do not rely on the multiple crude assumptions used in the conventional PMP approach (e.g., the linear maximization model between PW and rainfall depth). Combining high-performance computing with advances in both data and numerical models, it is now possible to address issues and reevaluate various assumptions that are implicit in the current PMP estimation methods, as well as to understand the sensitivity of PMP in a changing environment (Abbs, 1999; Ohara et al., 2011;

Woldemichael et al., 2012 and 2014; Ishida et al., 2014 and 2015; Chen and Hossain, 2016; Rastogi et al., 2017). Topics for further research and consideration also include improving the estimation of PW (i.e., not only basing it not only on surface dew point temperature), incorporating PW trends, and the concept of a non-static PMP upper bound. To move away from a purely deterministic approach, agencies have also started to consider the use of probabilistic flood hazard assessment techniques (US Nuclear Regulatory Commission, 2013) for a more-informed and risk-based regulatory decision-making process. Given the lack of research progress in the past few decades since the development of the HMRs, many improvements can be made in both deterministic and probabilistic PMP estimation.

Hurricane Harvey demonstrates that an extremely large PMP-scale storm is physically possible. Therefore, the design of critical infrastructures using PMP and PMF estimates should not be considered overly conservative. Given its intensity, precipitation data from Hurricane Harvey should be used to update current PMP estimates and to assess whether infrastructure protection requirements are adequate. Furthermore, given the increasing PW and dew point temperature trends calculated from NCEP Reanalysis and surface weather stations, consideration should be given to incorporating long-term climatological trends in PMP estimation methods. We hope this study can raise the community's attention with regard to the research needed for accurate calculation of PMP so that we may continue to ensure the safety of our critical infrastructures in a changing environment.

Acknowledgment

This study was supported by the Oak Ridge National Laboratory (ORNL) Laboratory Directed Research and Development Program. The research used resources of the Oak Ridge Leadership Computing Facility at ORNL. The authors are employees of UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy. Accordingly, the US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes.

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Table 1. The depth-area-duration table of (a) Hurricane Harvey maximum NCEP stage IV QPE rainfall, (b) HMR51 PMP depths for Houston, TX, and (c) Harvey divided by HMR51. Red cells mark where Harvey exceeds HMR51.

(a) Hurricane Harvey maximum NCEP Stage IV QPE rainfall (mm)					
	6-h	12-h	24-h	48-h	72-h
10 mi^2 (25.9 km^2)	565	676	932	1125	1241
200 mi^2 (518 km^2)	427	525	736	937	1061
1000 mi^2 (2590 km^2)	273	354	565	757	965
5000 mi^2 (12950 km^2)	154	250	423	636	**805**
10000 mi^2 (25900 km^2)	121	204	349	543	**686**
20000 mi^2 (51800 km^2)	93	158	272	449	554
(b) HMR51 PMP depths for Houston, Texas (mm)					
	6-h	12-h	24-h	48-h	72-h
10 mi^2 (25.9 km^2)	813	983	1196	1316	1415
200 mi^2 (518 km^2)	625	792	1003	1125	1240
1000 mi^2 (2590 km^2)	462	632	843	958	1049
5000 mi^2 (12950 km^2)	257	381	556	676	**780**
10000 mi^2 (25900 km^2)	193	300	447	572	**673**
20000 mi^2 (51800 km^2)	142	234	345	457	559
(c) Harvey / HMR51 (%)					
	6-h	12-h	24-h	48-h	72-h
10 mi^2 (25.9 km^2)	70%	69%	78%	85%	88%
200 mi^2 (518 km^2)	68%	66%	73%	83%	86%
1000 mi^2 (2590 km^2)	59%	56%	67%	79%	92%
5000 mi^2 (12950 km^2)	60%	66%	76%	94%	**103%**
10000 mi^2 (25900 km^2)	63%	68%	78%	95%	**102%**
20000 mi^2 (51800 km^2)	65%	68%	79%	98%	99%

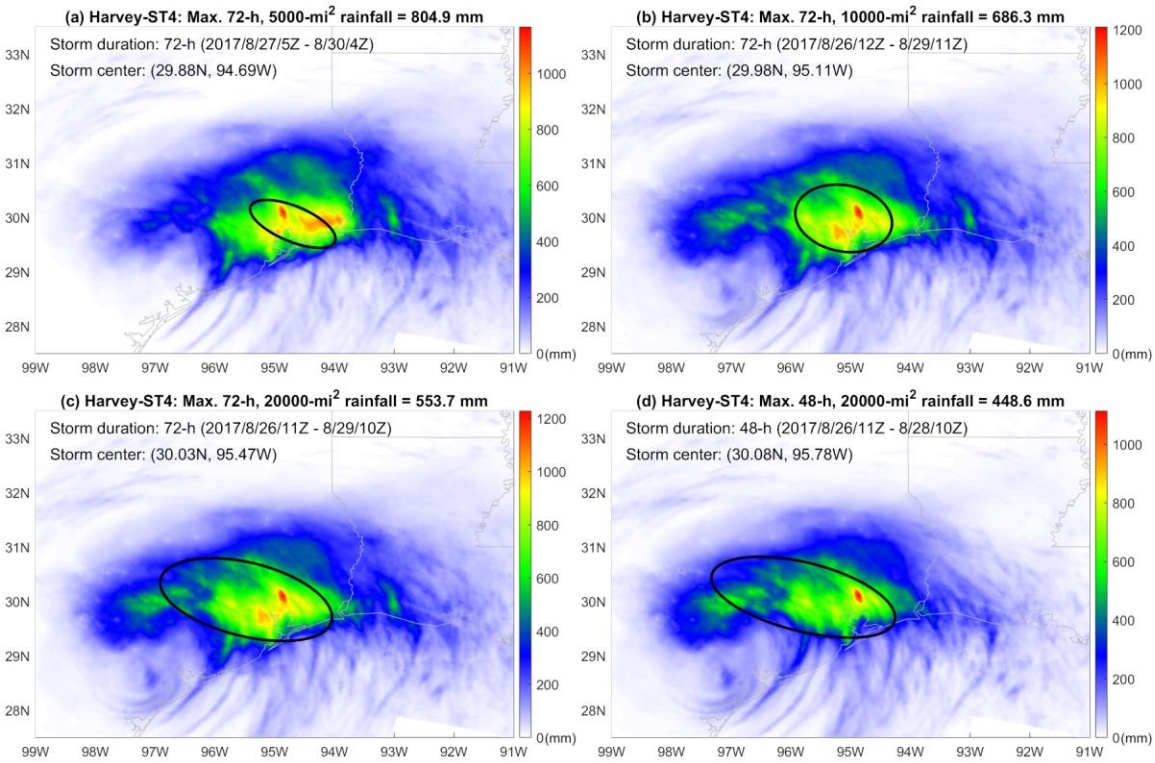

Figure 1. NCEP Stage IV QPE rainfall of Hurricane Harvey during (a) 72 h from 2017/8/27/5Z to 8/30/4Z, (b) 72 h from 2017/8/26/12Z to 8/29/11Z, (c) 72 h from 2017/8/26/11Z to 8/29/10Z, and (d) 48 h from 2017/8/26/11Z to 8/28/10Z. The ellipses mark the heaviest 5,000-mi^2, 10,000-mi^2, and 20,000-mi^2 average rainfall during the entire Harvey event. Both upper panels (a) and (b) exceed HMR51 PMP estimates.

