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Paper:

What Factors Contributed to the Torrential Rainfall of Hurricane Harvey over Texas?

Satoshi Iizuka† and Naoki Sakai

National Research Institute for Earth Science and Disaster Resilience (NIED)
3-1 Tennodai, Tsukuba, Ibaraki 305-0006, Japan
†Corresponding author, E-mail: iizuka@bosai.go.jp

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In August 2017, Hurricane Harvey brought an unprecedented amount of rainfall and catastrophic flooding to the Houston metropolitan area, as it stalled near the coast of Texas for several days after weakening to a tropical storm intensity. The present study examines the relationship between tropical cyclone rainfall totals over Texas and the track, residence time, rainfall intensity, and rainfall area coverage of past tropical cyclones that approached Texas after 1979. The most significant factor affecting rainfall totals over Texas is whether a tropical cyclone makes landfall on the central coast of Texas and travel inland. Another significant factor is the length of time a tropical cyclone resides near Texas. Rainfall intensity also contributes in part to rainfall totals over Texas, whereas contribution of rainfall area coverage is not significant. The track of a tropical cyclone traveling near Texas is controlled by the steering winds over Texas, while its residence time near Texas is related partly to the meandering of the subtropical jets. Rainfall rate depends on the intensity of tropical cyclone. No significant relationship between rainfall intensity and environmental moisture in the lower atmosphere is found in the present analysis. Furthermore, the extreme rainfall totals over Texas induced by Harvey can be attributed to the combined effect of extreme long-term stalling of Harvey near the central coast of Texas and the higher rainfall rate.

Keywords: Hurricane Harvey, rainfall, flood, Texas

1. Introduction

Hurricane Harvey made landfall in Texas as a Category 4 storm on the Saffir-Simpson scale and was rapidly downgraded to a tropical storm. However, Harvey stalled near the coast of Texas for several days, dropping abundant rainfall over Southeastern Texas. Large parts of the Houston metropolitan area received over 1000 mm of rain from August 25–31, 2017, leading to catastrophic flooding in Harris and Galveston counties [1]. The areal extent of the heavy rainfall caused by Harvey is overwhelming compared with historical United States (US) tropical cyclone events. Moreover, the annual exceedance probability of a flood over a large portion of Southeastern Texas was less than 0.1% chance of occurring in any given year (e.g., a 1,000-year or greater flood) [1].

Most studies have examined the impact of global warming on the unprecedented rainfall of Hurricane Harvey. Risser and Wehner [2] reported that precipitation accumulations in Texas were likely increased by at least 18.8% due to global warming over the past half century, which surpasses the 6–7% increase predicted with a warming of 1°C in the Clausius-Clapeyron scaling. Wang et al. [3] assessed the impact of long-term climate trends on Harvey's precipitation through 60-member ensemble simulations. The results suggest that post-1980 climate warming may have contributed to the extreme precipitation that fell on Southeast Texas during August 26–29, 2017 by approximately 20%. They also demonstrated that sea surface temperature and troposphere warming caused an increase in precipitation by 3% and 17%, respectively.

Although a tropical cyclone with high precipitation rate has the potential to deposit a vast amount of rainfall, rainfall totals are also in part dependent on the stalling time. If the tropical cyclone stagnates or moves slowly, successive heavy rain over the same area may bring abundant rainfall totals. For example, in August 2016, Louisiana, a state east of Texas, underwent catastrophic flooding caused by rainfall associated with a slow-moving tropical low-pressure system interacting with an eastward traveling baroclinic trough to the north [4]. Hurricane Harvey also stalled near the coast of Texas for several days [1]. However, the relative importance of stalling time and precipitation intensity of Hurricane Harvey to the extreme rainfall totals has not been compared within the same framework elsewhere to our knowledge.

The scales such as the Saffir-Simpson scale represent the severity of tropical cyclone intensity. However, there is no proper index to represent the total amount of tropical cyclone rainfall. The timing and spatial distribution of precipitation within a stream basin are the key factors in determining whether flooding will occur [5]. Excessive point precipitation accumulation, which is a convenient benchmark for assessing the extremeness of precipitation, often provides little information regarding the potential for stream basin flooding. The cumulative rainfall totals over land and associated flood damage induced by a tropical cyclone depend not only on rainfall rate and transla-

