Hurricane Matthew
Event Recap Report

April 2017

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Executive Summary

Hurricane Matthew was the most intense October hurricane in the Atlantic on record and made three official landfalls across the Caribbean and in the United States. The storm led to the deaths of at least 604 people in the Atlantic Basin, including 53 in the United States. The official death toll in Haiti was reported at 546 but unofficial tallies suggested it may be as high as 1,332.

The system made two initial landfalls in the Caribbean – October 4 in Haiti as a 150 mph (240 kph) Category 4 major hurricane and October 5 in eastern Cuba as a 130 mph (215 kph) minimal Category 4 major hurricane. While tracking through the Bahamas, on October 6-7, the center of Matthew began to erratically wobble to the east and northeast due to a prolonged eyewall replacement cycle which would ultimately spare South Florida from receiving the brunt of Matthew. Matthew made a third landfall on October 6 on Grand Bahama Island as a minimal Category 4 major hurricane (130 mph (215 kph)).

Matthew tracked along the east coast of Florida bringing hurricane-force wind gusts and coastal storm surge to several locales before moving towards the Georgia and South Carolina coastlines. Despite the overall weakening trend of Matthew, the storm's rain shield began to significantly expand due to interaction with a frontal boundary. Matthew made its lone US landfall on October 8 in South Carolina as an 85 mph (140 kph) Category 1 hurricane. Exceptional rainfall totals were accumulated across the Carolinas and Georgia. It would be nearly two weeks until all rivers fully crested in North Carolina.

The remnants of Matthew continued to bring heavy rainfall and near-hurricane force winds to portions of the US Northeast and Atlantic Canada on October 9-11 before the remnant system moved into the open waters of the North Atlantic on October 11.

The United States endured the largest damage footprint from Matthew. As it grazed the coastlines of Florida, Georgia, South Carolina, North Carolina, and Virginia the cyclone brought notable coastal storm surge and hurricane-force wind gusts that left considerable damage to property and infrastructure. The most significant impacts occurred in North Carolina as prolific rainfall caused historic flooding. Many rivers surpassed record levels established by Hurricane Floyd in 1999.

Widespread damage was also cited across the Caribbean and in Canada. Parts of Haiti were left crippled by damage after Category 4 winds and a 9.8-foot (3.0-meter) storm surge inundated the southern Tiburon Peninsula. At least 200,000 homes were destroyed in Haiti and 13 percent of the population (1.4 million people) were in immediate need of assistance. Substantial damage was also registered to property and infrastructure in eastern Cuba and the Bahamas as Matthew tracked through at Category 4 intensity. In Atlantic Canada, remnant rainfall from the storm led to extensive flooding in four provincial regions.

Total overall economic losses caused by Hurricane Matthew are estimated to be as high as USD15 billion. Insured losses are estimated around USD4.5 billion. The vast majority of these losses were incurred in the United States where economic losses exceeded USD10 billion. The private insurance industry and the National Flood Insurance Program (NFIP) paid out nearly USD4.0 billion in claims.

Haiti (USD2.8 billion), the Bahamas (USD600 million to 1.0 billion), Canada (USD150 million), and Cuba (at least USD100 million) also sustained heavy economic damage from the cyclone. At a minimum of USD400 million, Matthew became the costliest event ever recorded for the Bahamian insurance industry.

An estimated 30 percent of Matthew's overall economic cost was expected to be covered by insurance.

Matthew becomes the tenth-costliest hurricane ever recorded in the Atlantic Basin.

Meteorological Recap

On September 23, the National Hurricane Center (NHC) noted that a tropical wave had tracked off the west coast of Africa and began moving across the Atlantic Ocean. For the next several days, the area of low pressure slowly became better organized as the clusters of thunderstorms formed a closed low-level circulation center. With ample sea surface temperature warmth and somewhat favorable atmospheric conditions, the storm continued to organize and sufficiently obtained warm core tropical characteristics. The NHC officially began initiating advisories on Tropical Storm Matthew at 11:00 AM EST (15:00 UTC) on September 28 while located just 35 miles (55 kilometers) to the southeast of St. Lucia. The first advisory noted the system had 60 mph (95 kph) sustained winds as it moved into the eastern Caribbean.

The storm continued moving due west under the steering influence of a strong ridge of high pressure located to its north. Just one day after being declared a tropical storm, on September 29, data from a NOAA Hurricane Hunter reconnaissance aircraft determined that Matthew had sufficiently strengthened to Category 1 intensity with 75 mph (120 kph) winds. At the time, the NHC and all of the reliable forecast intensity computer models were projecting only minimal intensification given an increase in non-conducive atmospheric conditions – such as vertical wind shear. However, despite the presence of the noted wind shear, Matthew began an explosive intensification cycle on September 30 and October 1 that saw the storm double its maximum wind speed from 80 mph (130 kph) to 165 mph (270 kph) in a period of just 24 hours. The end of this burst of intensification saw Matthew reach its maximum intensity on October 1 at 00:00 UTC. The minimum central pressure dropped by 45 millibars down to 941 millibars during this time. Matthew became a Category 5 hurricane at 13.4 degrees north latitude, surpassing Hurricane Ivan (2004) as the southernmost hurricane at this intensity on record in the Atlantic Ocean.

Matthew's best track positions and intensity (Source: NHC)
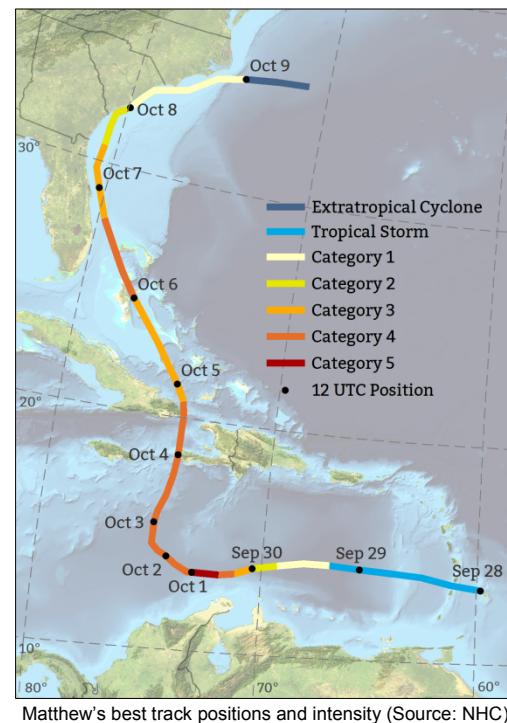
Despite most of the forecast model guidance performing quite poorly on the intensity of Matthew in the Caribbean Sea, the track model guidance was excellent during this portion of the path. All of the historically best-performing models (ECMWF and GFS) indicated a breakdown of steering currents that would bring the storm to a near stationary motion before re-gaining forward speed and taking a northward track towards Hispaniola, Cuba and the Bahamas. This northward motion was projected to begin on October 1. During this time, local governments throughout the Caribbean issued a series of hurricane and tropical storm watches and warnings to alert residents to the severity of the storm.

As the day progressed on October 1, the storm began a slight weakening trend and the steering currents started to change. The storm briefly became stationary before a building ridge of high pressure to Matthew's east started to slowly push the cyclone northward. At 00:00 UTC on October 4 Matthew reached its lowest minimum central pressure of 934 millibars which it maintained for 12 hours. Just after 7:00 AM local time (11:00 UTC) on October 4, Matthew made its first official landfall near Les Anglais, Haiti with maximum sustained winds of 150 mph (240 kph). This was the first Category 4 to make landfall in Haiti since Hurricane Cleo (1964).

The storm's inner core continued to meander northward for roughly 12 hours prior to making its second official landfall around 8:00 PM local time on October 4 (00:00 UTC October 5). The landfall location was near the town of Juaco, on the eastern tip of Cuba, at Category 4 strength with 130 mph (215 kph) winds.