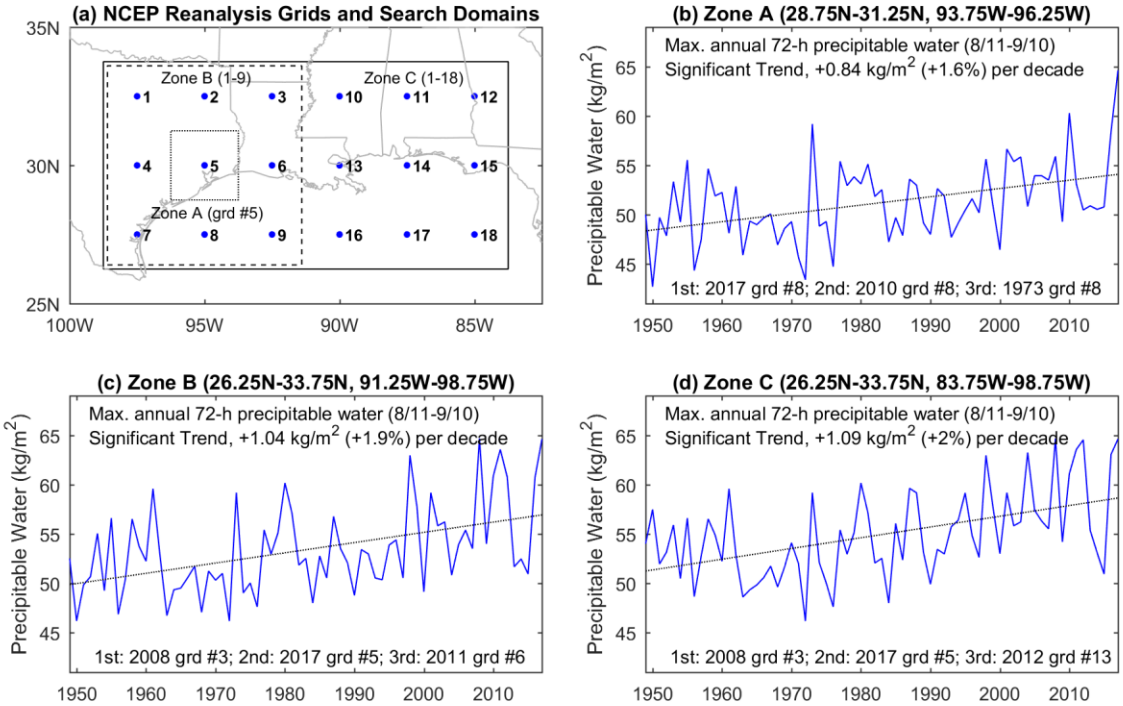

Figure 2. Time series and trend of annual maximum 72-h duration gridded NCEP precipitable water (kg/m^2) from three selected zones in the southern United States. The maximum 72-h precipitable water is selected from August 11th through September 10th each year from all grid points within the zone. Panel (a) shows the three search domains used for Panel (b) through Panel (d). A 5% significance level is used to judge if a trend is statistically significant.

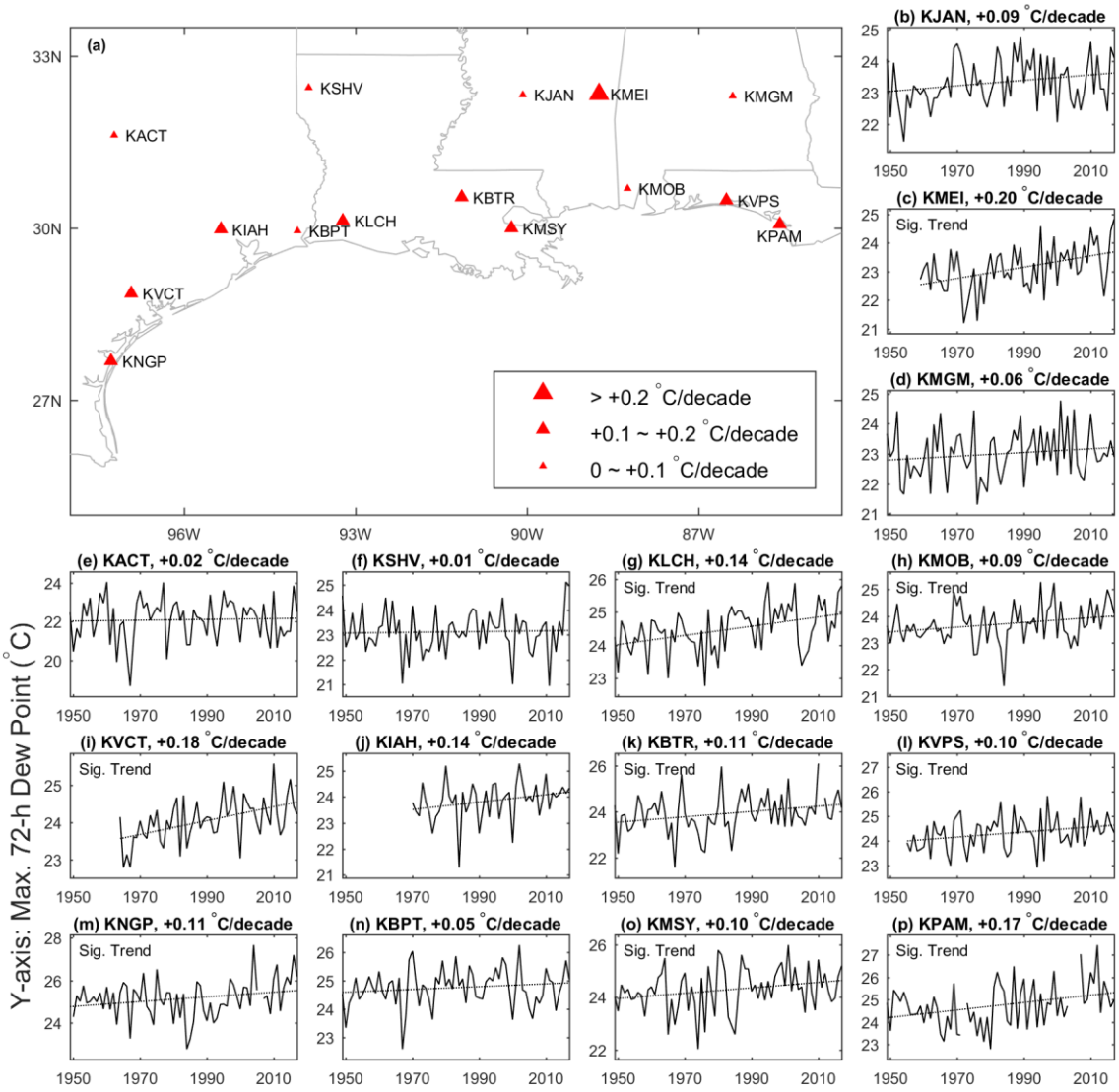

Figure 3. Time series and trend of annual maximum 72-h duration average dew point temperature (°C) occurring from August 11th to September 10th from 15 surface weather stations in the southern United States. A 5% significance level is used to judge whether a trend is statistically significant.