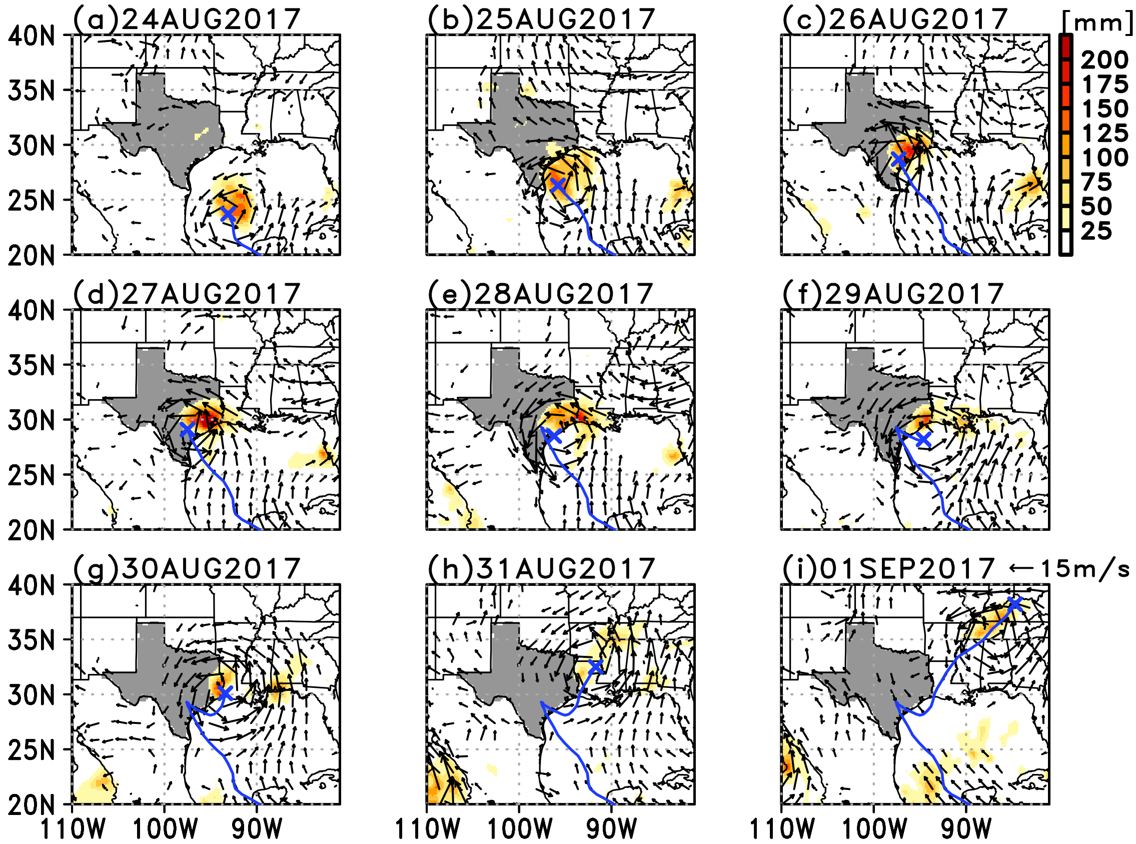

Fig. 1. Daily precipitation (shaded) and wind at 925 hPa (vector arrows) from August 24 to September 1, 2017. The blue crosses and lines indicate the position and track of Hurricane Harvey respectively. The gray-shade area represents Texas.

tion speed but also on rainfall area coverage [6] and trajectory of the tropical cyclone. If a tropical cyclone travels inland, the total amount of rainfall accumulated over land would be more than that of a tropical cyclone that narrowly misses land [5].

The present study attempts to assess the extremeness of the rainfall totals of Harvey using an ingredient-based methodology. The ingredients involved are the track, stagnation days, rainfall intensity, and rainfall area coverage of a tropical cyclone. This method may provide useful information for assessing the severity of hazards associated with tropical cyclones. An explanation of the data and methodology is given in Section 2, followed by an overview of Hurricane Harvey in Section 3. Results describing the relationship between tropical cyclone rainfall totals over Texas and track, residence time, rainfall intensity, and rainfall area coverage of past tropical cyclones that approached Texas are presented in Section 4, and the impact of the ingredients on the extreme rainfall totals of Harvey is discussed in Section 5. A summary is given in Section 6.

2. Data and Methodology

The present study acquired atmospheric data from the North American Regional Reanalysis (NARR) dataset [7], which has a spatial resolution of 32 km and a temporal resolution of 3 hours, and has the potential advantage of assimilating precipitation data from land stations. The accumulated tropical cyclone precipitation totals over Texas were correlated with the Climate Prediction Center US unified gauge-based analysis of daily precipitation [8] using the optimal interpolation objective analysis technique ($r = 0.97$). The tropical cyclone data were obtained from the National Hurricane Center best track dataset [9]. Sea surface temperature data produced by the US Naval Oceanographic Office were used in this study.

In order to assess the extremeness of the rainfall totals of Harvey, tropical cyclones that passed within a 500 km radius of Texas (gray-shaded area in **Fig. 1**) were selected for comparison (**Table 1**). The 500 km radius was selected based on the findings of several previous studies [10, 11] and applied around the position of the center of the selected tropical cyclones. The 3-h NARR rainfall data within the 500 km radius were identified as the rainfall associated with tropical cyclones, while the rest of the rainfall data were labeled as non-tropical cyclone related rainfall. In addition, tropical cyclone related rainfall over Texas was identified as the contribution of tropical cyclones to total rainfall over Texas.

Total rainfall accumulation over land depends on the movement speed, size, and strength of a tropical cyclone as well as its track over land [5, 12]. Therefore, total trop-

Table 1. List of tropical cyclones that passed within a 500 km radius of Texas (gray-shaded area in **Fig. 1**).

No.	Year	Name	No.	Year	Name
1	1979	Claudette	23	1998	Charley
2	1979	Elena	24	1998	Frances
3	1980	TS#02	25	1999	Bret
4	1980	Allen	26	2000	TS#09
5	1980	Danielle	27	2001	Allison
6	1980	Jeanne	28	2002	Bertha
7	1981	TS#04	29	2002	Fay
8	1981	TS#12	30	2003	Claudette
9	1982	Chris	31	2003	Grace
10	1983	Alicia	32	2004	Ivan
11	1985	Juan	33	2005	Rita
12	1986	Bonnie	34	2007	Erin
13	1986	TS#04	35	2007	Humberto
14	1987	TS#03	36	2008	Dolly
15	1988	Beryl	37	2008	Edouard
16	1988	Florence	38	2008	Ike
17	1988	TS#17	39	2008	Two
18	1989	Allison	40	2010	Hermine
19	1989	Chantal	41	2011	Don
20	1989	Jerry	42	2015	Bill
21	1993	Arlene	43	2017	Cindy
22	1995	Dean	44	2017	Harvey

ical cyclone induced rainfall accumulation over Texas is expressed as follows:

$$R_{TX} = \varepsilon \times R_{TC} = \varepsilon \times RA_{TC} \times RI_{TC} \times T_{TC}, \quad . \quad . \quad (1)$$

where R_{TX} is the tropical cyclone rainfall totals over Texas (mm), R_{TC} is the tropical cyclone rainfall totals (mm), RA_{TC} is the time-averaged rainfall area (%), RI_{TC} is the time-averaged rainfall intensity (mm d^{-1}) within 500 km radius of a tropical cyclone, and T_{TC} is the residence time of a tropical cyclone within 500 km radius of Texas. As described later, ε is the ratio of R_{TX} to R_{TC} (%) and reflects the difference in the tropical cyclone track over Texas.

