

THE 2017 ATLANTIC HURRICANE SEASON:

Catastrophic Losses and Costs

by Eric S. Blake

The extremely active 2017 Atlantic hurricane season was one of the most destructive on record for the basin, with damage costs exceeding \$250 billion in the United States alone. For the first time on record, three Category 4 hurricanes made landfall in the United States (Harvey, Irma and Maria), and five Category 5 landfalls occurred across the Caribbean basin from Irma and

Maria. Several hundred people died either directly or indirectly from the effects of these hurricanes. Of the 17 tropical storms that formed during 2017, 10 became hurricanes, and six reached major hurricane strength (Category 3 or higher on the Saffir-Simpson Hurricane Wind Scale). In comparison, the 1981–2010 averages are 12 tropical storms, six hurricanes and three major hurricanes. The Accumulated Cyclone Energy



Aerial view of flooding caused by Hurricane Harvey in Columbus, Texas.

(ACE) index, a measure that takes into account both the strength and duration of the season's tropical storms and hurricanes, was about 241% of the long-term median value and the seventh highest in the Atlantic historical record, which extends back to 1851. September was also the busiest month on record, in terms of ACE, for any tropical cyclone basin worldwide since more reliable records began in the early 1970s. Figure 1

depicts the tracks of the tropical storms and hurricanes of the 2017 Atlantic hurricane season.

While this article will primarily focus on the catastrophic landfalls of Hurricanes Harvey, Irma, and Maria, other storms also had some notable impacts. Tropical Storm Cindy hit Louisiana in June and led to the drowning death of one person in Alabama. Two people died when Hurricane Katia made landfall in eastern Mexico

in September. Hurricane Nate made landfall in Louisiana and Mississippi in October, causing an estimated \$225 million of damage, and 43 people died in Central America from flooding during Nate. Dates are based on Coordinated Universal Time (UTC).

Hurricane Harvey

Harvey was generated from a tropical wave that moved off the coast of West Africa on August 12. Little development occurred for the next several days until the wave encountered a lower-shear, warmer-water environment while it approached the Windward Islands. A tropical depression formed early on August 17 about 500 miles east of Barbados, and it intensified into

a tropical storm 12 hours later. Harvey moved quickly westward to the south of a western Atlantic ridge, reaching an initial peak intensity of 45 mph early on August 18. The storm's center passed over Barbados at 1000 UTC that day and moved over Saint Vincent five hours later, although the effects were minimal. Increasing northerly wind shear caused Harvey to gradually weaken, first back to a depression early on August 19 and then into a tropical wave by late that day over the central Caribbean Sea.

The remnants of Harvey moved rapidly to the west and west-northwest for the next few days, eventually showing signs of organization on August 22 over the Yucatan Peninsula. An Air Force Reserve Hurricane Hunter aircraft

2017 Atlantic Tropical Storms and Hurricanes (preliminary)

Name	Class ^a	Dates ^b	Winds (mph)	Pressure (millibars)	Direct Deaths
Arlene	TS	April 19–21	50	990	
Bret	TS	June 19–20	45	1007	
Cindy	TS	June 20–23	60	991	1
Don	TS	July 17–18	50	1005	
Emily	TS	July 30–August 1	60	1002	
Franklin	H	August 6–10	85	981	
Gert	H	August 13–17	110	962	
Harvey	MH	August 17–September 1	130	937	68
Irma	MH	August 30–September 12	180	914	44
Jose	MH	September 5–22	155	938	
Katia	H	September 5–9	105	972	2
Lee	MH	September 15–30	115	962	
Maria	MH	September 16–30	175	908	112
Nate	H	October 4–9	90	981	45
Ophelia	MH	October 9–15	115	959	
Philippe	TS	October 28–29	40	1000	
Rina	TS	November 5–9	60	991	

^aTS = tropical storm, maximum sustained winds 39–73 mph; H = hurricane, maximum sustained winds 74–110 mph; MH = major hurricane, maximum winds 111 mph or greater.

^bDates begin at 0000 UTC and include tropical/subtropical depression stage, but exclude post-tropical stage.