Matthew just after Haiti landfall (Source: NASA)

Steering currents continued to become more complex as the forecast track models began to indicate that the ridge of high pressure in the Atlantic Ocean would be stronger than initially projected. This suggested that the storm would take a more northwesterly track through the Bahamas and take Matthew very close to the east coast of Florida. The storm would briefly weaken to a Category 3 storm (120 mph (195 kph) winds) early on October 5 as the cyclone's inner core was disrupted by the mountainous terrain of Cuba. However, the weakening was short-lived as Matthew began to reconsolidate its core while entering the Bahamas on October 5.

By late on October 5 into October 6, Matthew began to show signs of additional intensification as the minimum central pressure began to rapidly fall while tracking through the southern and central Bahamas. With very warm sea surface temperatures and easing wind shear, the inner core of Matthew was able to quickly re-organize once it stopped interacting with Cuba's mountainous terrain. The storm's pressure dropped by 26 millibars in 24 hours as winds strengthened back to Category 4 intensity at 140 mph (220 kph). The inner core of the cyclone tracked just south of Nassau, Bahamas and lashed the island with wind gusts well in excess of minimal hurricane strength. Several Bahamian islands endured wind and rain embedded within the storm's outer eyewall.

During the overnight hours of October 6 and early on October 7, the center of Matthew began to erratically wobble to the east and northeast while shifting through the Bahamas. This wobble was primarily due to Matthew undergoing a prolonged eyewall replacement cycle that saw the storm have two separate eyewalls (a smaller eye feature surrounded by a much larger secondary eye). These wobbles would ultimately spare South Florida from receiving the brunt of Matthew.
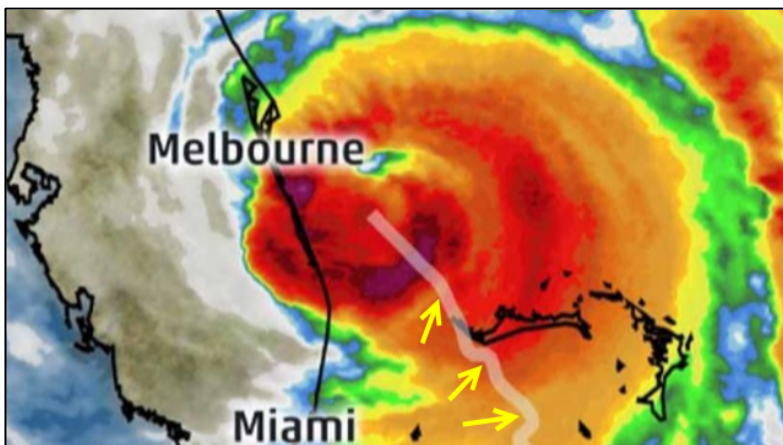
Storm track of Matthew showing brief wobbles on October 6/7 (Source: The Weather Channel)

The graphic above shows the wobbles in Matthew's track. However, the one of the wobbles took Matthew on a track that led to its third official landfall, near West End on Grand Bahama Island, around 8:00 PM local time on October 6 (00:00 UTC October 7). Landfall intensity was 130 mph (215 kph); Category 4.

As October 7 progressed, Matthew started to track much closer to the east coast of Florida. Intense rainbands with high winds, torrential rains and coastal storm surge impacted areas of the state from the city of Melbourne northward to Fernandina Beach. Wind gusts in excess of 100 mph (160 kph) were recorded at elevated towers in Cape Canaveral, Daytona Beach and other coastal spots in Florida.

Matthew continued to track up the east coast of Florida on October 7 into early October 8 prompting hurricane-force wind gusts and tremendous coastal storm surge in St. Augustine and Jacksonville, Florida, before moving due north towards the Georgia and South Carolina coastlines. The upper level steering currents began to change as the ridge of high pressure in the Atlantic Ocean continued to build and a developing frontal boundary started to track across the central and eastern United States. Despite the overall wind speed of Matthew gradually declining as it shifted northward, the coastal surge remained a dangerous threat and the storm's rain shield began to significantly expand as the cyclone started to interact with the noted frontal boundary.

Radar imagery on October 8, 12 UTC (Source: NOAA)

The storm officially made its lone US landfall at approximately 10:45 AM local time (14:45 UTC) on October 8 near McClellanville, South Carolina at the Cape Romain National Wildlife Refuge with maximum sustained winds of 85 mph (140 kph). This made Matthew a Category 1 storm at landfall. During this time, exceptional rainfall totals were accumulated across the Carolinas and Georgia as a stationary surface frontal boundary interacted with the extreme amount of moisture associated with Matthew to spawn intense hourly rainfall rates. This led to the National Weather Service (NWS) issuing numerous Flash Flood Emergency declarations in several counties. It would be nearly two weeks (mid-October) until all rivers fully crested in North Carolina.

By the end of October 8 into October 9, Matthew began a rapid transition to an extratropical cyclone as the storm became more embedded within the larger frontal boundary and started to interact with the mid-latitude westerlies. *As a reminder, the NHC defines an extratropical cyclone as a cyclone of any intensity for which the primary energy source is baroclinic; or a system that results from the temperature contrast between warm and cold air masses.*

The storm maintained 75 mph (120 kph) winds as satellite imagery clearly showed the storm taking on frontal characteristics. Storm surge remained a problem for the outer banks of North Carolina: both sides of the islands were affected as the winds shifted directions due to Matthew's eastward track. Additional heavy rains with moisture associated with Matthew were recorded as far north as Massachusetts before the entire system finally was absorbed and became frontal.

The last NHC advisory was sent at 5:00 PM local time (21:00 UTC) on October 9. The storm intensity remained 75 mph (120 kph). This meant that Matthew throughout its entire life cycle was only weaker than 75 mph (120 kph) for just the first 24 hours after NHC initiation.

Despite the storm losing its tropical characteristics and the NHC ceasing to issue advisories, the remnants of Matthew continued to bring heavy rainfall to portions of the US Northeast on October 9 before shifting into Atlantic Canada. Environment Canada recorded heavy rains and near hurricane-force winds through October 10-11 in the provincial regions of Nova Scotia, New Brunswick, Prince Edward Island, and Newfoundland and Labrador. The remnants of Matthew would finally move away from Canada and into the open waters of the North Atlantic Ocean on October 11.

Storm Records*

- Category 4/5 intensity for at least 114 consecutive hours; longest during October in the Atlantic on record
- 186 consecutive hours (7.75 days) at Category 3+ intensity; fifth place for Atlantic Ocean major hurricane activity since 1966 (start of satellite era)
- Third-strongest rapid intensification (80 mph) in a 24-hour period in the Atlantic on record; trailed only Wilma (2005) and Felix (2007)
- Thirty-first Category 5 hurricane in the Atlantic on record; first since 2007 (Felix)
- Lowest latitude Category 5 hurricane in the Atlantic on record
- Longest-lived Category 4/5 hurricane in the eastern Caribbean Sea on record
- Generated the most ACE for any hurricane in the Eastern Caribbean on record
- First Category 4 hurricane to make landfall in Haiti since 1964 (Cleo)
- First Category 4 hurricane to make landfall in Cuba since 2008 (Ike)
- First time on record for a major hurricane to strike Haiti, Cuba and the Bahamas
- First hurricane to make landfall in South Carolina since 2004 (Gaston)
- Only the second major hurricane since 1900 to track within 100 miles of Jacksonville, Florida (Dora, 1964)
- First hurricane to make landfall north of the US state of Georgia in October since 1954 (Hazel)

Thanks to Phil Klotzbach, Colorado State University

The <u>A</u>ccumulated <u>C</u>yclone <u>E</u>nergy (ACE) Index is equal to the sum of the squares of the 6-hourly maximum sustained wind speeds (in knots) for all systems while they are at least tropical storm strength.