3. Overview of Hurricane Harvey

On August 17, 2017, tropical storm Harvey moved westward with a wind speed exceeding 17 m s^{-1} on the east of the Bahamas (**Fig. 2**). When it reached the center of the Caribbean Sea on August 19, it weakened to a tropical disturbance, following which it turned west-northwestward and passed over the Yucatan Peninsula. As it moved over the western part of the Gulf of Mexico on August 23, it re-developed into a tropical cyclone with wind speeds exceeding 17 m s^{-1} (**Fig. 3**).

On August 24, Harvey became a hurricane and on August 25, it became a Category 3 storm with wind speed exceeding 50 m s^{-1}. As Harvey approached the coast of Texas on August 26, the wind speed reached Cate-

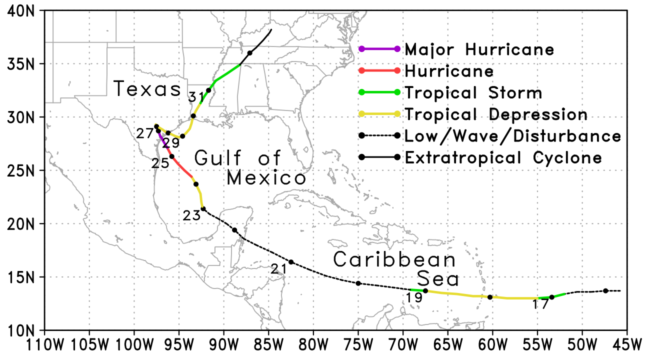

Fig. 2. 24-hour track of Hurricane Harvey from August 16 to September 2, 2017.

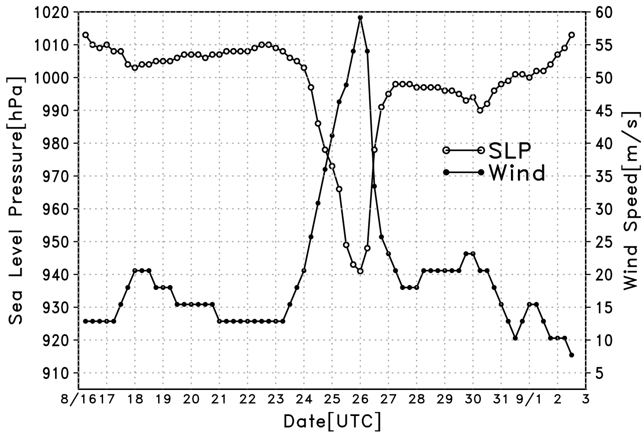

Fig. 3. Time series of sea level pressure and maximum sustained wind speed for Hurricane Harvey from August 16 to September 2, 2017.

gory 4 intensity, exceeding 59 m s^{-1} and Harvey soon made landfall in the central coast of Texas.

Although Harvey downgraded to a tropical storm after landfall, it changed its direction to the southeast and moved again over the Gulf of Mexico while maintaining its power. After that, it turned northeastward and made landfall again; this time to the west of Louisiana on August 30. Meanwhile, the rain lasted in Southeast Texas, mainly in Houston (**Fig. 1**). After August 31, the storm increased its speed, and on September 1, it moved over Tennessee and was downgraded to an extratropical low-pressure system.

The movement of tropical cyclones is controlled primarily by the surrounding large-scale winds [13]. **Fig. 4** shows the environmental steering winds (averaged vertically from lower (850 hPa) to upper troposphere (here 200 hPa)) and geopotential height field at 500 hPa from August 24 to September 1, 2017 when Hurricane Harvey was near Texas. The environmental fields were obtained as the residual that resulted from the removal of local disturbance fields, using the technique proposed by [14, 15].

Until Hurricane Harvey made landfall in Texas, there were no remarkable steering wind fields over South Texas