Supporting Information for

Hurricane Harvey Highlights the Challenge of Estimating Probable Maximum Precipitation

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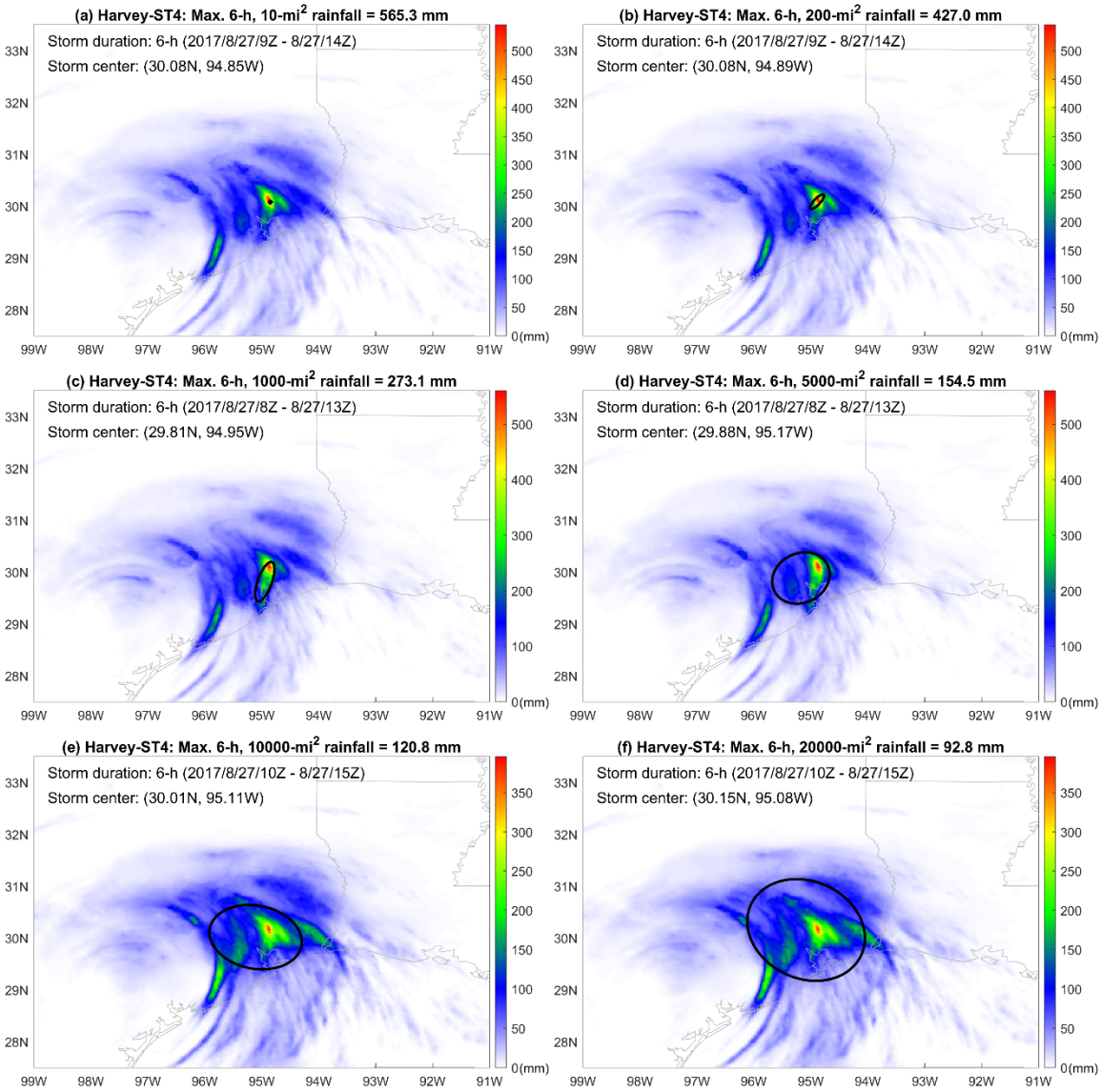

Figure S1. Maximum 6-h NCEP Stage IV QPE of Hurricane Harvey. The ellipses mark the heaviest 10 m^2 (upper-left), 100 m^2 (upper-right), 1,000 mi^2 (mid-left), 5,000 mi^2 (mid-right), 10,000 mi^2 (lower-left), and 20,000 mi^2 (lower-right) average rainfall during the entire Harvey event. The specific timing and storm center are reported in each panel.