Storm Data

Wind & Central Pressure

Below is a graph highlighting Matthew's life cycle in terms of pressure and wind speed from genesis until dissipation.
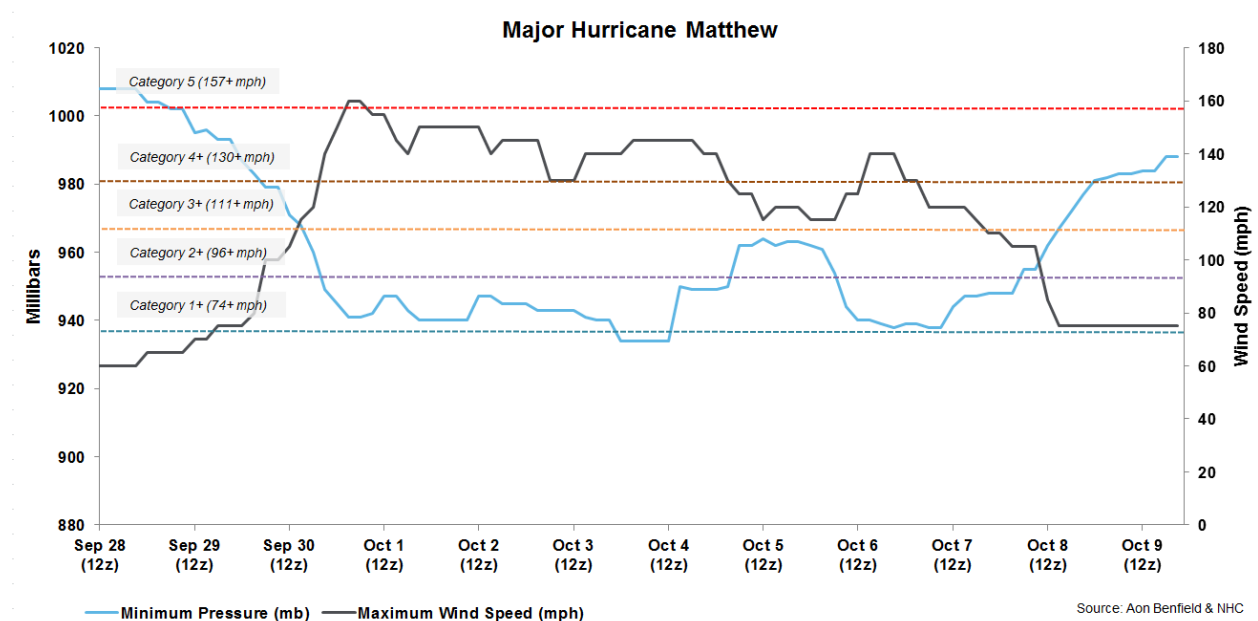
US Surface Wind Gusts

Location	Wind Gust (mph)	Location	Wind Gust (mph)
Winyah Bay, SC	104	Embry Riddle, FL	84
Jennette's Pier, NC	97	Ocracoke, NC	84
Tybee Island, GA	96	Fripp (nearshore buoy 41003), SC	84
New Smyrna Beach, FL	94	Ponce Inlet, FL	83
Patrick Air Force Base, FL	88	Beaufort, SC	83
Hilton Head Airport, SC	87	Edgewater, FL	82
Murrells Inlet, NC	87	Federal Point, NC	82
Pamlico Sound, NC	87	Wanchese, NC	82
St James Plantation, NC	86	Fort Pulaski, GA	78
Duck Research Pier, NC	85	Cocoa Beach, FL	77

Source: NOAA

Caribbean & Bahamas Surface Wind Gusts

| Location	Wind Gust (mph)	Location	Wind Gust (mph)
Jamal, Cuba	174	Freeport, Bahamas	121
Baracoa, Cuba	155	Les Cayes, Haiti	107
Punta de Maisí Airport, Cuba	152	Settlement Point, Bahamas	105
Exuma Int'l Airport, Bahamas	144	Coco Cay, Bahamas	101
Moss Town, Bahamas	131	Fond-Denis-Cadet, Martinique	100
Nassau Airport, Bahamas	128	Lynden Pindling, Bahamas	97

Source: NOAA

Rainfall

US Rainfall

Location	Rainfall (in.)	Location	Rainfall (in.)
Evergreen, NC	18.95	Kinston, NC	16.50
Elizabethtown, NC	18.85	Godwin, NC	16.32
Garland, NC	18.52	Fayetteville, NC	15.62
Savannah-Hunter Air Field, SC	17.49	Mullins, SC	15.57
Hope Mills, NC	17.05	Goldsboro, NC	15.48
Cape Canaveral Air Force Station, FL	17.01	Steadman, NC	15.34
Edisto Island, SC	16.90	Pikeville, NC	15.12
Duart, NC	16.87	Lumberton, NC	15.09
Salemburg, NC	16.60	Marion, SC	15.02
Hilton Head Island, SC	16.58	Chesapeake, VA	14.21

Source: NOAA

Caribbean & Bahamas Rainfall
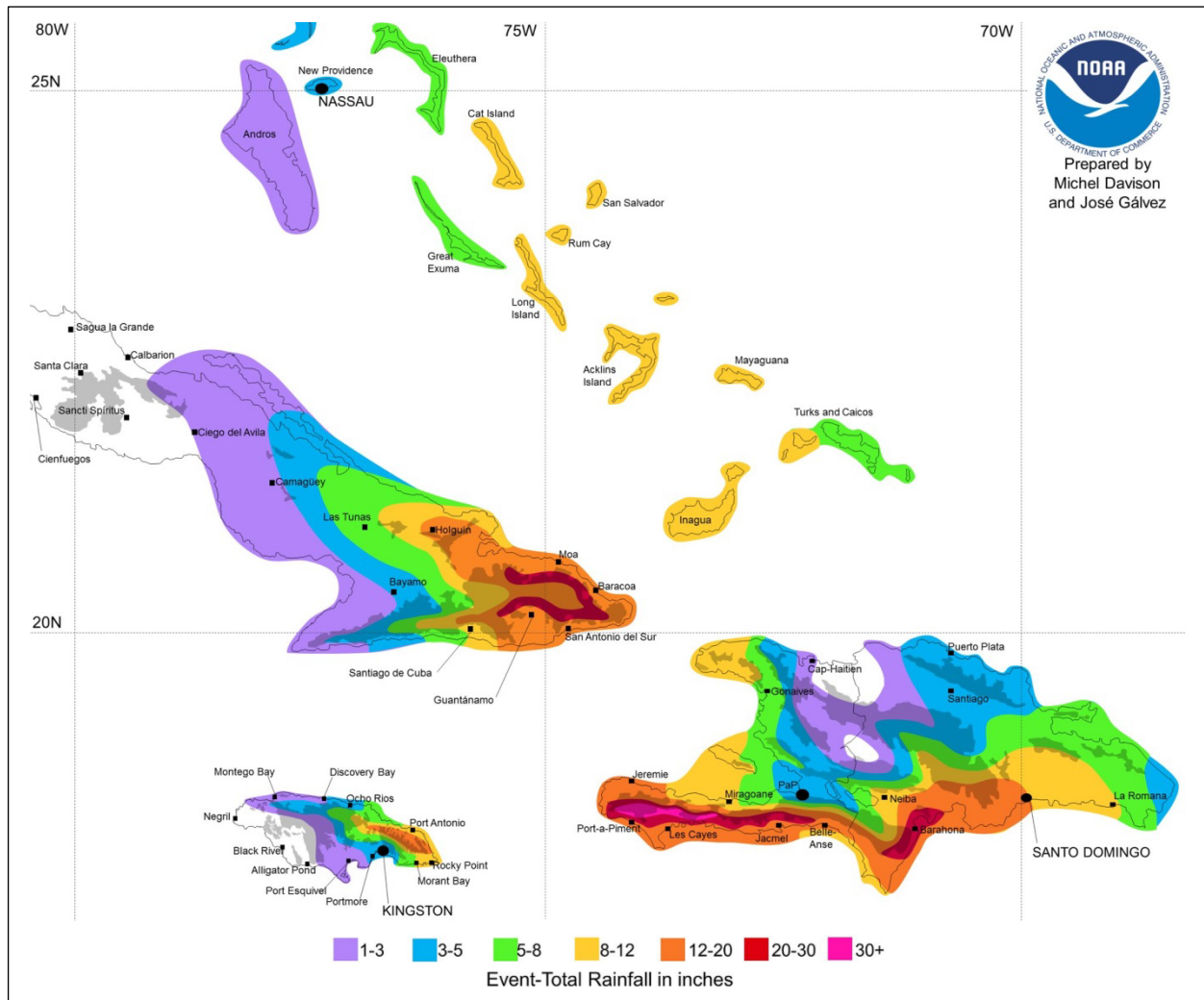
Hurricane Matthew event-Total rainfall projection (Source: NOAA)