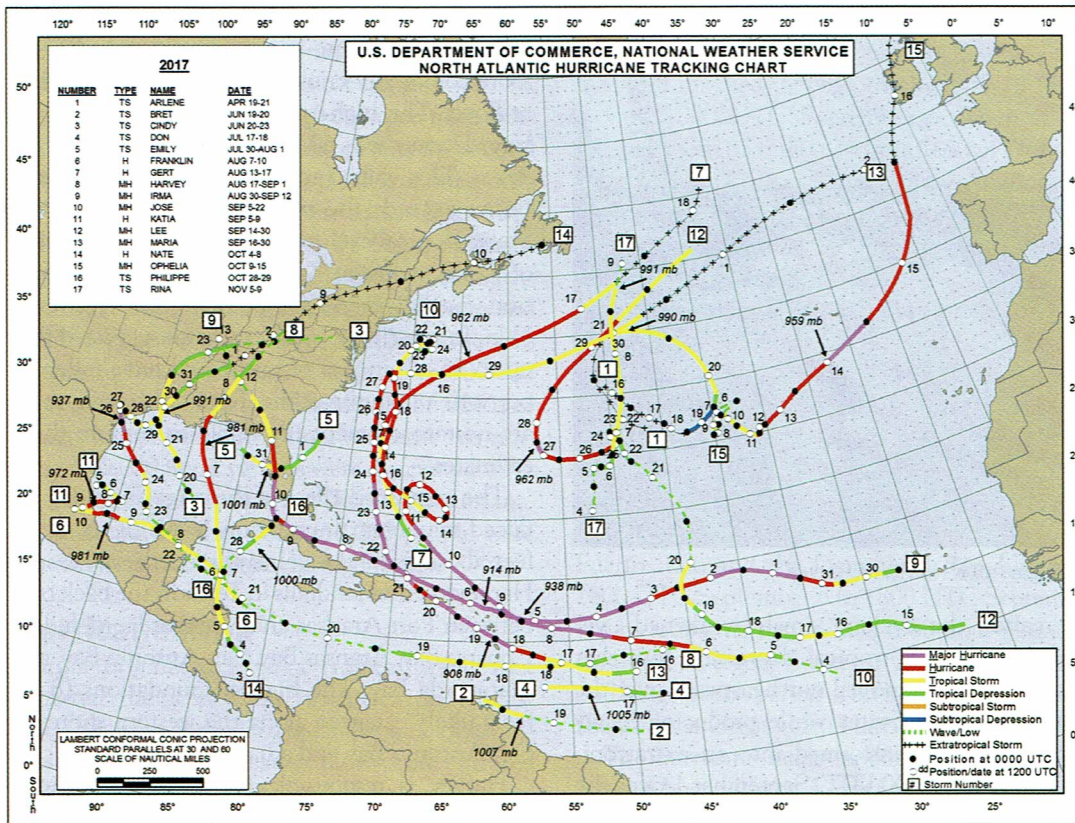


Figure 1. Tracks of the Atlantic tropical storms and hurricanes of 2017.

flying over the Bay of Campeche on August 23 found that the wave had regenerated into a tropical depression about 175 miles west of Progreso, Mexico, while the system turned northwestward. By late that day, Harvey began to rapidly intensify in an environment of light shear, very warm water and high mid-level moisture. The storm turned northward, steered around the western edge of the distant subtropical ridge, and its track gradually bent back toward the northwest during the next day or two. Harvey became a hurricane later on August 24, and by that night a well-defined eye appeared. The hurricane reached Category 3 status by midday on August 25 while it approached the middle Texas coast and intensified into a Category 4 hurricane that night. Harvey made landfall on the northern end of San Jose Island about 5 miles east of Rockport, Texas, at 0300 UTC August 26, with maximum sustained winds of 130 mph and a minimum central pressure of 937 mb. The hurricane then made a second landfall on the Texas mainland three hours later, slightly weakened due to land interaction, with 120 mph winds on the northeast coast of Copano Bay west of Holiday Beach. Harvey rapidly weakened to a tropical storm within 12 hours after landfall and maintained an intensity near 40 mph for the next day or so, aided by the sustaining effects of the southeastern portion of its circulation remaining over water.