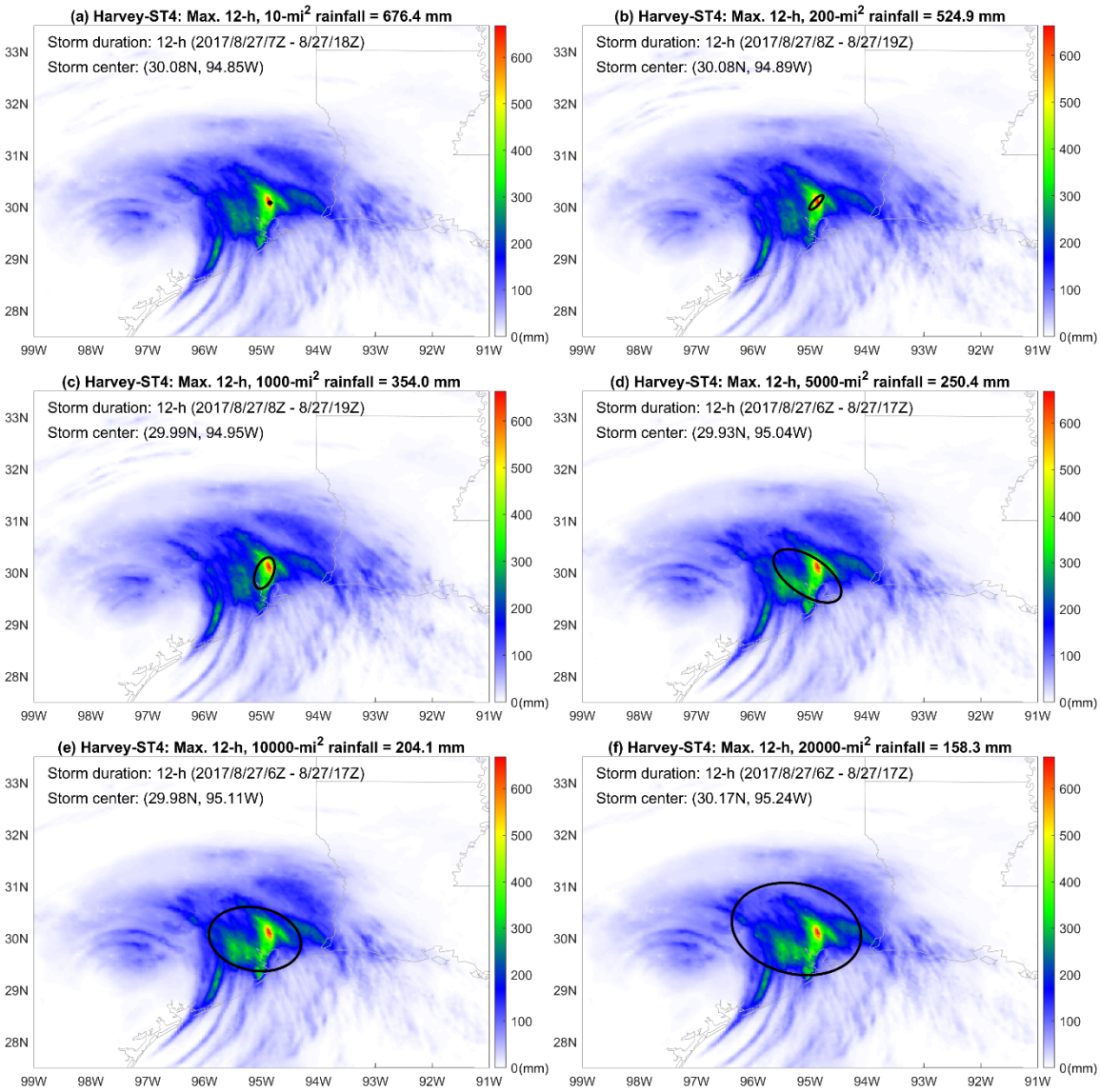

Figure S2. Maximum 12-h NCEP Stage IV QPE of Hurricane Harvey. The ellipses mark the heaviest 10 m^2 (upper-left), 100 m^2 (upper-right), 1,000 mi^2 (mid-left), 5,000 mi^2 (mid-right), 10,000 mi^2 (lower-left), and 20,000 mi^2 (lower-right) average rainfall during the entire Harvey event. The specific timing and storm center are reported in each panel.

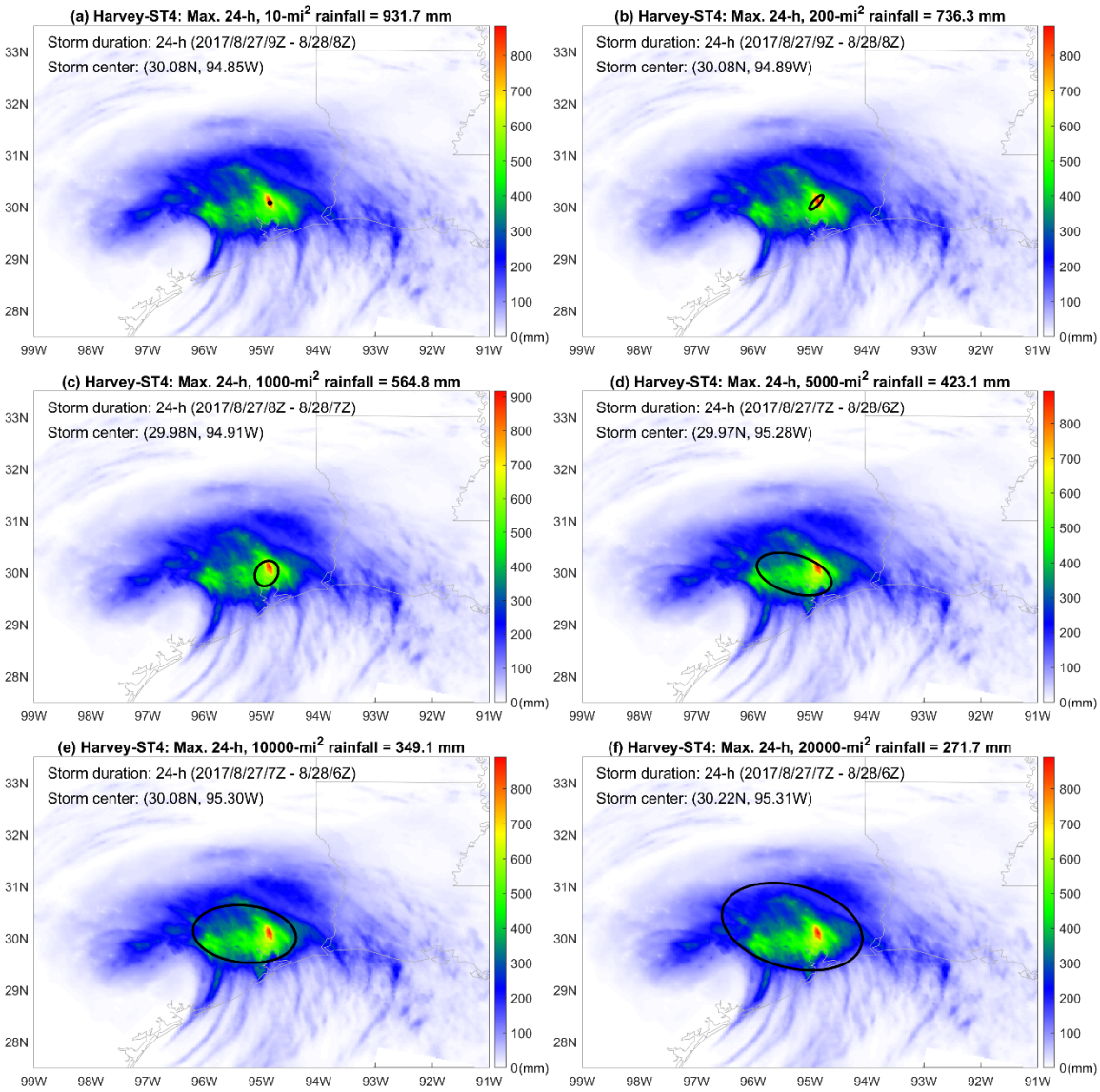

Figure S3. Maximum 24-h NCEP Stage IV QPE of Hurricane Harvey. The ellipses mark the heaviest 10 m^2 (upper-left), 100 m^2 (upper-right), 1,000 mi^2 (mid-left), 5,000 mi^2 (mid-right), 10,000 mi^2 (lower-left), and 20,000 mi^2 (lower-right) average rainfall during the entire Harvey event. The specific timing and storm center are reported in each panel.