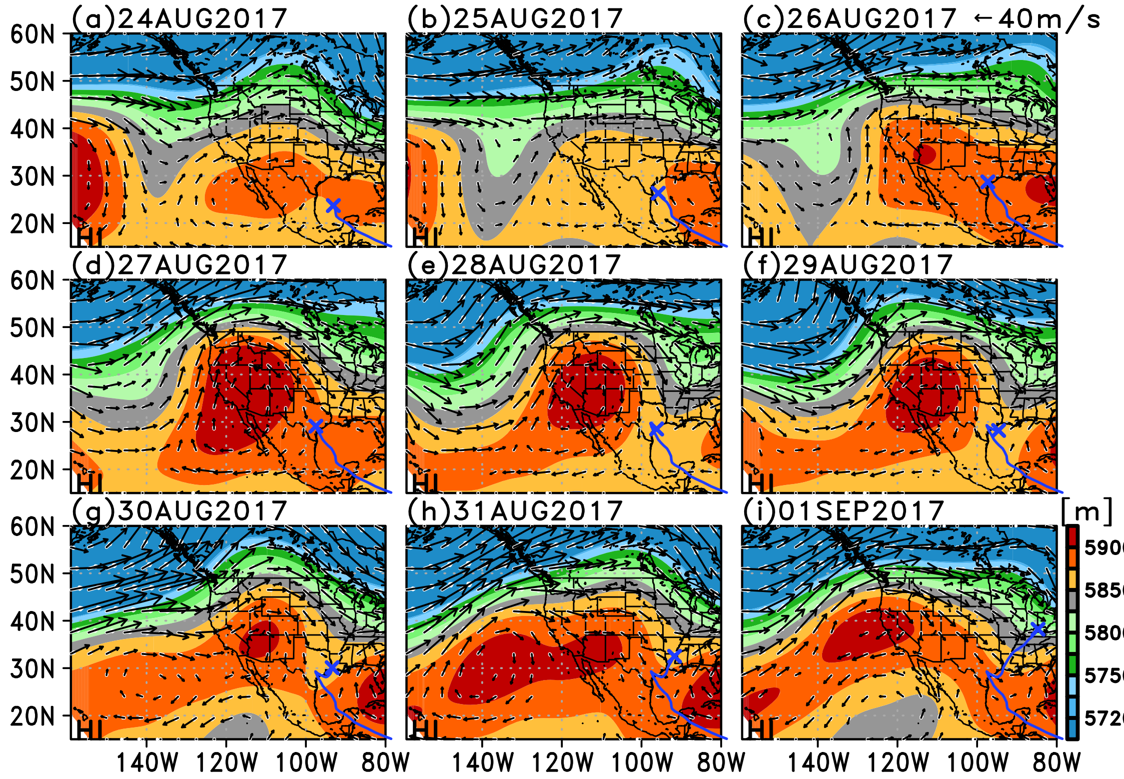

Fig. 4. Environment steering wind (vector arrows) and geopotential height at 500 hPa (shaded) from 12:00 UTC, August 24 to 12:00 UTC, September 1, 2017. The blue crosses and lines indicate the position and track of Hurricane Harvey, respectively. HI represents Hawaii.

(**Figs. 4(a)–(c)**). However, after making landfall on August 27, an intensification of the high geopotential height field was observed over the western US along with a meandering subtropical jet starting from the periphery of Hawaii and heading toward the southern US, particularly Texas (**Fig. 4(d)**). The intensification lasted for several days (**Figs. 4(e)**, **(f)**). It seems that the southward flow of the jet over Texas caused Harvey to travel southward after it made landfall (**Fig. 2**).

Sea surface temperatures exceeded 30°C were spread almost over the entire Gulf of Mexico when Hurricane Harvey was in the vicinity of Texas (**Fig. 5**). The warm sea-surface temperatures were favorable for maintaining tropical cyclone intensity. It appears that these atmospheric and oceanic conditions caused Hurricane Harvey to stay around Texas for a long period of time as a tropical storm. Trenberth et al. [16] suggested that the highest oceanic heat content on record for the Gulf of Mexico occurred during the summer of 2017 and contributed to the increased rainfall and subsequent flooding in Texas.

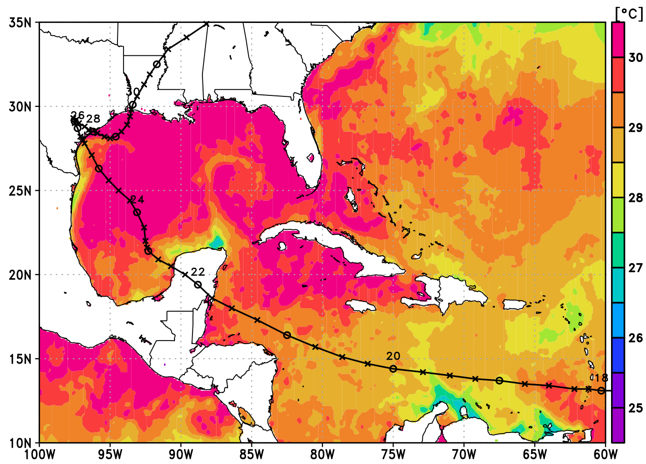

Fig. 5. Sea-surface temperature on August 24, 2017. The black line indicates the 6-hour track positions of Hurricane Harvey.

4. Results

Here we examine the relationship between tropical cyclone rainfall totals over Texas and the track, residence time, rainfall intensity, and rainfall area coverage of past tropical cyclones that approached Texas. **Figs. 6(a)** and **(b)** show the relationship between R_{TX} and R_{TC}, with ε being the difference in tropical cyclone track over Texas for the 44 tropical cyclones that approached Texas since 1979. The six tropical cyclones with the largest rainfall totals over Texas are Harvey 2017, Dean 1995, Hermine 2010, Fay 2002, Bill 2015, and Erin 2007. Hurricane Harvey recorded the largest rainfall totals over