The steady northwestward motion of the cyclone stopped as Harvey became embedded in light steering currents between one mid-tropospheric high over the Four Corners region and another high over the northern Gulf of Mexico. The storm made a slow loop late on August 26 into August 27, and it drifted eastward or southeastward for the next couple of days. Although the center passed well south of the Houston Metro and Golden Triangle (southeastern Texas between Beaumont, Port Arthur and Orange) areas, torrential rains fell in these locations as the storm's frontal system on the north and east side of Harvey.

The storm center moved back offshore early on August 28 over Matagorda Bay, its winds slightly re-strengthening with deep convection reforming near and north of the center. However, the vertical wind shear was too strong for much intensification, and Harvey reached a final peak intensity of 50 mph late on August 29. By that time, the storm turned to the north-northeast due to a strengthening ridge over the western Atlantic, its center never having moved more than 70 miles offshore of the Texas coast. Extremely heavy rains, however, continued on the north and northwest side of the tropical cyclone, most concentrated near the Beaumont-Port Arthur area. Harvey made its final landfall in southwestern Louisiana at 0800 UTC August 30 near Cameron with 45-mph sustained winds.



Flooded streets in Houston in late August after Hurricane Harvey.

Thereafter, the cyclone slowly weakened over land, becoming a tropical depression late that day. Harvey then moved northeastward over the southern United States while producing heavy rainfall, and it transformed into an extratropical cyclone by 0600 UTC September 1 over the Tennessee Valley. The cyclone dissipated over northern Kentucky late the next day.

Harvey was the most significant tropical cyclone rainfall event in United States history, both in scope and peak rainfall amounts, since reliable rainfall records began around the 1880s. Many areas of southeastern Texas experienced

a flood with less than a one-in-1,000 (0.1%) chance of occurring in any given year, which is more commonly known as a 1,000-year or greater flood. The highest storm-total rainfall report from Harvey was 60.58 inches near Nederland, Texas. This value (and those from six other stations) exceeds the previously accepted United States tropical cyclone storm total rainfall record of 52.00 inches at Kanaloahuluhulu Ranger Station, Hawaii, in August of 1950 from Hurricane Hiki. Interestingly, radar estimates suggested that up to 65–70 inches of rain could have fallen in portions of southeastern Texas, although there are no measurements available to confirm those estimates.

The combined effect of the surge and tide produced maximum inundation levels of six to 10 feet above ground level to the north and east of Harvey's center landfalls in Texas in the back bays between Port Aransas and Matagorda, including Copano Bay, Aransas Bay, San Antonio Bay, and Matagorda Bay. The highest inundations (8–10 feet) likely occurred along the western shores of San Antonio Bay and adjacent Hynes Bay.

Harvey is responsible for at least 68 direct deaths, all in Texas. Over half of the deaths (36) were in Harris County in the Houston Metro area. All but three of the deaths were from freshwater flooding, and none of the deaths can be linked to the storm surge, which is quite remarkable for a Category 4 hurricane landfall. Still, Harvey is the deadliest hurricane to hit Texas since 1919. About



A looter searches through the remains of a fishing boat on September 1 in Rockport, Texas. The man made off with a propane tank and a stove.

35 additional deaths are ascribed to indirect causes, such as electrocution, motor-vehicle crashes, and isolation from necessary medical services.

The latest NOAA damage estimate from Harvey is \$125 billion, which places it as the second costliest United States tropical cyclone, only behind Katrina (2005) when adjusted to 2017 dollars. The damage caused by Harvey's flooding was catastrophic over a large part of southeastern Texas, including the Houston Metro and Golden Triangle areas. Over 300,000 structures in that region were flooded, with up to 500,000 cars reported flooded as well. About 336,000 customers lost power during the hurricane. An estimated 40,000 flood victims were evacuated to or took refuge in shelters across Texas or Louisiana. FEMA reported that about 30,000 people were rescued from floodwaters during Harvey.