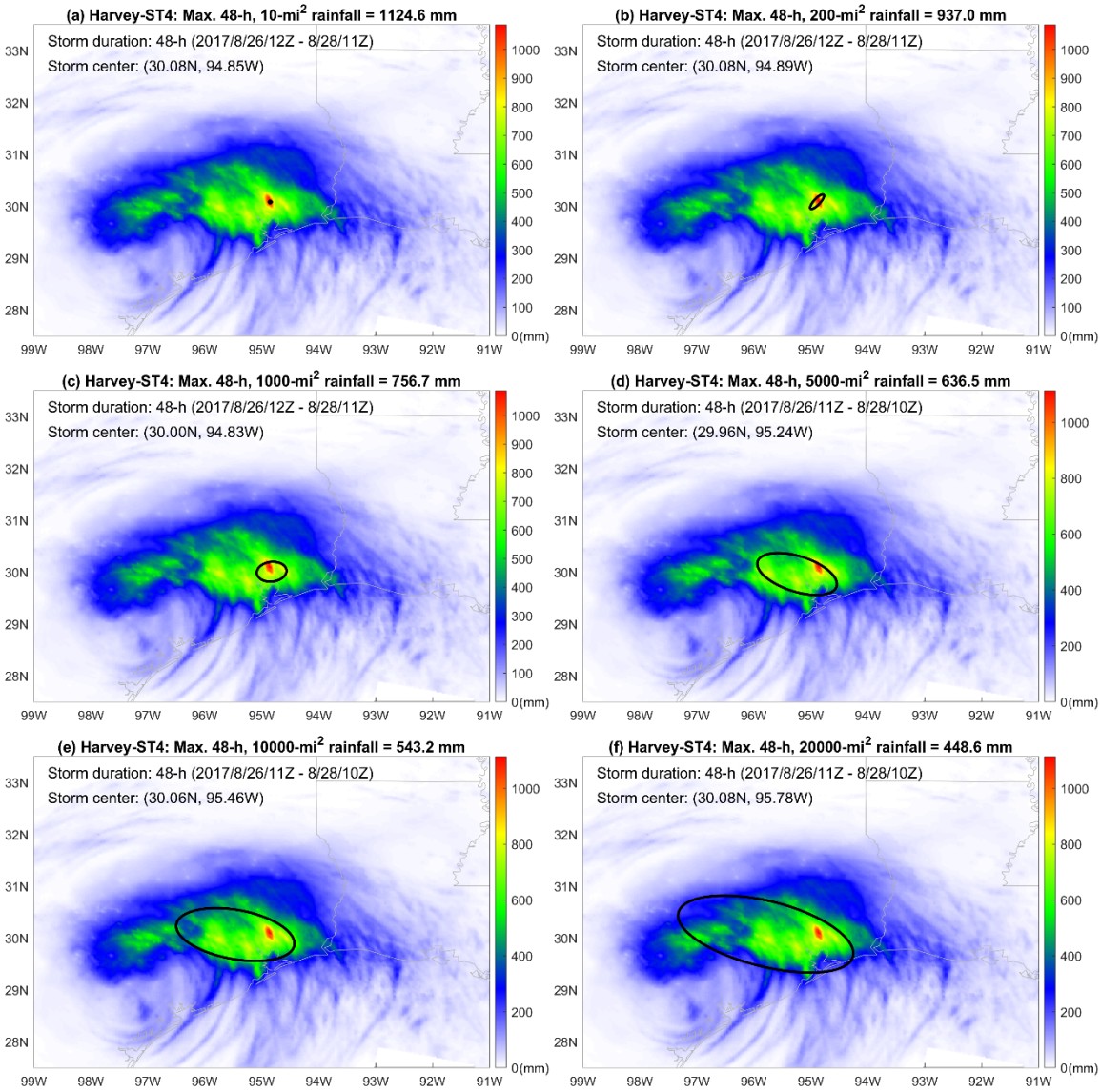

Figure S4. Maximum 48-h NCEP Stage IV QPE of Hurricane Harvey. The ellipses mark the heaviest 10 m^2 (upper-left), 100 m^2 (upper-right), 1,000 mi^2 (mid-left), 5,000 mi^2 (mid-right), 10,000 mi^2 (lower-left), and 20,000 mi^2 (lower-right) average rainfall during the entire Harvey event. The specific timing and storm center are reported in each panel.

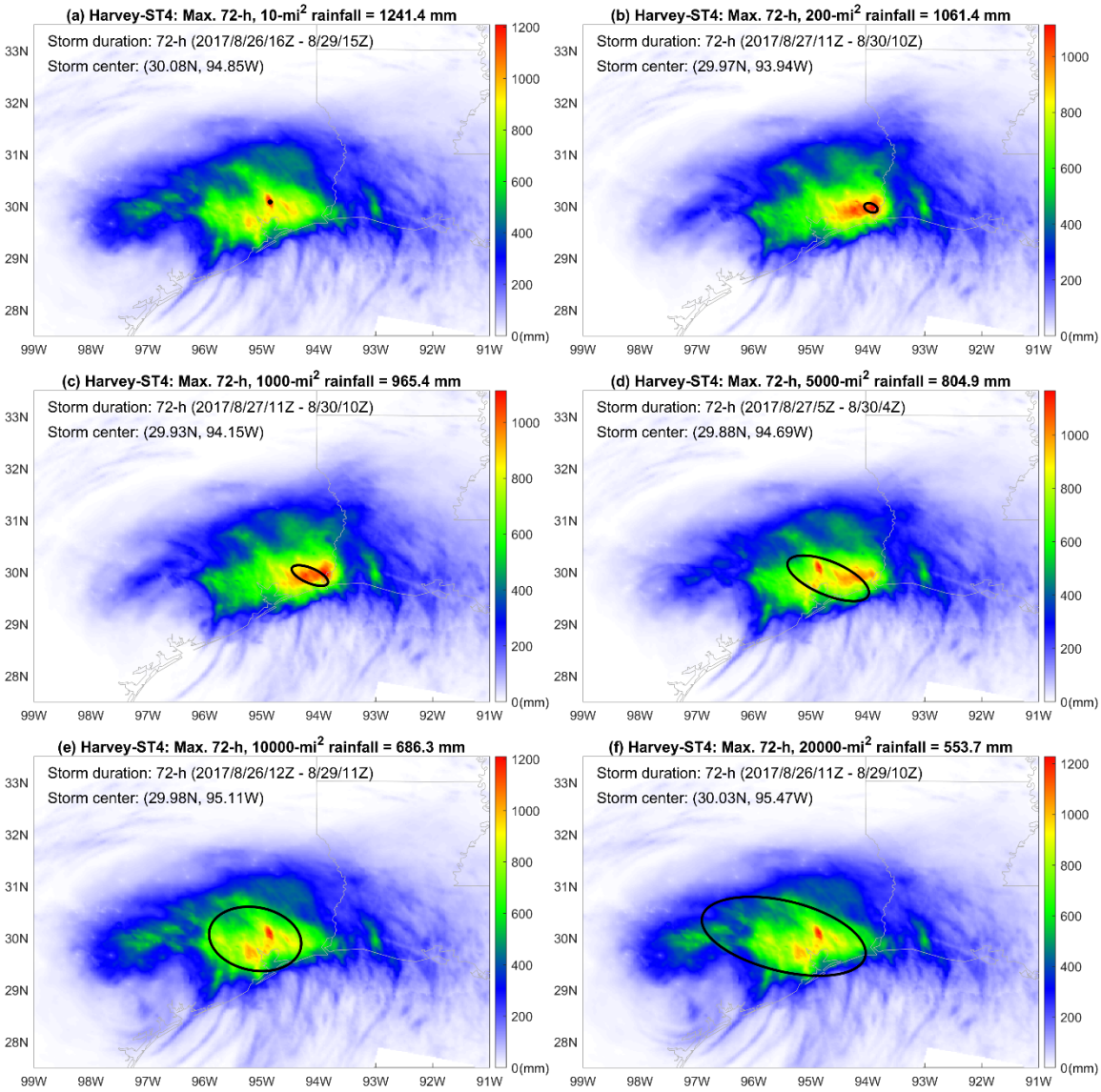

Figure S5. Maximum 72-h NCEP Stage IV QPE of Hurricane Harvey. The ellipses mark the heaviest 10 m^2 (upper-left), 100 m^2 (upper-right), 1,000 mi^2 (mid-left), 5,000 mi^2 (mid-right), 10,000 mi^2 (lower-left), and 20,000 mi^2 (lower-right) average rainfall during the entire Harvey event. The specific timing and storm center are reported in each panel.