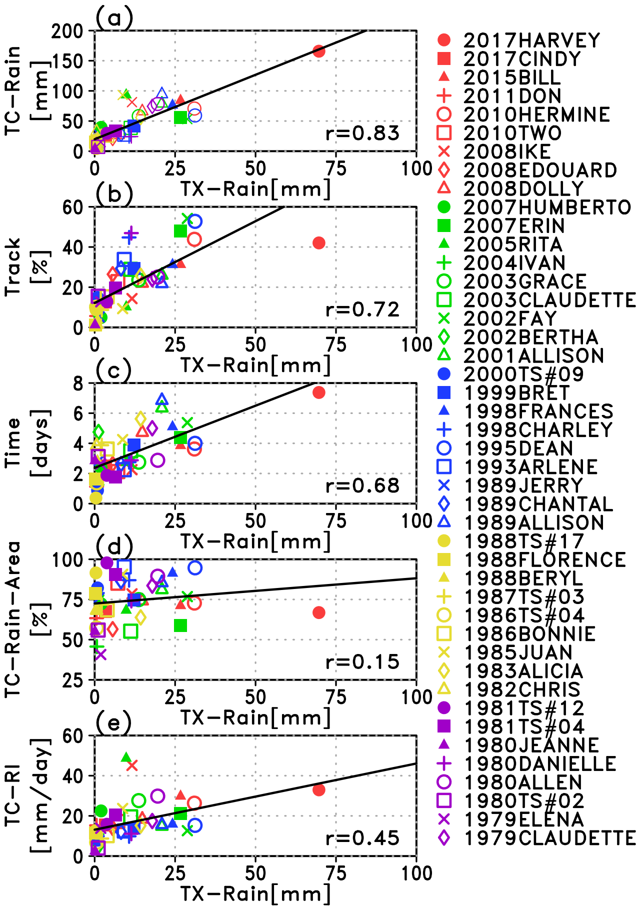

Fig. 6. Scatter plots showing the relationship between total amount of rainfall over Texas and (a) total rainfall within 500 km radius of tropical cyclone accumulated over the stagnation days, (b) parameter representing the difference of track over Texas, (c) number of stagnation days, (d) rainfall area within 500 km radius of tropical cyclone, and (e) time averaged tropical cyclone rainfall intensity, respectively. The symbols on the right represent the tropical cyclones listed in **Table 1**. Note that total rainfall is divided by the area of Texas (gray-shaded region in **Fig. 1**).

Texas, which was twice that of the second largest hurricane Dean.

The rainfall totals over Texas correlate not only with the tropical cyclone rainfall totals (**Fig. 6(a)**) but also with ε (**Fig. 6(b)**). In fact, for the 44 tropical cyclones that approached Texas from 1979 to 2017, the correlation coefficients between the two parameters and the rainfall totals over Texas are as high as 0.83 and 0.72, respectively. **Fig. 7** shows the environmental geopotential height at 500 hPa (contour lines) and steering winds (vector arrows) regressed on ε of each tropical cyclone. Note that the sign is reversed. This relationship suggests that smaller (larger) ε values are associated with stronger (weaker) eastward steering winds over Texas, accompanied by the anomalous trough (ridge) to the north of Texas.

The distribution of total rainfall for several tropical cy-

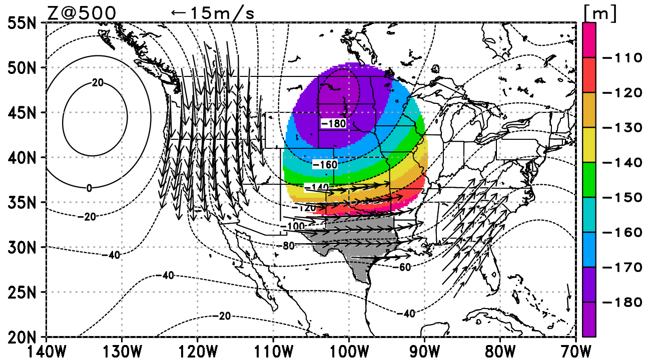

Fig. 7. Environmental geopotential height at 500 Pa (contour lines) and steering winds (vector arrows) regressed on ε of each tropical cyclone. Colored region and vector arrows indicate statistically significant results at the 99% confidence level. The sign is reversed.

clones is shown in **Fig. 8**. Among the six tropical cyclones with the largest rainfall totals over Texas, Hurricanes Fay 2002, Dean 1995, and Erin 2007 that made landfall to the central coast of Texas and moved inland had the three largest values of ε. Hurricanes Hermine 2010, Harvey 2017, and Bill 2015 had the sixth, seventh, and ninth largest values, respectively. Thus, tropical cyclones that make landfall on the central coast of Texas and travel inland (**Fig. 8**) tend to have a larger value of ε and are more likely to produce more inland rainfall totals over Texas.

The rainfall totals will increase if a storm stalls for a long period of time. **Fig. 6(c)** shows the relationship between rainfall totals over Texas and the number of stagnation days. Stagnation days are defined as the number of days that a tropical cyclone stalls within the 500 km radius of Texas. The correlation coefficient between the two is as high as 0.68. Environmental atmospheric conditions can also affect the movement of tropical cyclones. Recent studies [17, 18] have documented an increase in number of stalling tropical cyclones and associated rainfall along the North American coast. One of the possible reasons for the slowdown of tropical cyclone translation speed is the reduction of robust steering flow because of an increase in the waviness of mid-latitude tropospheric zonal winds [19]. **Fig. 9** shows the relationship between the meridional component of the steering flow and stagnation days of tropical cyclones approaching Texas. The wavy pattern in the jet is observed over North America, although there is no significant relationship with the zonal component of the steering flow. This suggests that the meandering of the mid-latitude tropospheric jet can make a tropical cyclone stall around Texas.