Hurricane Irma

Irma originated from a tropical wave that departed the west coast of Africa on August 27. The wave produced a large area of thunderstorms, which became more concentrated near the northern portion of the wave axis on August 28 and 29. The next day, satellite images indicated that a well-defined surface circulation had developed, and the system became a tropical depression when it was centered about 140 miles west-southwest of São Vicente in the Cabo Verde Islands.

While moving westward to the south of a mid-level ridge over the eastern Atlantic, Irma strengthened rapidly. The small storm developed a ragged eye around the time it became a hurricane near 0600 UTC August 31, which was only 30 hours after it became a tropical depression. Irma reached hurricane strength when it was still located over the eastern Atlantic about 460 miles west of the Cabo Verde Islands, and it reached major hurricane status by 0000 UTC September 1, only two days after genesis. This 80-mph increase in intensity over a 48-hour period was a remarkable rate only achieved by a small fraction of tropical cyclones.

Irma fluctuated between Category 2 and 3 strength for the next few days in response to eyewall cycles and dry air intrusions. Meanwhile, the hurricane turned west-southwestward in response to a strong high pressure system to its north, which was very significant because the motion brought the hurricane over higher sea surface temperatures and in a position poised to affect the northern Leeward Islands.

By early on September 4, Irma was on a strengthening trend once again, and it was headed toward the northern Leeward Islands.

While Irma turned west-northwestward, it went through another round of rapid intensification and reached its peak intensity of 180 mph around 1800 UTC September 5, when it was located about 85 miles east-southeast of Barbuda. As a Category 5 hurricane, Irma made landfall on Barbuda around 0545 UTC September 6 with estimated maximum winds of 180 mph and a minimum pressure of 914 mb.

After crossing Barbuda, Irma made landfalls that day on Saint Martin at 1115 UTC and on Virgin Gorda at 1630 UTC, both still as a 180-mph Category 5 hurricane. Later that day, as Irma moved away from the Virgin Islands, the hurricane weakened slightly due to the formation of concentric eyewalls. The eye of Irma passed about 60 miles to the north of the northern shore of Puerto Rico and the Dominican Republic from 1800 UTC September 6 to 1800 UTC September 7. Overall, Irma maintained a 60-hour period of sustained Category 5 intensity, which is the second longest such period of all hurricanes on record (behind the Great Cuba Hurricane of 1932).

The hurricane made landfall as a strong Category 4 hurricane on Little Inagua Island in the Bahamas at 0500 UTC September 8. Irma then turned slightly to the left and re-intensified, making its fifth landfall near Cayo Romano, Cuba, at 0300 UTC September 9 with maximum winds estimated to be 170 mph. This marked the first Category 5 hurricane landfall in Cuba since 1932. Irma tracked along the Cuban Keys throughout that day, and its interaction with land caused it to weaken significantly, down to a Category 2 hurricane by 1800 UTC that day when the eye was very near Isabela de Sagua. Shortly after that time, Irma slowed and began to make a turn to



Residential property severely damaged by Hurricane Irma in Key West, Florida, on Monday, September 18, 2017.

FEMA/JT. BLATTY



Damage at a pier in St. Mary's, Georgia, from Hurricane Irma, on September 23.

the northwest, which caused the core of the hurricane to move over the Florida Straits early on September 10.

When Irma moved over the warm waters of the Florida Straits, the hurricane intensified once again. Data from the Air Force Hurricane Hunters indicate that Irma became a Category 4 hurricane by 0600 UTC September 10 when it was about 65 miles south-southeast of Key West, Florida. Meanwhile, Irma turned to the north-northwest in the flow between a subtropical ridge over the western Atlantic and a mid- to upper-level low pressure system over the Gulf of Mexico. The hurricane made landfall on Cudjoe Key in the lower Florida Keys around 1300 UTC that day with maximum winds of 130 mph and a minimum pressure of 931 mb, and it made a final landfall near Marco Island, Florida, at 1930 UTC September 10 with estimated maximum winds of 115 mph (Category 3 strength). Irma weakened quickly as it moved up the spine of the Florida peninsula due to the influences of land and strong wind shear. Although Irma was weaker while over Florida, the wind field of the hurricane spread out significantly, with tropical-storm-force winds extending out up to 400 miles from the center.