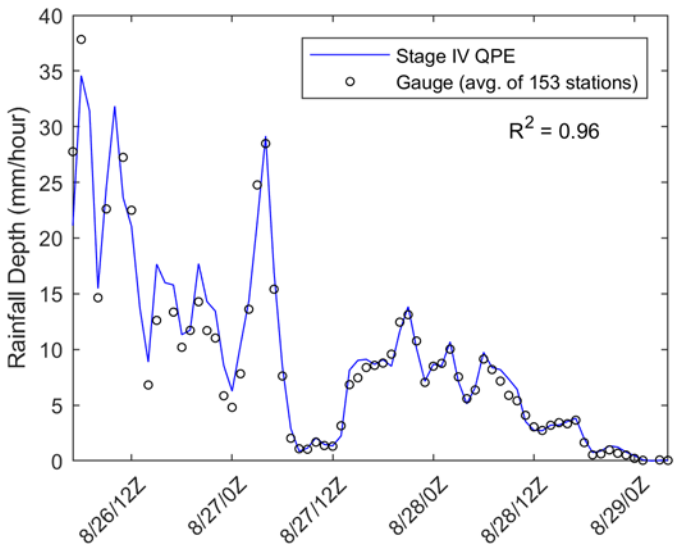

Figure S6. Validation of NCEP Stage IV QPE by gauge observations. The hourly rainfall data from 153 Harris County rain gauges are obtained from the Houston Urban Data Platform Harvey-Related Data Portal (http://harveyudp.rice.edu/) and averaged across all stations. At each rain gauge location, the corresponding Stage IV QPE data are looked up and compared. The 72-h timing (2017/8/27/5Z – 2017/8/30/4Z) corresponds to the maximum 5000-mi^2 rainfall identified in Figure 1(a). Overall a very high R^2 value is found between the two data series.

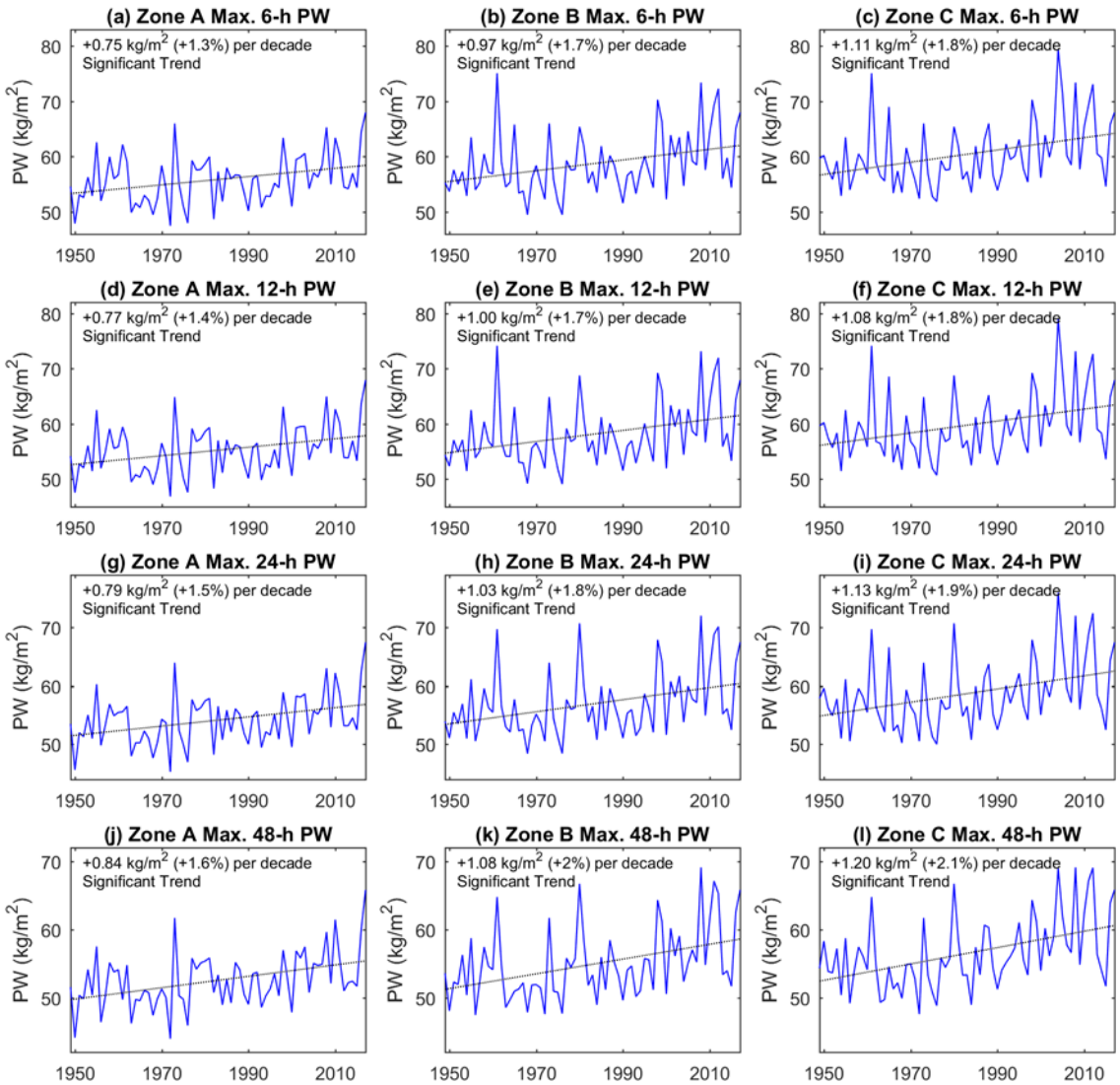

Figure S7. Time series and trend of annual maximum 6-, 12-, 24, and 48-h duration gridded NCEP precipitable water (kg/m^2) from three selected zones in the southern United States. The maximum precipitable water is selected from August 11th through September 10th each year from all grid points within the zone. A 5% significance level is used to judge whether a trend is statistically significant.