Canada Rainfall

Location	Rainfall (mm)	Location	Rainfall (mm)
Burgeo, Newfoundland and Labrador	263.3	Point Leamington, Newfoundland and Labrador	156.0
Sydney, Nova Scotia	228.2	Badger, Newfoundland and Labrador	155.0
Eskasoni, Nova Scotia	199.6	Georges River, Nova Scotia	151.9
Grand Falls-Windsor, Newfoundland and Labrador	181.3	Granite Lake, Newfoundland and Labrador	150.5
Gander, Newfoundland and Labrador	176.8	Aspy Bay, Nova Scotia	149.9

Source: Environment Canada

Storm Surge & Inundation

US Storm Surge Heights

Location	Storm Surge Height (feet)	Location	Storm Surge Height (feet)
Fort Pulaski, GA	7.70	Mayport, FL	4.69
Fernandina Beach, FL	6.91	St Johns River (Racy Point), FL	4.58
Charleston, SC	6.20	Myrtle Beach (Springmaid Pier), SC	4.43
Station Hatteras, NC	6.06	Money Point, VA	4.16
Oyster Landing, SC	5.51	Trident Pier, FL	4.09

Source: NOAA

Storm Surge: *The observed storm tide minus the normal or astronomical high tide.*

US Storm Tide Heights

Location	Storm Tide Height (feet)	Location	Storm Tide Height (feet)
Fort Pulaski, GA	8.46	Myrtle Beach (Springmaid Pier), SC	5.20
Oyster Landing, SC	7.11	Wrightsville Beach, NC	4.40
Fernandina Beach, FL	6.96	Sewells Point, VA	4.25
Charleston, SC	6.15	Dames Point, FL	4.18
Mayport, FL	5.22	Station Hatteras, NC	4.15

Source: NOAA

Storm Tide: *The actual level of sea water resulting from the astronomic tide plus storm surge. (Datum: NAVD88)*

Caribbean Storm Surge Heights

A lack of official recording stations has led to a dearth of robust storm surge data throughout the Caribbean and Bahamas. There was an unofficial report of a 9.8-foot (3.0-meter) storm surge along southern Haiti's Tiburon Peninsula that caused considerable coastal inundation in at least 11 municipalities while Cuba's Meteorological Institute reported a storm surge of up to 13.0-feet (4.0-meters) along the southern coast of Guantánamo province and a surge of at least 11.0-feet (3.4-meters) along the northern coast. In Guantánamo and Holguin provinces coastal inundation extended as much as 300 feet (91 meters) inland while in Santiago de Cuba it extended more than 200 feet (61 meters) inland.

Impacted Areas and Effects

Lesser Antilles

Matthew passed through the Lesser Antilles chain between St Lucia and St Vincent on September 28 as a tropical storm with sustained winds of 95 kph (60 mph) on its way westward. Several island nations were affected by heavy rains and strong winds.

In St Lucia, damage to infrastructure was reported, while downed power lines left about 70 percent of the island's population without power. The majority of the outages were fixed within 24 hours. At least 10 houses on the island were seriously damaged. The island's agriculture sector was also affected as approximately 85 percent of the country's agricultural producers reported damage as up to 13.2 inches (335 millimeters) of rain fell. This mainly impacted banana plantations. The government received an XCD10.2 million (USD3.8 million) payout from the Caribbean Catastrophe Risk Insurance Facility (CCRIF) parametric insurance coverage. According to the prime minister, the majority of the payout will be used to rebuild the country's agriculture sector.

Flooding in St. Lucia (Source: St. Lucia News)

One fatality was reported in St Vincent and the Grenadines, where heavy rains triggered landslides and flash flooding, mainly along the west coast, causing damage to at least 100 houses. The Hermitage River burst its banks on St. Vincent Island leading to flooding in parts of Vermont, South Rivers, Kingstown, Campden Park, Arnos Vale, and Langley Park. A preliminary estimate of losses to the tourism industry reached XCD624,000 (USD231,000). As in St Lucia, around 80 percent of the island's banana plantations were affected by the hurricane, where the total damage was estimated at XCD1.4 million (USD530,000). Agricultural damage poses a significant threat for local economies in the Caribbean as bananas and other products constitute a substantial part of the islands' exports. The government received an XCD675,000 (USD250,000) payout from the CCRIF.

Some minor damage was also reported from the islands of Dominica, Grenada, Martinique, and Barbados. The Barbadian government insurance payout totaled XCD4.6 million (USD1.7 million). The main electricity provider in Martinique, EDF, reported that 62,000 customers were left without power at the peak of the storm, which constitutes approximately 30 percent of all households on the island. Four thousand households were without a clean water supply.

South America

As Matthew passed just to the north of the South American coastline, it brought torrential rainfall to several localities. Among the hardest hit areas were Aruba and the Guajira Peninsula of Colombia. Some parts of Colombia reported up to 8.7 inches (222 millimeters) of rain. More than 73,000 people were directly impacted by the floods – including nearly 70 percent of the town of Tucurinca after the Magdalena River burst its banks. Despite the intensity of the hurricane, there was no significant economic loss reported in Colombia and the rains brought by Matthew were welcomed in parts of the country as they brought some relief after a five-year long drought.

Jamaica

Matthew's impacts in the Greater Antilles were first felt in portions of Jamaica as the hurricane's outer bands grazed the island on October 3. Authorities evacuated 3,500 residents from the parishes of St. Thomas and Portland to emergency shelters prior to the arrival of the hurricane. There were no reports of any significant damage or casualties as a result however there was widespread disruption to travel and transportation as airports and public transport systems closed down. Some flooding was also noted in southeastern and eastern parishes. Schools and government offices were also closed temporarily.

Haiti

In Haiti, local officials reported that the damage sustained due to Matthew was "catastrophic". The official death toll was listed at 546, but unofficial tallies suggest the final total was in excess of 1,000: Haitian media reported the toll at 1,332 citing local authorities. The total number of fatalities was likely to be higher due to cholera outbreaks caused by water contamination and destruction of health-care facilities. At least 439 people were injured. Matthew struck Haiti while at strong Category 4 intensity – the first landfalling Category 4 storm in Haiti since Hurricane Cleo in 1964 – and brought prolific rainfall, storm surge and mudslides to the poorest regions of the country. One report suggested that 70 percent of the population in the areas worst affected by Hurricane Matthew lived in poverty. Official estimates from the United Nations (UN) indicated that more than 2.1 million people were affected and 1.4 million people (or roughly 13 percent of the country's entire population) were in need of immediate assistance in the aftermath of the storm.

The highest wind gust registered by an anemometer was at Antoine-Simon Airport in Les Cayes. The gust of 107 mph (172 kph) was recorded before the station was knocked offline. Winds additionally gusted to 60 mph (95 kph) in Port-au-Prince. Rainfall totals ranging from 20 to 40 inches (510 to 1,020 millimeters) were reported across southern Haiti. The highest storm surge was estimated at up to 9.8 feet (3.0 meters). These weather conditions would lead to catastrophic widespread devastation.

The UN reported that as many as 210,000 homes were damaged or destroyed in Haiti – including at least 80 percent of all buildings in Jérémie (Grand'Anse department) and 80 percent of homes in Les Cayes (Sud department). The hardest-hit departments included Grand'Anse, Sud, Nippes, Sud-Est, Ouest, and Nord-Ouest. Additionally, up to 80 percent of the country's 3,952 schools in the country's south and northeast were also destroyed, leaving as many as 400,000 schoolchildren affected. Relief and rescue teams struggled to reach the hardest-hit areas of Grand'Anse due to the collapse of the Ladigue Bridge at Petit Goâve during a flash flood. Severe damage to roads that linked the department to the capital, Port-au-Prince, also hampered the ability to reach these regions on the ground.