Irma weakened to a tropical storm early on September 11 when it was centered about 20 miles west of Gainesville, Florida. The center of Irma moved over southern Georgia just west of Valdosta around 1800 UTC that day with maximum winds

of 50 mph, and the system became a remnant low once it crossed into Alabama early on September 12. The remnant low continued northwestward while weakening and dissipated on the morning of September 13 over southeastern Missouri.

Some notable observations from Irma include a weather station on Saint Barthelemy reporting a minimum pressure of 915.9 mb, and a station on Barbuda that reported a minimum pressure of 916.1 mb. Also, an unofficial observation in Saint Barthelemy reported a maximum wind gust of 199 mph. In Florida, a weather spotter in Marco Island reported a minimum pressure of 936.9 mb, with maximum sustained winds of 112 mph and a gust of 129 mph. In addition, the Marco Island Police Department reported a wind gust of 130 mph, and the Naples Pier reported a 142-mph wind gust.

Irma caused 44 direct deaths as a result of its strong winds, heavy rains, and high surf across the Caribbean Islands and the southeastern United States. The majority of the casualties were in the Caribbean Islands, where Irma's winds were the strongest. Eleven direct deaths were reported in Saint Martin and Saint Barthelemy combined, nine in Cuba, four in Sint Maarten, four in the British Virgin Islands, three in the U.S. Virgin Islands, three in Barbuda, one in Barbados, one in Haiti, and one in Anguilla.

In the mainland United States, seven direct deaths were reported, and an additional 85 indirect deaths occurred, 80 of which were in Flori-

da. Hundreds more were injured before, during, or after the hurricane. About 6 million residents in Florida were evacuated from coastal areas. NOAA estimates Irma caused about \$50 billion of damage in the United States. This makes Irma the fifth-costliest hurricane to affect the United States, behind Katrina (2005), Harvey (2017), Maria (2017), and Sandy (2012).

Barbuda and Saint Martin/Sint Maarten took direct hits from Irma at its peak intensity. Irma's catastrophic winds caused destruction across Barbuda, damaging or destroying about 95% of the structures, including the local airport. That island had no water or communications after the storm, and it was considered nearly uninhabitable. The damage was so significant that the entire population (~2,000 people) was evacuated to nearby Antigua after the hurricane, leaving the island abandoned for the first time in 300 years. Preliminary estimates of property damage on Barbuda are between \$150 million and \$300 million. On Saint Martin/Sint Maarten, about two-thirds of structures on the island were severely damaged, and total damage is estimated to be around \$1.5 billion.

The northern eyewall of Irma passed over Anguilla and caused widespread damage. Most homes and schools were destroyed, and the only hospital on the island was severely damaged. About 90% of the roads were impassable, and total damage from the hurricane is estimated to

be at least \$190 million. Damage was also severe in Saint Barthelemy, which was in the southern eyewall, with the French government indicating that damage could exceed \$480 million.

Damage in the U.S. Virgin Islands was most severe in Saint Thomas and Saint John. In both islands, widespread catastrophic damage was reported, and the islands were stripped of most of their foliage. Irma's direct hit on the British Virgin Islands caused extensive damage there. Numerous buildings and roads were destroyed in Tortola. On the island of Culebra (Puerto Rico), there was also a near-total power and water loss. Many homes on the island were destroyed or suffered major damage, and widespread uprooted trees were reported.

Irma's northern eyewall passed near or over the Turks and Caicos Islands, causing significant damage to the islands' structures and communication infrastructure, especially in Providenciales. The damage was estimated to be at least \$500 million in the Turks and Caicos. In the southeastern Bahamas, Irma damaged about 70% of the homes on Great Inagua Island, and widespread damage also occurred on Crooked Island.