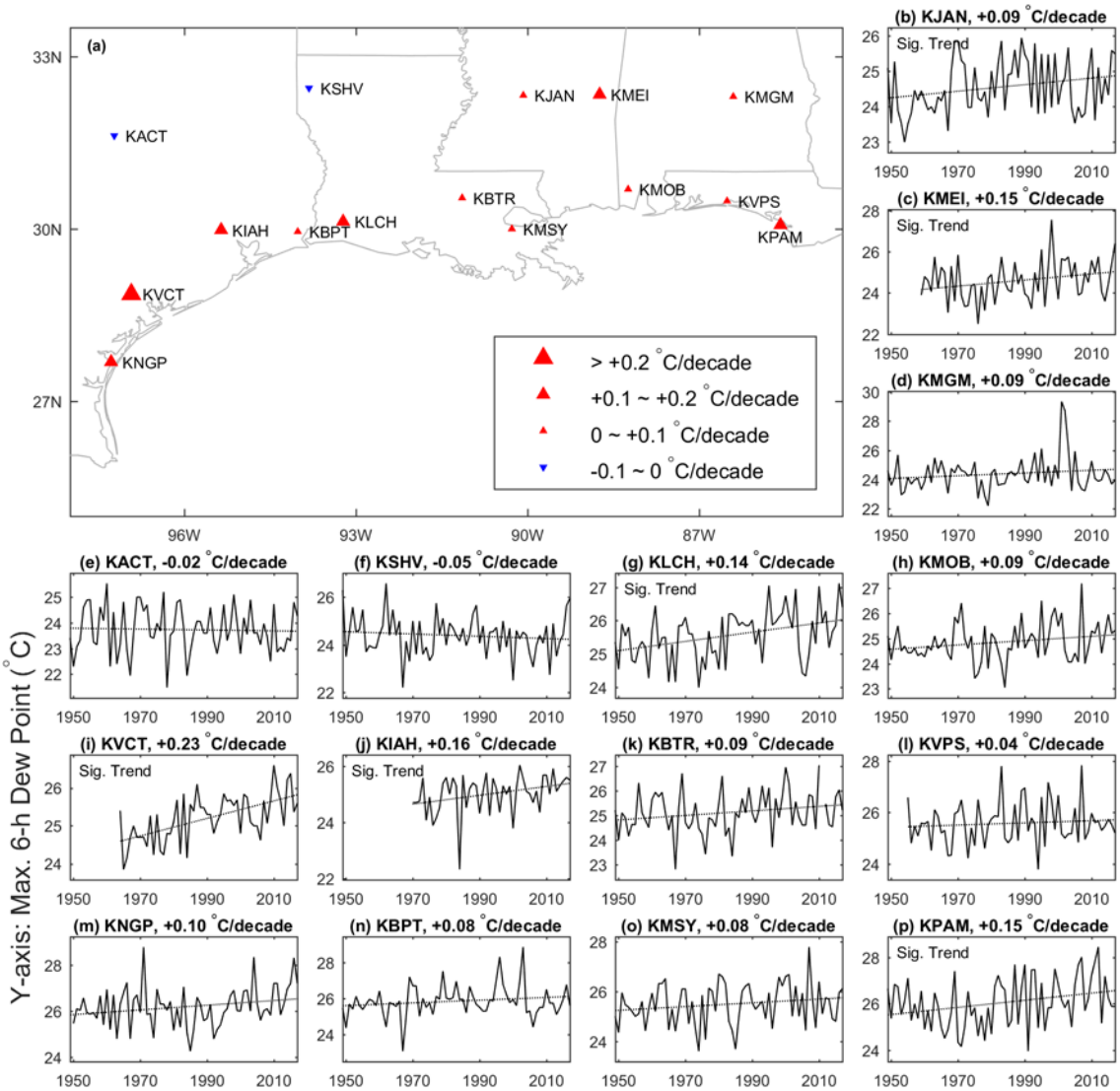

Figure S8. Time series and trend of annual maximum 6-h duration average dew point temperature (°C) occurring from August 11th through September 10th from 15 surface weather stations in the southern United States. A 5% significance level is used to judge whether a trend is statistically significant.

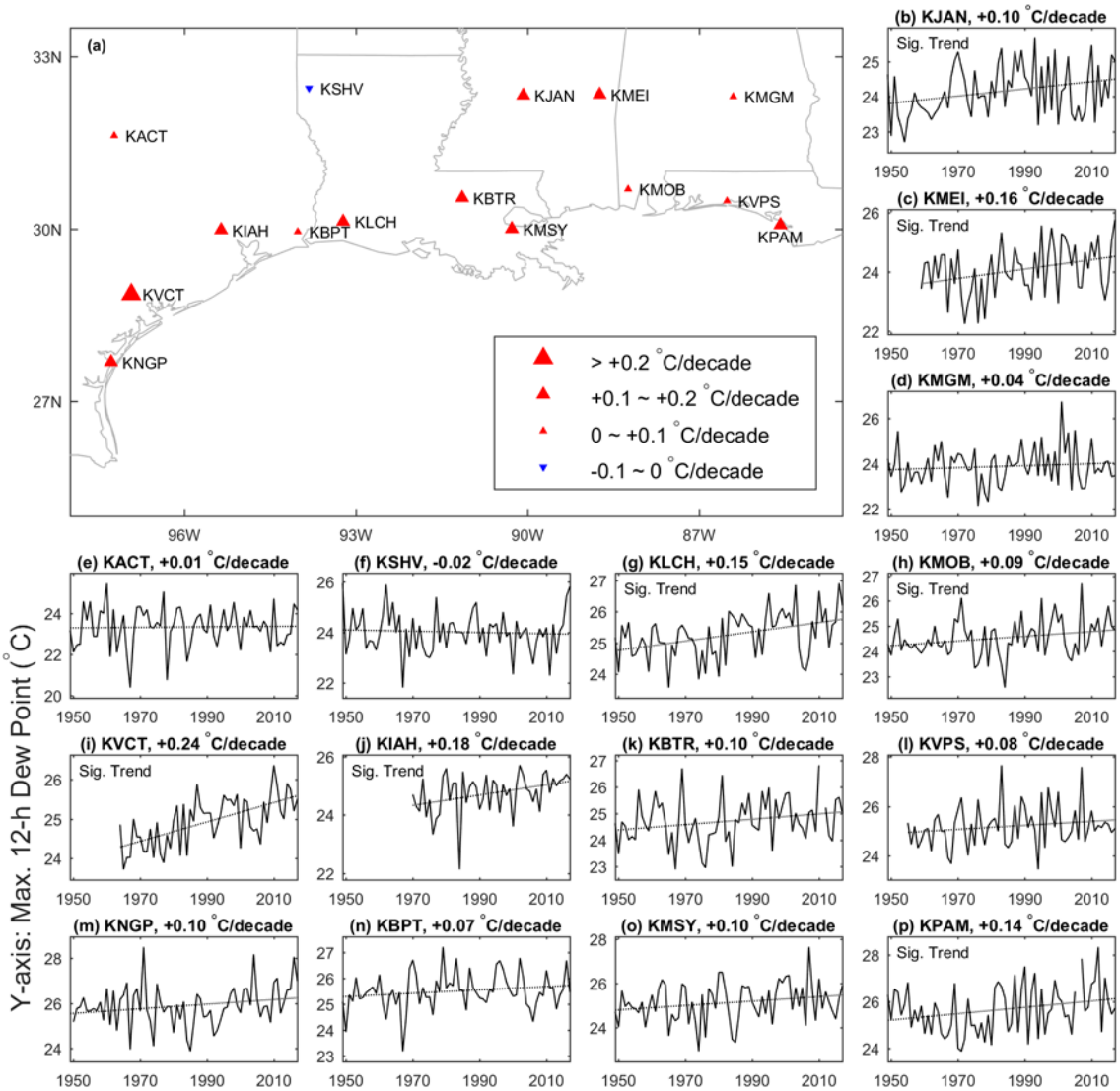

Figure S9. Time series and trend of annual maximum 12-h duration average dew point temperature (°C) occurring from August 11th through September 10th from 15 surface weather stations in the southern United States. A 5% significance level is used to judge whether a trend is statistically significant.