Rainfall coverage area of a tropical cyclone may also contribute to the cyclone's rainfall totals [6, 20, 21]. Tropical Storm No. 12 in 1981, Hurricanes Arlene 1993 and Dean 1995 are three tropical cyclones with the largest coverage area. However, no significant relationship was found between tropical cyclone rainfall coverage area

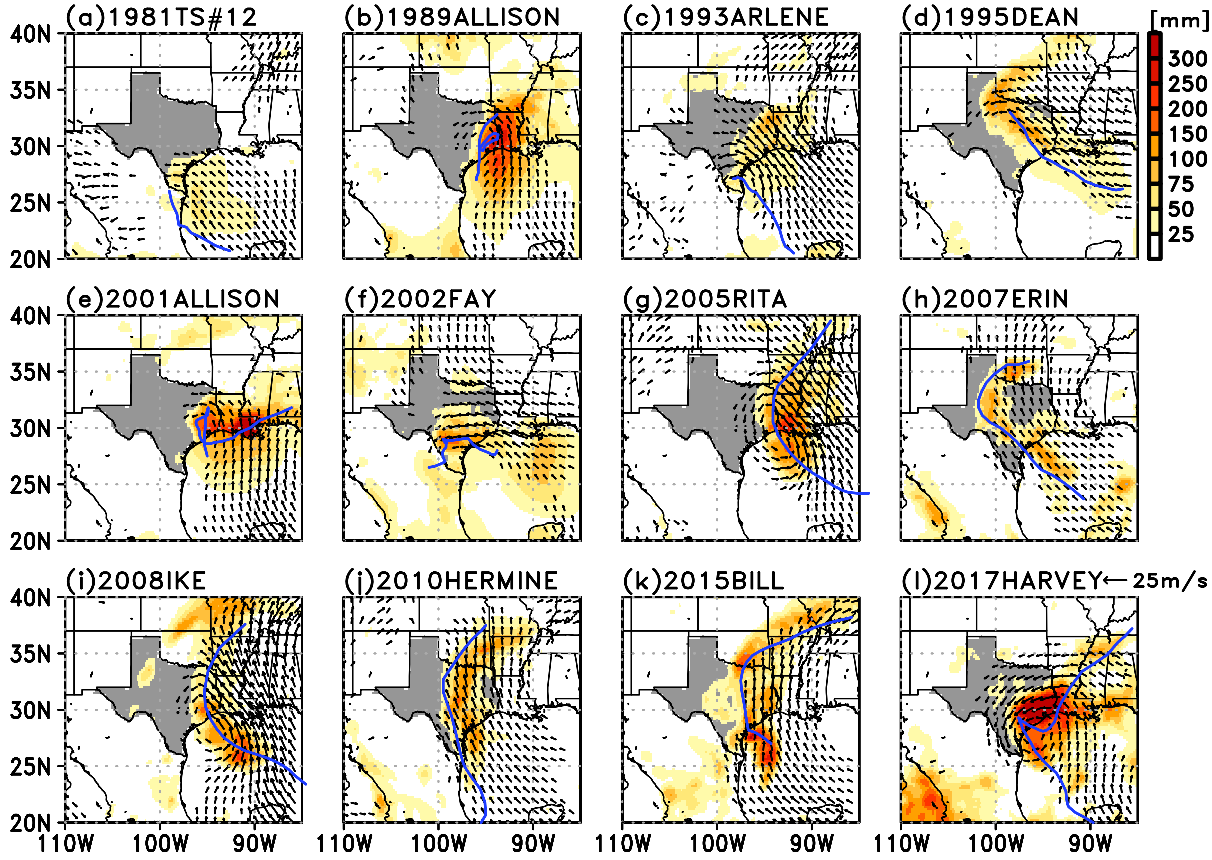

Fig. 8. Total rainfall (shading) and time averaged 925 hPa winds (vector arrows) for Tropical Storm (a) No. 12, 1981, (b) Allison 1989, (c) Arlene 1993, (d) Dean 1995, (e) Allison 2001, (f) Fay 2002, (g) Rita 2005, (h) Erin 2007, (i) Ike 2008, (j) Hermine 2010, (k) Bill 2015, and (l) Harvey 2017. The blue lines indicate the track of each storm.

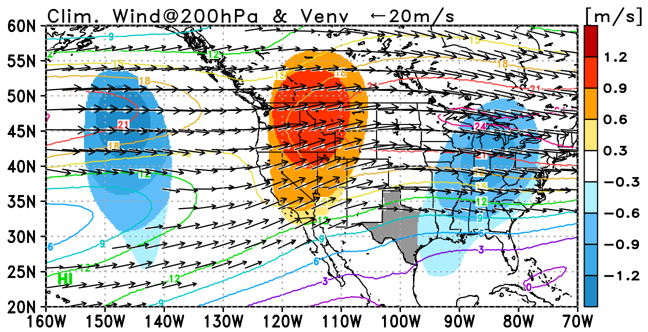

Fig. 9. Color shading indicates the meridional environmental steering winds regressed on stagnation days of each tropical cyclone at the 95% confidence level for significance. Climatological long-term mean 200 hPa zonal winds (contour) and winds (vector arrows) averaged for June–September are also shown.

and total rainfall accumulated over Texas (**Fig. 6(d)**). The rainfall coverage area of Hurricane Harvey is the 11th smallest among the 44 tropical cyclones.

Figure 6(e) shows the relationship between rainfall totals over Texas and the rainfall intensity averaged over the stagnation days. The correlation coefficient of 0.45 indicates that rainfall intensity contributes in part to the rainfall totals over Texas.

The increase in tropical cyclone rainfall rate is explained by a combined increase in environmental water vapor and tropical cyclone intensification [22]. Here we examine the difference in rainfall intensity among tropical cyclones in terms of a moisture budget analysis. Time-averaged rainfall intensity may be expressed as follows [10]:

$$\overline{P} = \overline{\text{Local change of } TPW} + \overline{MFC} + \overline{E} - \overline{C}, \quad . \qquad (2)$$

where the overbar indicates the time averaging during stagnation days. P is the rainfall intensity (mm d^{-1}), MFC is moisture flux convergence vertically integrated for the entire atmospheric column (mm d^{-1}), E is moisture flux from the surface (mm d^{-1}), TPW is total perceptible water (mm, equivalent to kg m^{-2}), and C is amount of liquid and solid water stored in a cloud (cloud storage, mm d^{-1}). Local changes in TPW and cloud storage are insignificant, and P is balanced by the sum of E and MFC ($r = 0.9$).