In Cuba, more than 150,000 homes were damaged with nearly 15,000 completely destroyed by Irma. The tourist areas of Cayo Coco, Cayo Guillermo, Cayo Santa Maria, and the town of Caibarien experienced the worst effects, with widespread damage in those areas. Severe dam-



FEMA/ANDREA BOOHER

Damage on the main road through Humacao, Puerto Rico, on November 1. The area was hit with up to six feet of tidal surge from Hurricane Maria.

age also occurred in the provinces of Ciego de Ávila and Villa Clara. Uninsured losses from damage caused by Irma in Cuba are estimated to be near \$200 million, which is the highest value there during the past 55 years.

In Florida, maximum inundation levels of five–eight feet above ground level were noted for portions of the lower Florida Keys from Cudjoe Key eastward to Bahia Honda Key, near and to the east of where Irma's center made landfall. In Miami-Dade County, maximum inundation levels of four–six feet were observed, especially along Biscayne Bay. Significant flooding occurred in downtown Miami, and the flooding there was likely caused by a combination of heavy rainfall and urban runoff, wave overwash becoming trapped behind seawalls, and seawater coming up from below through the city's drainage systems. Farther north, Jacksonville experienced one of the worst floods in the city's 225-year history.

Interestingly, offshore winds on the northern side of Irma's circulation initially caused water levels to recede below normal levels along much of the west coast of Florida, including Tampa Bay. In fact, some normally submerged areas went virtually dry, allowing people to (inadvisably) walk out onto the sea or bay floor, while also stranding marine vessels and even manatees.

Hurricane Maria

Maria came from a well-defined tropical wave that departed the west coast of Africa on September 12. The wave moved westward over the tropical Atlantic for the next several days, and it began to show some banding features on Septem-

ber 15. Early the next day the system became better organized, and a tropical depression formed about 625 miles east of Barbados.

Moving westward to west-northwestward to the south of a mid-level high pressure area, Maria quickly intensified into a hurricane just 24 hours after it became a tropical storm. While situated in an environment of warm sea surface temperatures and light vertical shear, the hurricane strengthened extremely rapidly. Maria became a 115-mph major hurricane by midday on September 18, and just 12 hours later, as it neared Dominica, it became a Category 5 hurricane with maximum winds of 165 mph. The hurricane made landfall on the island with that intensity and an estimated minimum central pressure of 922 mb around 0115 UTC September 19. Maria is the strongest hurricane on record to make landfall on Dominica (or strike within 70 miles of that island).

After pounding Dominica, Maria entered the northeastern Caribbean Sea. Slight weakening had occurred due to the mountains of Dominica, but the hurricane soon regained intensity and strengthened to its peak intensity of 175 mph around 0300 UTC September 20 while centered about 30 miles south of Saint Croix. At that time, Maria had a minimum pressure of 908 mb, the lowest on record for the Atlantic basin east of 70°W. Maria moved west-northwestward to northwestward toward Puerto Rico and weakened somewhat due to an eyewall replacement, but the hurricane also grew in size. Maria's center crossed the southeast coast of Puerto Rico near Yabucoa around 1015 UTC September 20, and its maximum winds at that time were near 155 mph (Category 4), which makes it the strongest hurricane to hit that island since 1928. It should be noted however that in Puerto Rico, winds of Category 5 intensity (greater than 156 mph) were almost certainly felt at some elevated locations on the island. The hurricane's center moved across the island, roughly diagonally from southeast to northwest, for several hours and emerged into the Atlantic late on September 20 as a Category 2 cyclone with 110-mph winds.

Over the next couple of days, the hurricane moved northwestward along the southwestern periphery of a mid-level high over the western Atlantic while gradually re-strengthening. Although Maria never regained its former intensity, its maximum winds increased to near 125 mph early on September 22 while the hurricane was centered about 75 miles southeast of Grand Turk Island. Maria turned toward the north-northwest, and its center passed 35–45 miles east



Pile-up at San Juan's Isla Grande Airport on October 17, a result of Hurricane Maria's winds.