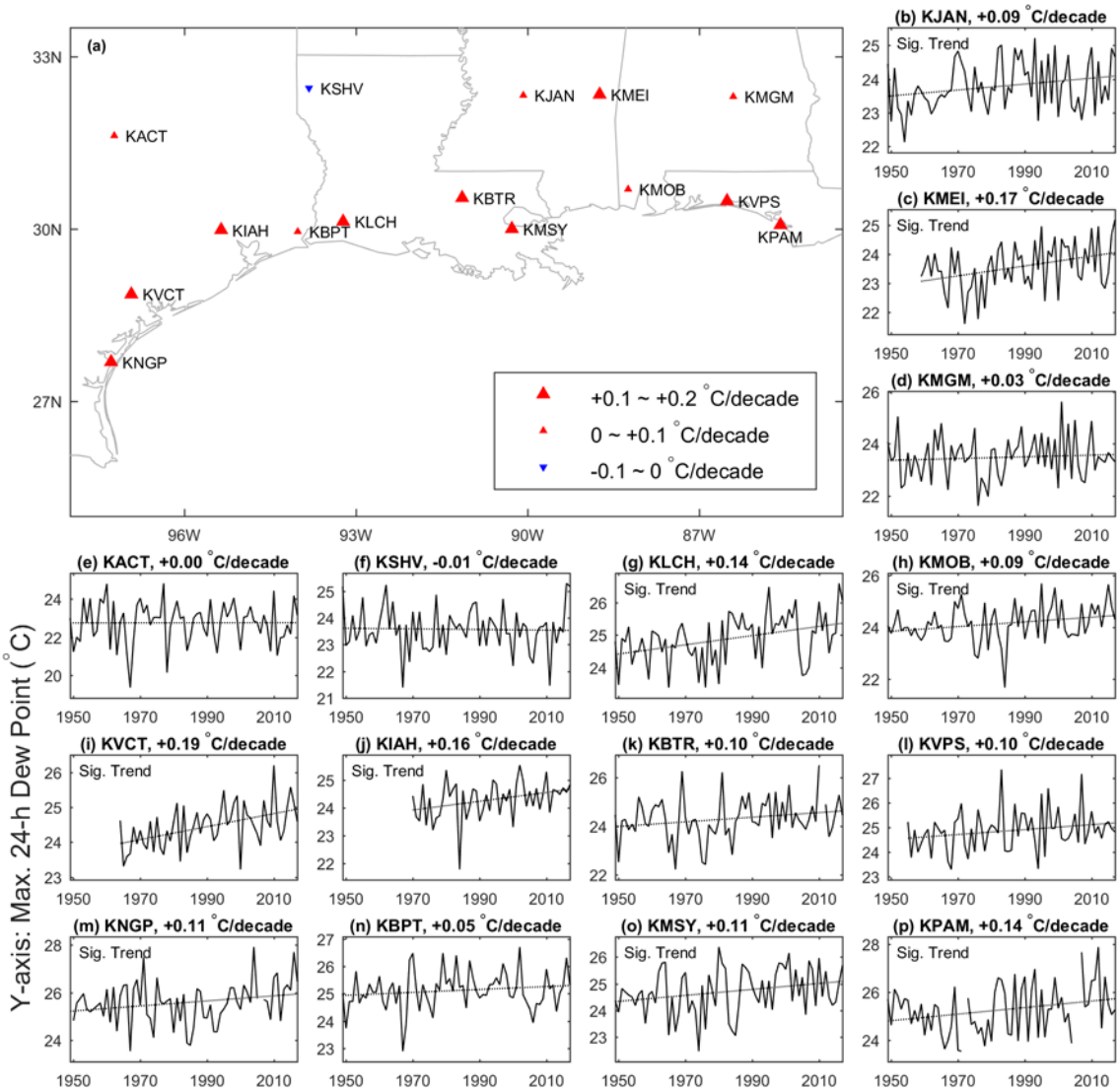

Figure S10. Time series and trend of annual maximum 24-h duration average dew point temperature (°C) occurring from August 11th through September 10th from 15 surface weather stations in the southern United States. A 5% significance level is used to judge whether a trend is statistically significant.

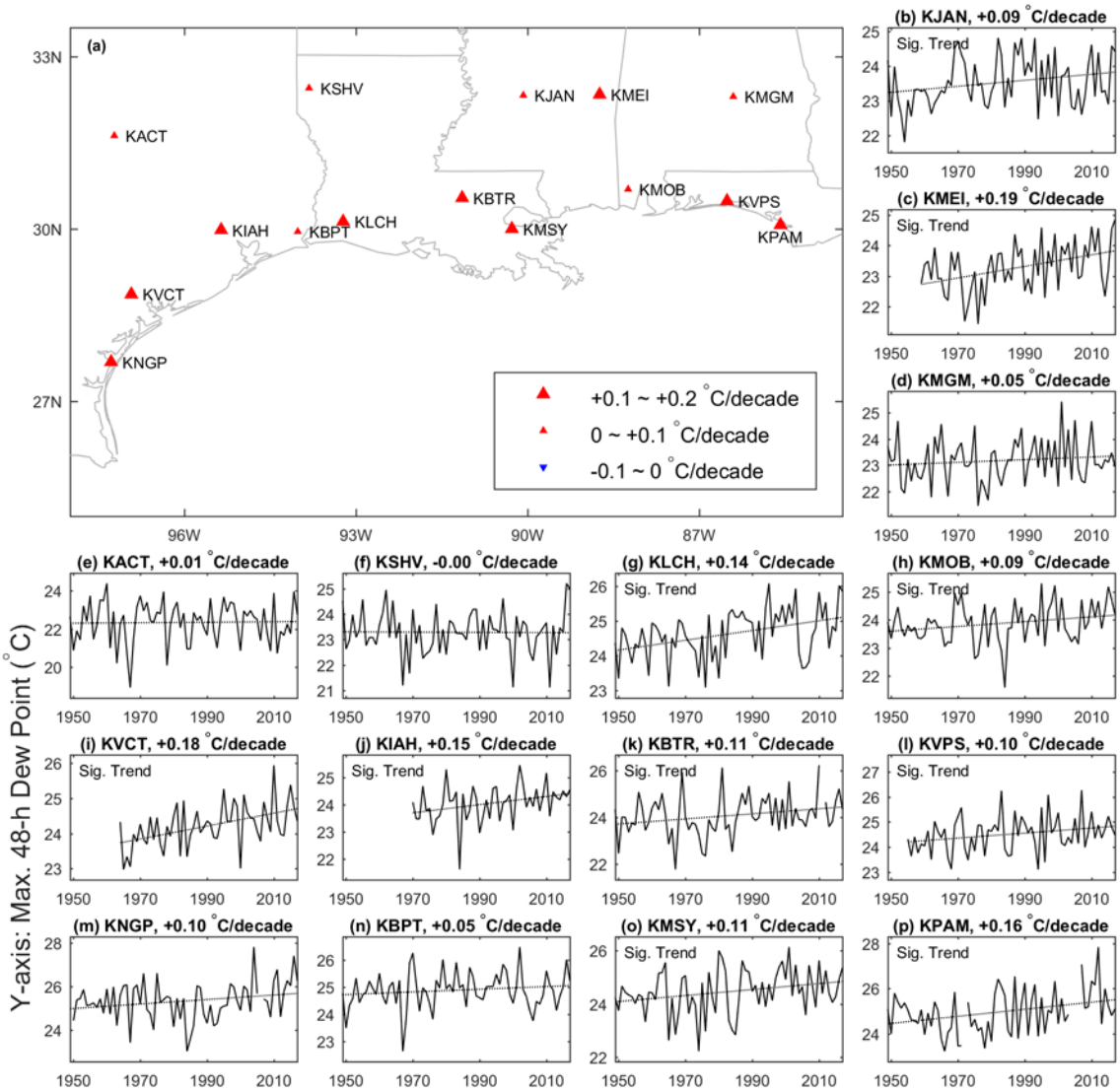

Figure S11. Time series and trend of annual maximum 48-h duration average dew point temperature (°C) occurring from August 11th through September 10th from 15 surface weather stations in the southern United States. A 5% significance level is used to judge whether a trend is statistically significant.