Aerial view of Haiti on October 9 (Source: AFP)

In Les Cayes, the local mayor reported that "devastation was everywhere". He stated that every home and building in the city had lost its roof, including the main cathedral, and that every plantation was destroyed. At least 30,000 homes were damaged or destroyed in Sud department alone. Most ports in Sud department were also damaged. Overall, 15 of Sud's 18 communes were severely impacted.

Similar destruction was noted in Jérémie, Grand'Anse, where every building not made of concrete was completely destroyed. Government buildings and shelters, including the city's main hospital, were also destroyed. Power lines and the telecommunications infrastructure sustained catastrophic impacts that further hindered the efforts of relief workers in the country. Significant damage and losses to agricultural interests also occurred. Many farmers reported that entire fields with livestock were washed away.

The UN appealed for USD139 million in an emergency relief fund for Haiti. According to the UN, the total humanitarian funding had reached USD64 million by the end of December 2016; the United States being the largest contributor. The Ministry of Economy and Finance initially reported that the minimum overall economic impact was HTG124 billion (USD1.9 billion). However, a later study by the United Nations' Office for Disaster Risk Reduction cited that the direct economic cost was HTG191 billion (USD2.8 billion); or 32 percent of the country's GDP. Of that total, individual damage costs to the agricultural sector and private property were each at least HTG40 billion (USD600 million). The government of Haiti also received a one-time USD23.4 million payment from CCRIF.

Death toll: *546 (official); 1,332+ (unofficial)*
Damage: *~210,000 homes (UN estimate)*
Affected: *2.4 million people*
Economic Cost: *USD2.8 billion (United Nations)*
Insured Cost: *USD23.4 million (partial; Caribbean Catastrophe Risk Insurance Facility payment)*

Dominican Republic

In the neighboring country of the Dominican Republic almost 25,500 people were evacuated as all 31 provinces were under alert. At least four people were killed in Santo Domingo where a further 43 people had to be rescued. Major flooding was reported in Santo Domingo, Monte Plata, San Pedro de Macoris, La Romana, San Cristobal, Peravia, San Jose de Ocoa, Azua, San Juan, Barahona, Bahoruco, Pedernales, Independencia, Monsenor Nouel, and La Vega. Reports indicated that 1,263 homes were damaged and a further 26 were destroyed. At the peak of the event, at least 31 communities were isolated due to flooding and damage to infrastructure.

Santo Domingo (Source: Agence France-Presse)

Death Toll: *4*
Damage: *1,500+ homes*
Economic Cost: *Millions (USD)*

Cuba

Authorities in Cuba evacuated more than one million residents from eastern portions of the country. The hardest-hit provinces were Guantánamo and Holguín where severe damage was reported. Five municipalities (including Imías and Yateras) in Guantánamo, home to more than 176,000 residents, were at one point isolated due to bridge collapses and landslides. Thanks to massive evacuations that took place in eastern Cuba prior to the hurricane's landfall, no fatalities were reported from the island.

Among the worst-affected areas was the municipality of Baracoa where local reports indicated that up to 90 percent of homes were damaged or destroyed. Significant damage to housing as well as to coconut and cocoa plantations (the province's main crops) were reported. Additionally the municipality's main city hall, the airport, a medical supply warehouse, a media outlet's headquarters, four hotels, the Municipal Museum Fuerte Matachin, and all public parks sustained varying levels of damage. La Farola Viaduct – a national monument – was also severely damaged. In the municipality of Maisí, several homes with lightweight roofs were destroyed. In total, more than 33,000 homes were damaged in Guantánamo province. A high volume of homes and structures were also impacted in Holguín, Granma, and Santiago de Cuba provinces. The Cuban government reported that Matthew affected at least 42,338 homes across Eastern Cuba; 8,413 of which were totally destroyed and 6,552 of which sustained major structural damage. Other damage included 15,235 homes that lost their roofs and 12,138 others that suffered partial roof damage.

Baracoa, Cuba (Source: ABC News)

Widespread damage to roofs, structures, and roads that was reported throughout eastern Cuba was accompanied by damage to electrical, commercial, tourist, and telecommunications infrastructure. Heavy damage, landslides, and washouts on roads leading from Guantánamo City to Baracoa, Imías, Maisí, Yateras, and San Antonio del Sur municipalities hindered relief and recovery operations. Hundreds of schools, daycare centers, and government offices were closed. According to state media, more than 70,000 hectares (173,000 acres) of agricultural land was damaged.

According to the Cuban Civil Defense Council, a preliminary calculation of partial economic damage caused by Hurricane Matthew was estimated at roughly CUP1.58 billion (USD63.4 million). This amount is likely to increase significantly once final assessments are conducted. The Cuban government also announced its decision to finance 50 percent of the construction material price for people whose houses were damaged. They also announced a grace period of one year to the farmers who cannot fulfill their credit repayments. The private sector also received a three-month grace period for tax payments.

Death Toll: *0*
Damage: *43,000+ homes*
Economic Cost: *USD100+ million (Minimum estimate; final total TBD)*
Insured Cost: *N/A*

Bahamas

Matthew traversed through much of the Bahamian region as a Category 4 hurricane and caused significant damage on many islands. There were no reports of any casualties. The Bahamas National Emergency Management Agency (NEMA) reported that some of the most extensive damage occurred on the islands of Grand Bahama, New Providence (including the capital of Nassau), Andros, and Exuma. Physical damage to residential and commercial properties was notable on these four islands, with major power outages leaving some resort areas closed for several days. Bahamas Power and Light (BPL) noted challenges in restoring power due to the large volume of trees that were stuck in power lines and that access points to several areas, such as Sea Breeze and South Beach, was difficult given varying levels of structural damage to some 80 percent of communities on the island. BPL struggled to restore power in North and Central Andros, where the electrical grid was severely damaged. At the early stages of the event, BPL initiated a controlled shut down of electricity in hopes to protect their infrastructure.

Physical damage reports were widespread on the hardest-hit islands, with high winds ripping off or partially collapsing roofs and downing trees and power lines. On West Grand Bahama Island, an estimated 95 percent of all homes in the townships of Eight Mile Rock and Holmes Rock were severely damaged. Even the Department of Meteorology in Nassau had to be evacuated after a window shutter came loose and a window was shattered by strong winds. Several churches and schools on New Providence and Grand Bahama additionally reported varying levels of roof and siding damage.

Damage in Nassau (Source: Jamaica Observer)

Coastal storm surge and overflowing rivers brought considerable water damage, too. The tourism industry on most islands was left generally unscathed, but there was some minor damage reported in New Providence, Grand Bahama, Andros, and Exuma. On Exuma, damage was extensive at the Sandals Emerald Bay Golf, Tennis, and Spa Resort which forced the resort to close for repairs until December 2016. Nearly all ports in the Bahamas had reopened by October 11 and cruise ship arrivals and departures had resumed. However, the port at Freeport on Grand Bahama remained closed until mid-November due to the widespread nature of damage to local infrastructure and businesses. All airports in the Bahamas were also fully operational by October 11 after several – including Lynden Pindling International Airport – were temporarily closed during Matthew's track across the archipelago.

The Prime Minister reported that the physical damage from Matthew would be "three to four times" the damage of Hurricane Joaquin (USD100 million). This did not include additional economic losses such as business interruption, infrastructure, and agriculture. Several major underwriters reported substantial losses, including Royal Star Assurance (USD90 million; 1,600 claims), Bahamas First (USD80 million; 2,800 claims) and Summit Insurance (USD37 million; 1,500 claims). The Bahamas Insurance Association (BIA) indicated that total insured losses were minimally USD400 million and could possibly reach as high as USD600 million. Either total would make Matthew the costliest event in the local industry's history.

In April 2017, the BIA reported that local underwriters paid out USD409 million in gross claims. The association also provided a breakdown of insured losses by island: more than USD267 million in claims, or 65 percent of the total, were submitted by businesses and residents of Grand Bahama Island. A further 31 percent of the total insured losses (USD125 million) were incurred on New Providence Island. Property claims comprised the vast majority of nationwide losses at more than 98 percent, while motor and marine accounted for only one percent and less than one percent respectively. Almost 75 percent of property claims were related to business property while residential claims accounted for remaining 25 percent.