FEAMA/ANDREA BOOHER

of the Turks and Caicos Islands later that day. The system maintained major hurricane status until early on September 24 while turning toward the north. Maria continued to gradually weaken due to shear, and it lost its eyewall structure by September 25 while continuing northward at a slow forward speed well offshore of the southeastern coast of the United States. The cyclone then weakened to Category 1 status and by early on September 27 the center of the 75-mph hurricane passed about 150 miles east of Cape Hatteras, North Carolina. On September 28, Maria turned sharply toward the east and began to accelerate as it weakened to a tropical storm. Moving rapidly eastward to east-northeastward, the system became an extratropical cyclone late on September 30 while centered about 530 miles southeast of Cape Race, Newfoundland. The cyclone moved east-northeastward until dissipation over the north Atlantic about 460 miles southwest of Ireland late on October 2.

Maria caused catastrophic damage in Dominica, with the majority of structures seriously damaged or destroyed, and the once-lush tropical island was effectively reduced to an immense field of debris. According to media reports, the estimated damage total in Dominica is at least \$1.31 billion. The roofs of most of the buildings and homes were either damaged or blown off. Power, phone, and Internet service was cut off, leaving the country almost incommunicado with the outside world.

Puerto Rico was devastated by winds and floods. The NOAA estimate of damage in Puerto Rico and the United States Virgin Islands due to Maria is \$65–\$90 billion, which makes it the third costliest hurricane in United States history, behind Katrina (2005) and Harvey (2017). Maria is by far the most destructive hurricane to hit Puerto Rico in modern times, as the previous costliest hurricane on record for the island was Georges (1998), which in 2017 dollars “only” caused about \$5 billion of damage. Many buildings suffered significant damage or were destroyed. Numerous trees were downed, splintered, and/or defoliated. River flooding was unprecedented in some areas, especially in the northern portion of the island. The La Plata River flooded the entire alluvial valley, including the municipality of Toa Baja, where hundreds of families needed to be rescued from their roof tops. Maria knocked down 80% of Puerto Rico’s utility poles and all transmission lines, resulting in an extended loss of power to essentially all of the island’s 3.4 million residents. Practically

all cell phone service was lost, and municipal water supplies were knocked out. Among all the U.S. Virgin Islands, Saint Croix was the most severely affected by Maria. Wind damage was evident across the entire island, with many fallen trees, downed signs, roof damage, and complete destruction of many wooden houses.

Maria caused 31 direct deaths in Dominica, two in Guadeloupe, two in Saint Thomas, five in the Dominican Republic, three in Haiti, and four in the mainland United States. In Puerto Rico, the death toll is highly uncertain, and the official number stands at 65, which includes an unknown number of indirect deaths. It should be noted that hundreds of additional indirect deaths in Puerto Rico might eventually be attributed to Maria’s aftermath pending the results of an official government review.

In addition to its furious winds, the hurricane produced torrential amounts of rain. Dominica recorded a maximum total of 22.8 inches. Even heavier rainfall occurred in Puerto Rico, where one location south of Caguas had a storm total of nearly 38 inches. River discharges at many locations in the island were at record or near-record levels. Heavy rains, with totals of at least 10–13 inches, also occurred in Guadeloupe and portions of the Dominican Republic, and these rains also likely led to significant flooding and mud slides.

The combined effect of the surge and tide produced maximum inundation levels of six–nine feet above ground level to the north of Maria’s landfall along the coasts of Humacao, Naguabo, and Ceiba municipalities in Puerto Rico. Maximum inundation levels of three–five feet occurred along the coast of northeastern Puerto Rico, especially in the municipalities of Ceiba and Fajardo, and along much of the southern coast from Ponce eastward. The combined destructive power of storm surge and wave action from Maria produced extensive damage to coastal homes and marinas along the east and southeast coast of Puerto Rico, as well as the south coasts of Vieques and Saint Croix.

*The cyclone summaries are based on Tropical Cyclone Reports prepared by the author and Lixion Avila, Robbie Berg, Jack Beven, Michael Brennan, Daniel Brown, John Cangialosi, Chris Landsea, Richard Pasch, Stacy Stewart, and David Zelinsky. These reports are available at <http://www.nhc.noaa.gov/data/tcr/index.php?season=2017&basin=atl>. **W***

ERIC S. BLAKE is a hurricane specialist at NOAA’s National Hurricane Center in Miami, Florida.