Figure 10 shows the relationship between rainfall intensity and average values of E and MFC during stagnation days. The rainfall intensity is more closely related to MFC than E. **Fig. 11** shows the relationship be-

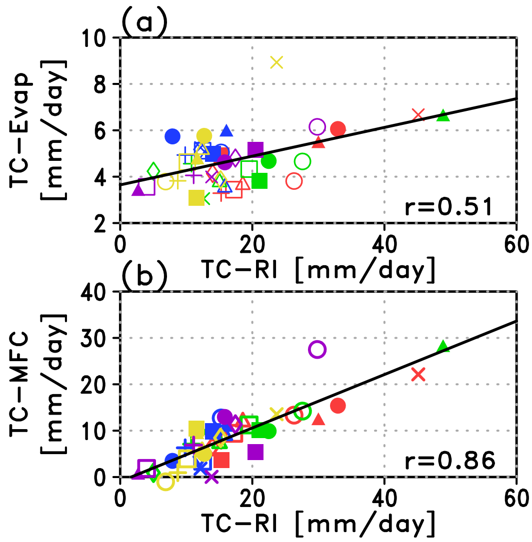

Fig. 10. Scatter plots showing the relationship between rainfall intensity and (a) evaporation, and (b) moisture flux convergence. The symbols are same as the ones in **Fig. 6**.

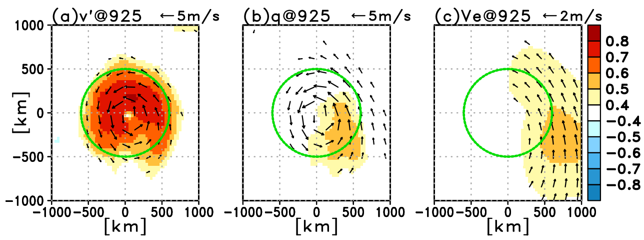

Fig. 11. Correlation between *MFC* within 500 km radius and (a) wind speed of local components associated with hurricanes, (b) specific humidity, and (c) environmental steering wind speed, at 925 hPa on the coordinates centered on the hurricanes. Winds associated with hurricanes are defined as the residual of environmental wind. Vector arrows represent (a) local components associated with hurricanes, (b) winds, and (c) environmental steering winds, at 925 hPa, regressed on *MFC*. Colored region and vector arrows indicate statistically significant results at the 99% confidence level. Green circle represents the area covered by 500 km radius centered on hurricanes.

tween *MFC* and moisture and wind speeds in the lower atmosphere. *MFC* is well correlated with wind speeds within 500 km radius of tropical cyclones (**Fig. 11(a)**), suggesting that the intensity of tropical cyclone itself is linked to an increase in *MFC* and rainfall rate. There is no significant relationship between *MFC* and environmental moisture in the lower atmosphere (**Fig. 11(b)**), and convective available potential energy that positively correlates with storm intensification [23] (not shown) in the preset analysis. A moderate correlation between *MFC* and environmental low-level winds is observed on the southeastern side of tropical cyclones (**Fig. 11(c)**). Although these low-level winds can help enhance moisture flux into tropical cyclones, they may result from

Table 2. Rate of change (%) in factors contributing to total rainfall accumulation over Texas against the values averaged for 44 tropical cyclones.

Name	R_{TX}	ε	T_{TC}	RA_{TC}	RI_{TC}
TS#12 1981	−66	−40	−43	32	−6
Allison 1989	85	3	108	15	−6
Arlene 1993	−19	58	−31	28	−26
Dean 1995	175	147	21	27	−9
Allison 2001	85	22	93	9	−11
Fay 2002	154	153	63	3	−25
Rita 2005	−13	−51	−17	−8	190
Erin 2007	135	124	32	−21	25
Ike 2008	2	−33	−32	6	168
Hermine 2010	174	105	10	−2	56
Bill 2015	135	47	17	−4	78
Harvey 2017	515	96	123	−10	96

the cumulative circulation associated with the northward-moving tropical cyclones [11].

In summary, the most significant factor affecting rainfall totals over Texas is whether the tropical cyclone makes landfall on the central coast of Texas and travels inland. Another significant factor is the length of time a tropical cyclone resides near Texas. Rainfall intensity also contributes in part to rainfall totals over Texas, whereas contribution of rainfall area coverage is not significant.

5. Discussion

In this section, we compare the factors that caused the extraordinary rainfall of Harvey with those of past tropical cyclones that approached Texas. **Table 2** presents, for some tropical cyclones, the rate of change in factors contributing to the rainfall totals over Texas against the values averaged for the 44 tropical cyclones. A notable feature of Hurricane Harvey is its abundant rainfall, corresponding almost to a 500% increase in rainfall totals to the average. As mentioned earlier, the most significant factor contributing to the rainfall totals of tropical cyclones over Texas is whether a tropical cyclone makes landfall on the central coast of Texas and travels inland. Larger rainfall totals over Texas for Hurricanes Dean 1995, Fay 2002, Erin 2007, Hermine 2010, and Bill 2015 are associated with the relatively larger value of ε, exceeding a 100% increase, as the storms made landfall on the central coast and traveled inland across Texas (**Fig. 8**), whereas ε of Harvey was slightly below 100%.