Death Toll: *0*
Economic Cost: *~USD600 million to 1.0 billion (federal government)*
Insured Cost: *USD400 to 600 million (Bahamas Insurance Association)*

United States

Florida

Across Florida, scores of businesses, including the state's famous theme parks, closed early ahead of Matthew's arrival as officials turned major highways into one-way roads to expedite the evacuation process. Despite the mass evacuations and emergency measures in place, Hurricane Matthew still claimed eleven lives in the state. Fatalities were noted in Volusia, Miami-Dade, Duval, Orange, and Putnam Counties. Damage along the coastline was extensive from areas around Melbourne towards Jacksonville. The National Weather Service reported that Matthew created a new inlet on the Florida coastline between Marineland and Mantanzas Inlet, St Johns County. Additional severe coastal damage was noted at Summerhaven.

Jacksonville Beach (Source: Action News Jacksonville)

Areas along the Atlantic Ocean coast sustained major infrastructure damage – including the main A1A highway – as multiple feet of storm surge and battering waves led to substantial coastal impacts. At Cape Canaveral, wind gusts at Kennedy Space Center reached 80 mph (130 kph) at the surface (though a gust of 136 mph (219 kph) was registered at a 500-foot (150-meter) elevated tower that led to millions of dollars' worth of damage to the main facility. The roof of Operations Support Building II was partially damaged and rainwater damaged the interior. Matthew also delayed the planned launch of NASA's next generation weather satellite, GOES-R. *(NB. GOES-R, now known as GOES-16, was eventually launched on November 19 and was transmitting data by mid-December).*


Coastal damage near St. Augustine, Florida (Source: Impact Forecasting)

The most substantial damage occurred in Volusia, Flagler, St. Johns, Duval, and Nassau counties. More than 12,000 homes in Volusia sustained damage, while a further 69 were destroyed. St. Johns officials reported that roughly 2,000 homes suffered "substantial damage" during Matthew from wind, flooding and coastal erosion; equal to more than 50 percent of homes in the county. Most of them – including some that dated to the 1700s – were located in the historic city of St. Augustine. Water damage at Flagler College's main Spanish Renaissance-style main hall (built in 1888) was estimated in excess of USD1.0 million. County infrastructure damage was listed at USD138 million, including USD120 million alone due to coastal erosion. The United States Geological Survey (USGS) indicated that 53 miles (85 kilometers) of dunes were damaged or destroyed.

Similar impacts were noted in Flagler County, where the Florida Division of Emergency Management (FDEM) reported that 1,276 homes were either damaged or destroyed with a preliminary economic cost listed at USD72 million. According to a report compiled by Brevard County Emergency Management, 11 homes were destroyed in Brevard, while 1,628 other structures were damaged, 182 of which sustained major damage. Beach and dune erosion in the county was estimated at USD25 million. Duval County recorded 498 homes either damaged or destroyed; while Nassau County tallied more than 700 homes and businesses. Nassau County cited more than USD10 million in damage, with Fernandina Beach Marina incurring USD3.0 million of the costs alone. Other FDEM county home damage statistics included Putnam with 639 affected properties.

At its peak on October 7, it was reported by Florida Light and Power that nearly 1.14 million customers across Florida had lost power as a result of the storm.
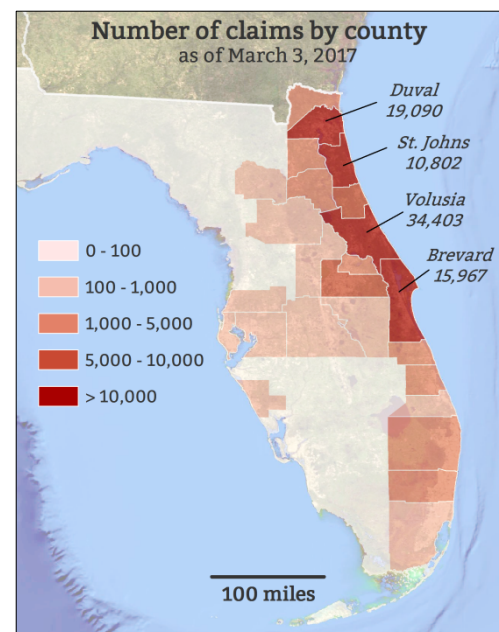
Source: FOIR, NASA

Total economic damage to residential and commercial properties – in addition to vehicles, infrastructure, and agriculture – were estimated to exceed USD2.0 billion in the state. In March 2017, the Florida Office of Insurance Regulation reported that nearly 119,350 residential and commercial claims alone had been filed with payouts totaling an estimated USD1.2 billion. With approximately 11,340 claims still open it is expected that insurance payouts will settle around USD1.5 billion.

In terms of National Flood Insurance Program (NFIP) payouts, the agency cited that 5,326 claims had been filed with payouts nearing USD135 million. This data is accurate as of January 23, 2017.

Line of Business	No. Filed Claims	Claims Closed (03/03/2017)
Residential Property	**101,454**	**93.1%**
- Homeowners	82,957	93.0%
- Dwelling	11,383	92.9%
- Mobile Homeowners	6,599	96.7%
- Commercial Residential	515	57.7%
Commercial Property	**6,698**	**56.4%**
Flooding	**3,433**	**92.0%**
- Private Flood	145	93.1%
- Federal Flood	3,288	91.9%
Business Interruption	**229**	**71.2%**
Other Lines	**7,531**	**86.3%**
TOTALS	**119,345**	**90.5%**

Death Toll: *11*
Economic Cost: *~USD2.25 billion*
Insured Cost: *~USD1.5 billion (Florida Office of Insurance Regulation & FEMA)*

Georgia

A major disaster was declared for the state as Matthew claimed at least three lives. On Tybee Island, the hurricane set a record water height as water reached up to 12.5 feet (3.8 meters); breaking the previous record of 12.2 feet (3.7 meters) set by 1979's Hurricane David. However, damage on the island was largely limited to damaged roofs. More than 340,000 customers endured power outages across the state during the peak of the event as scores of trees and power lines were toppled. Prior to the storm's arrival state officials ordered mandatory evacuations for all residents and tourists located east of Interstate 95.

As many as 2,000 National Guard troops were deployed to help in the relief and recovery process. High water levels forced the closure of many major thoroughfares and bridges in southeast Georgia isolating many residents as Matthew passed. Most of the residential and commercial property damage resulted from high winds downing trees onto roofs or shattering windows: several thousand trees were toppled on Sapelo Island alone. Flooding and storm surge was noted in several coastal communities including St. Marys, Brunswick, and St. Simon's Island. The USGS cited that 32 miles (52 kilometers) of shoreline were damaged.

Source: FEMA

The agricultural sector endured widespread damage from Matthew, with the Commissioner of Agriculture noting that the pecan, cotton and Vidalia onion crop were hardest-hit. Some farmers lost up to one-third of their entire pecan operations as many downed pecan trees were more than 100 years old. (NB. It takes at least seven years for a new tree to start producing.) High winds were also attributed to driving cotton fiber into the ground or tangling cotton and making it hard to clean during the ginning process. However, losses to agriculture were not as catastrophic as initially feared.

Total economic damage to residential and commercial properties – in addition to vehicles, infrastructure, and agriculture – were estimated near USD1.0 billion in the state. Georgia Insurance Commissioner Ralph Hudgens estimated in late January, that the insured loss caused by Hurricane Matthew in Georgia is around USD500 million.

The Georgia Office of Insurance reported that tens of thousands of claims had been filed with payouts in the hundreds of millions. Payouts from the National Flood Insurance Program (NFIP) pushed the insured loss even higher.

Death Toll: 3
Economic Cost: USD1.0 billion
Insured Cost: ~USD500 million (Georgia Insurance Commissioner, FEMA, USDA)

South Carolina

A state and federal disaster was declared in South Carolina following Matthew's impacts resulting from high winds, coastal flooding, and overflowing rivers. Five people died in the state. South Carolina was the site of the storm's only official United States landfall near McClellanville at the Cape Romain National Wildlife Refuge with maximum sustained winds of 75 mph (120 kph). This made Matthew a Category 1 storm at the time of landfall.