Other factors contributing to the rainfall totals are how long a tropical cyclone resides near Texas and its rainfall intensity. Tropical cyclone with the longest residence time is Hurricane Harvey 2017, followed by Tropical Storms Allison in 1989 and 2001. Hurricanes Rita 2005, Ike 2008, and Harvey 2017 are the top three storms with the largest rainfall intensity among the 44 tropical cyclones. Although Tropical Storm Allison in 1989 and 2001 had stalled near the coast of Texas for several days comparable to Harvey, their rainfall intensity was much lower than that of Harvey. Both Tropical Storm Allison in 1989 and 2001 made landfall on the upper coast of Texas, whereas Harvey made landfall on the central coast of Texas (**Fig. 8**). The difference in track also led to smaller rainfall totals over Texas for Allison in 1989 and 2001 than Harvey 2017.

Though Hurricanes Rita 2005 and Ike 2008 had much larger rainfall rates than that of Harvey, they made landfall in East Texas (**Fig. 8**) in association with lesser stalling days around Texas. As a result, the rainfall totals over Texas associated with Rita and Ike were much less than those of Harvey. Thus, the present study demonstrates that the extreme rainfall totals over Texas induced by Hurricane Harvey can be attributed to the combined effect of extreme long-term stalling of Harvey near the central coast of Texas and the higher rainfall rate.

6. Summary

The cumulative rainfall totals over land and the associated potential flood damage induced by a tropical cyclone depend in large part on rainfall rate, translation speed, rainfall area coverage, and trajectory of a tropical cyclone. The present study examines the relationship between tropical cyclone rainfall totals over Texas and the track, residence time, rainfall intensity, and rainfall area coverage of past tropical cyclones that approached Texas.

The most significant factor affecting rainfall totals over Texas is whether a tropical cyclone makes landfall on the central coast of Texas and travels inland. Another significant factor is the length of time a tropical cyclone resides near Texas. Rainfall intensity also contributes in part to rainfall totals over Texas, whereas the contribution of rainfall area coverage is not significant. A tropical cyclone's track over Texas is controlled by the steering winds over Texas, while its residence time near Texas is related partly to the meandering of the subtropical jets. Rainfall rate depends on the intensity of tropical cyclones.

Furthermore, it is demonstrated that the extreme amount of rainfall totals over Texas induced by Harvey can be attributed to the combined effect of extreme long-term stalling of Harvey near the coast of Texas and the higher rainfall rate. The high pressure over the western US, along with the meandering path of the subtropical jet heading towards the south of Texas, partly caused Harvey to stall around the coast of Texas for several days.

Rainfall totals over land from tropical cyclones are also affected by other factors such as coastline and topography [24]. Non-uniform surface features such as coastal boundaries and mountains promote the upward vertical motion which increases the intensity of the tropical cyclone precipitation. As a tropical cyclone approaches land, surface friction gradient between land and sea induces a frictional convergence to the right side of the storm motion in the Northern Hemisphere. This in turn causes surface friction-induced low-level convergence and tropical cyclone rainfall on the right quadrant relative to the coastline [25–27]. This right-side favored feature of tropical cyclones' precipitation has been observed in tropical cyclones such as Allison 2001, Rita 2005, and Harvey 2017 (**Fig. 8**). However, the contribution of surface features to rainfall totals is not included in the analysis method of the present study. Further research is necessary to improve our understanding for providing useful information regarding the severity of hazards associated with tropical cyclones.

Acknowledgements

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Name:
Satoshi Iizuka

Affiliation:
Senior Research Scientist, Storm, Flood, and Landslide Research Division, National Research Institute for Earth Science and Disaster Resilience (NIED)

Address:
3-1 Tennodai, Tsukuba, Ibaraki 305-0006, Japan

Brief Career:
1997 Research Scientist, Frontier Research Center for Global Change (FRCGC)
1999 Research Scientist, NIED
2003 Senior Research Scientist, NIED

Selected Publications:
• S. Iizuka, T. Matsuura, and T. Yamagata, "The Indian Ocean SST dipole simulated in a coupled general circulation model," Geophysical Research Letters, Vol.27, Issue 20, pp. 3369-3372, 2000.
• S. Iizuka and T. Matsuura, "ENSO and western North Pacific tropical cyclone activity simulated in a CGCM," Climate Dynamics, Vol.30, Issue 7, pp. 815-830, doi: 10.1007/s00382-007-0326-x, 2008.
• S. Iizuka, "Simulations of wintertime precipitation in the vicinity of Japan: Sensitivity to fine-scale distributions of sea surface temperature," J. of Geophysical Research: Atmospheres, Vol.115, Issue D10, D10107, doi: 10.1029/2009JD012576, 2010.

Academic Societies & Scientific Organizations:
• Oceanographic Society of Japan (JOS)
• Meteorological Society of Japan (MSJ)
• American Geophysical Union (AGU)

Name:
Naoki Sakai

Affiliation:
Senior Researcher, Storm, Flood and Landslide Research Division, National Research Institute for Earth Science and Disaster Resilience (NIED)

Address:
3-1 Tennodai, Tsukuba, Ibaraki 305-0006, Japan

Brief Career:
2007 Researcher, NIED
2009 Senior Researcher, NIED
2019 Deputy Director-General, Center for Advanced Research Facility, NIED

Selected Publications:
• K. Sasahara and N. Sakai, "Shear and compression strain development in sandy model slope under repeated rainfall," Soils and Foundations, Vol.57, Issue 6, pp. 920-934, 2017.

Academic Societies & Scientific Organizations:
• American Society of Civil Engineers (ASCE)
• American Geophysical Union (AGU)
• Japanese Geotechnical Society (JGS)