Most of the incurred damage in the state was water-related. Several communities, including areas between Charleston and Columbia, were still in the midst of recovering from damage sustained during the historic floods in October 2015 that left considerable infrastructure damage and weakened dams and levees. Matthew's intense rainfall and gusty winds only further exposed weaknesses in this infrastructure and there was one report of a breached seawall near Charleston. A number of rivers and streams rose to well above normal water levels. Two specific locations that set record crests included the Waccamaw River at Conway – 17.89 feet (5.45 meters), breaking a record set by the 1928 Okeechobee hurricane – and the Little Pee Dee River at Galivant's Ferry – 17.10 feet (5.21 meters), also breaking a record set in 1928. The USGS estimated that 77 miles (124 kilometers) of dunes and coastline were damaged.

Thousands of homes and businesses were damaged or destroyed across the state; many of which were damaged after 25 state-regulated dams were broken. Many of the broken dams came in the Pee Dee region. The hardest-hit area in the state was Hilton Head Island, where officials indicated that 3,724 homes and buildings – or 19 percent of the total number of structures – were damaged or destroyed. Of that total, 392 incurred damage equal to 50 percent or more of the assessed valuation of the structure. Most of the damage was due to water inundation or fallen trees.

Storm damage in Edisto Beach, SC (Source: NOAA)

Elsewhere, the Emergency Management Division in Florence County (near Myrtle Beach) cited that 2,324 structures were affected. The rural town of Nichols saw all 261 of its homes left uninhabitable after flooding rains mixed with fuel, fertilizer and sewage to leave a toxic black mold on walls.

The South Carolina Department of Agriculture indicated that significant damage had occurred to the sector; in the same vein as the October 2015 flood event. The most catastrophic losses were incurred to the cotton crop, while moderate losses were sustained to soybeans. Poultry farmers noted that roughly 203,000 birds were killed. Total economic losses to the agricultural industry were expected to reach well into the hundreds of millions (USD); but slightly less than the USD587 million incurred in the October 2015 flood event.

The state's forestry industry reported that high winds and saturated soils led to a high number of fallen trees. They also reported that an estimated USD205 million in damage was incurred, though this value only represents roughly one percent of the industry's USD18.6 billion annual contribution to the state economy. Hurricane Hugo cost the industry USD1.0 billion in 1989.

More than 844,000 South Carolina Electric Cooperatives and Duke Energy customers were without electricity at the peak of the event. As many as 481 roads and bridges were closed during Matthew, and 58 percent of sand dunes on South Carolina beaches were washed over.

Death Toll: *5*
Economic Cost: *USD2.0 billion*
Insured Cost: *~USD700 million (South Carolina Department of Insurance, FEMA, USDA)*

North Carolina

The state of North Carolina sustained the most extensive damage from Matthew, and a federal disaster was declared. At least 32 people were killed following the storm's tremendous rainfall that prompted many rivers to establish new all-time crest levels, a coastal storm surge that inundated the state's outer banks and mainland, and hurricane-force winds gusting in excess of 80 mph (130 kph). It was the most significant hurricane to impact North Carolina since Hurricane Floyd in 1999.

Flooding along the Tar River near Grimesland, NC (Source: NOAA)

Despite the rain and wind from Matthew ending on October 9, the intensity of the rainfall – which impacted most of the central and eastern sections of the state – prolonged river flooding for more than a week in some locations. During one 36-hour period on October 8 and 9, some areas experienced more than 18.00 inches (457 millimeters) of rainfall. As many as 17 counties set single-day rainfall records. The inland riverine floods were exacerbated by the fact that upwards of 10 inches (254 millimeters) of rain had fallen across similar parts of North Carolina during the last week of September 2016. Those rains resulted from the remnants of Tropical Storm Julia. This meant that soils were already highly saturated even prior to Matthew's arrival. Among the many rivers and creeks to establish record flood heights were the Neuse River, Lumber River, Tar River, Lower Little River, and the Little Pee Dee River.

The scope of flood damage was enormous: local, state, and federal officials reported that nearly 110,000 physical structures (homes and businesses) were damaged or destroyed. Even more farm buildings were inundated. FEMA indicated that 71,000 individual households reported varying levels of flood damage and had applied for financial assistance. The extent of the floods far surpassed the 100-year floodplain in many areas, and some locales experienced 1,000-year flooding.

A report from the North Carolina governor's office reported that the most catastrophic damage occurred in the following counties: Columbus, Cumberland, Edgecombe, Lenoir, Robeson, and Wayne. A few of the hardest-hit cities and towns included Fayetteville, Princeville, Lumberton, Fair Bluff, Goldsboro, and Kinston. At the peak of the event, 3,744 individuals were evacuated to 109 separate shelters to escape rising water. It was determined that 78,757 homes were damaged or destroyed and that damage minimally totaled USD777 million. This did not include additional losses to indoor contents. Based on policy coverage data from the National Flood Insurance Program (NFIP), it was determined by the state government that a minimum of USD402.5 million of the structural damage would be uninsured.

Widespread impacts were additionally prevalent within the commercial and agricultural sectors. A state report indicated that more than 30,000 businesses suffered physical damage or interruption losses. The physical damage to businesses alone were estimated at USD550 million. The overall economic loss – including business interruption – was estimated at USD2.0 billion. Similar financial costs were incurred by agriculture as a Farm Service Agency (FSA) study determined that 43 counties had farms reported losses greater than 30 percent of their projected output. This translated to a minimal USD400 million crop loss, which became even higher once the millions of lost livestock and farm animals were included. As many as five million chickens and 3,000 hogs were killed after 140 pig and poultry barns were flooded. Officials from the North Carolina Department of Agriculture and Consumer Services would later report to local media that expected crop and farm damage would be in the billions of dollars (USD).

Road damage in Greene County, NC (Source: NOAA)

Beyond physical damage to structures, Matthew heavily impacted North Carolina's transportation infrastructure and electrical grid. At the peak of the event, 635 roads were closed. Critical pieces of infrastructure were closed for 7 to 10 days including a section of Interstate 40 West in Johnston County and Interstate 95 North and South in Robeson and Cumberland counties. Other smaller roads were expected to be closed for months given the severity of damage and the need for the Department of Transportation to conduct safety surveys. In terms of electricity, more than 714,000 households were at one point without power. Electric companies reported that most of the outages were due to downed trees, inundated transfer stations and blown transformers.

Other damage in the state resulted in the temporary lack of clean drinking water in dozens of counties. Following the rupture of waterlines and a loss of electricity, all or part of 31 counties were advised to boil water prior to consumption. Damage to the water treatment facility in Robeson County led to a prolonged period of service disruption; while and the town of Fairmont had its wastewater treatment plant dumping 500,000 gallons of raw sewage a day into a nearby creek after a main broke.

Death Toll: *32*
Economic Cost: *USD5.0 billion*
Insured Cost: *~USD1.0+ billion (North Carolina Department of Insurance, FEMA, USDA)*

Virginia

Two people were killed in Virginia as a result of Hurricane Matthew according to information from the Virginia Department of Emergency Management (VDEM). One of the fatalities was reported in Suffolk County as the victim was swept away by floodwaters while the second was reported in Chesapeake as the result of a car accident on Interstate 64.

Damage to 2,306 private property structures was reported across the state, with the majority occurring in Virginia Beach. A high portion of the residential damage across the state was uninsured as most of the damage was flood-related and latest statistics indicated that roughly seven percent of Virginia homeowners were National Flood Insurance Program (NFIP) policyholders at the time. In the hardest-hit area of Virginia Beach, only eight percent of the damaged homes had NFIP policies in place as Matthew struck. This reality prompted the state to request federal funding to aid residents in the recovery process. The number of properties damaged by county is summarized in the table below, which has been provided by the state of Virginia, and includes tallies through October 20, 2016.

Locality	Destroyed	Major Damage	Minor Damage	Affected	Total
Chesapeake (City)	4	48	209	378	639
Hampton (City)	1	7	67		75
Isle of Wight (County)		1	7	4	12
Newport News (City)		2	102	3	107
Norfolk (City)	6	19	28	38	91
Portsmouth (City)		6	37	3	46
Suffolk (City)		1	8	6	15
Virginia Beach (City)	8	119	1,103	85	1,315
York (County)	1	1	3	1	6
TOTALS	**20**	**204**	**1,564**	**518**	**2,306**

Extensive damage to public properties was also reported in the aforementioned counties as well as Accomack, Amelia, Southampton, and Franklin City. Worst affected was Virginia Beach where damage to public properties reached USD4.0 million. Damage to public properties included the cost of debris clearance, emergency protective measures, damage to roads and bridges, water control, damage to public buildings and equipment, damage to public utility systems, and parks and recreation. An overall preliminary estimate of the economic impact to public structures was USD12.1 million.

It is worth noting that while Virginia did not endure the worst of Matthew's impacts, the eastern half of the state was already coping with oversaturated soils following rainfall amounts ranging from 400 to 600 percent above normal during the previous 12 months. In the 30 days prior to Matthew's arrival, the remnants of Hurricane Hermine and Tropical Storm Julia brought a combined average of 22.00 inches (559 millimeters) of rain to the region.
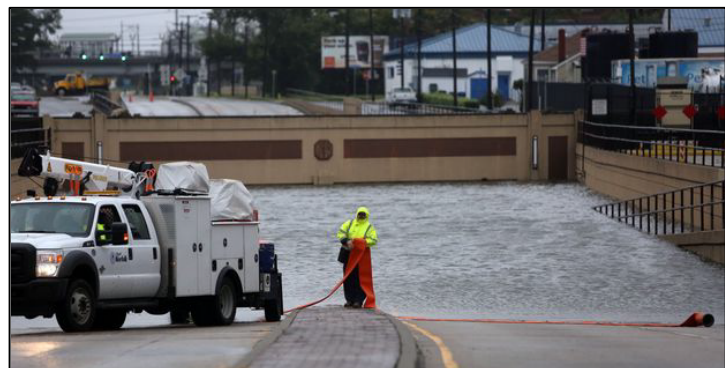
Flooding in Roanoke, VA (Source: The Associated Press)

Some 260,000 customers endured power outages across the state at the peak of the disruption caused by the hurricane on October 9. The combination of oversaturated soils and winds gusting to tropical storm strength led to hundreds of trees (ranging from 1 to 3 feet (0.30 to 0.91 meters) in diameter) being uprooted and knocking down power lines.

Additionally, all four terminals of the Port of Virginia were temporarily closed. Hundreds of roads and bridges were also closed due to high water levels or debris; while rail services – including Amtrak – saw extended disruption.

As of January 10, the Virginia Department of Emergency Management reported that at least USD47 million in NFIP payments had been made to 2,263 claims filers.

Death Toll: *2*
Economic Cost: *~USD400 million*
Insured Cost: *~USD200 million*

Canada

Portions of Atlantic Canada were lashed by a low pressure area, fueled by the remnant tropical moisture of Hurricane Matthew, which brought significant heavy rainfall to parts of Prince Edward Island, Nova Scotia, and Newfoundland from October 9-11.

Much of Newfoundland experienced heavy and continuous rainfall throughout the day on October 10 with the highest rainfall rate of 42 millimeters (1.7 inches) per hour reported at Burgeo. Other locations reported rates of 10-20 millimeters (0.4-0.8 inches) per hour which are still considered to be very high. The strongest of the wind gusts were largely restricted to coastal areas on October 9 and into October 10, while in northern portions of Newfoundland there were reports of accumulating snowfall. States of emergency were declared in Sydney, NS, Lewisporte, NL, Little Burnt Bay, NL, Bishop's Falls, NL, and St. Alban's, NL. Despite the widespread damage and disruption, there were no reports of any fatalities as a result of the stormy conditions in Canada.

Among the worst affected communities were Sydney, on Cape Breton Island, NS, and Burgeo, on the southern edge of the Island of Newfoundland, where high wind gusts and flooding caused severe and widespread damage. Brookland Elementary School in Sydney was among the numerous buildings in the town to sustain extensive damage. As of November 10, the school remained closed and more than 300 students were being accommodated at other nearby schools. Nova Scotia Power reported that as many as 144,000 customers were without power on October 11 as powerful wind gusts toppled trees and power lines. Smaller power outages were reported by Maritime Electric in Prince Edward Island (7,800+) and Newfoundland. Additionally, local authorities reported that thousands of homes across Cape Breton Island suffered inundated basements and ground floors while there were numerous reports in local media of submerged vehicles and roads. Dozens of roads were closed due to flooding and washouts.

Morrisville, Newfoundland (Source: VOCM)

In Newfoundland, the town of St. Alban's was cut-off from the surrounding area as the main bridge into the town, the Swanger Cove Bridge, was swept away by floodwaters while in Lewisporte at least 40 homes were flooded. Across the island there were dozens of reports of road washouts, displaced culverts, and vehicle accidents, the causes of which were attributed to the inclement weather. Roads affected included the Trans-Canada Highway (Highway 1) in Terra Nova National Park. One landslide was reported in Benoit's Cove that caused damage to at least one home. By the evening of October 12, some 17 communities were still cut-off due to road and bridge washouts and displaced culverts.

Swanger Cove Bridge (Source: The Globe and Mail)

Marine Atlantic, which operates ferry services between Argentia, NL, North Sydney, NS, and Port aux Basques, NL, suspended all services on October 10 due to adverse weather conditions. Maximum wave height recorded by a buoy on Burgeo Bank reached 8.50 meters (28 feet) on October 10. Additionally Marine Voyager which provides ferry services between Francois, Grey River, and Burgeo, NL, was also out of service on October 10.

Local officials in Cape Breton Island reported that damage was likely to be well in the 10s of millions (CAD). The repair bill for damage to roads in Newfoundland alone was expected to top CAD1.5 million (USD1.1 million).

Loss estimates from the Canadian insurance industry show that more than 5,000 claims were filed in New Brunswick, Prince Edward Island, Newfoundland, and Nova Scotia pertaining to damage incurred as the result of remnants from Hurricane Matthew. A published report by Catastrophe Indices and Quantification Inc. (CatIQ) cited claims payouts of roughly CAD110 million (USD80 million). The majority of this amount was incurred in Nova Scotia.

Death toll: *0*
Economic Cost: *~USD150 million (estimate)*
Insured Cost: *USD80 million (Catastrophe Indices and Quantification Inc.)*

Energy Impacts

Electricity

The impact of Hurricane Matthew on electric grids of the Caribbean Islands was extensive, yet only temporary. The Windward Islands experienced widespread power outages due to Matthew's sustained winds of around 60 mph (95 kph) when it passed through the area as a tropical storm. In St Lucia, about 70 percent of the population (120,000 people) lost power, while the primary electricity provider in Martinique reported 62,000 customers without power during the peak of the storm. Cuban authorities reported approximately 50,000 power outages and damage to 2,500 poles, 300 transformers, and 884 kilometers (550 miles) of wires.

The United States Department of Energy's Office of Electricity Delivery and Energy Reliability reported that approximately 3,150,390 customers lost electricity in Florida (990,355), Georgia (340,000), South Carolina (844,200), North Carolina (714,050), and Virginia (261,785) due to Hurricane Matthew. Numerous energy suppliers were impacted by the outages including Florida Power and Light Company, Duke Energy Florida, Jacksonville Electric Authority, Tampa Electric, Gulf Power, Clay Electric Cooperative, Georgia Power, South Carolina Electric and Gas, Santee Cooper, Duke Energy, and Dominion Power. A summary of peak outages by state and by date are shown below.
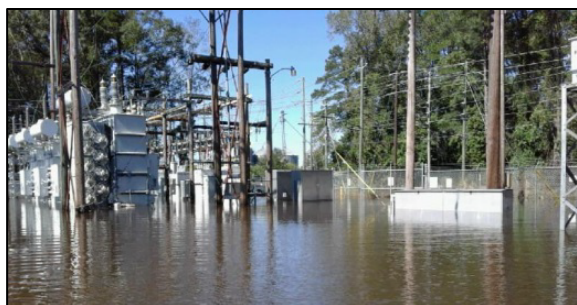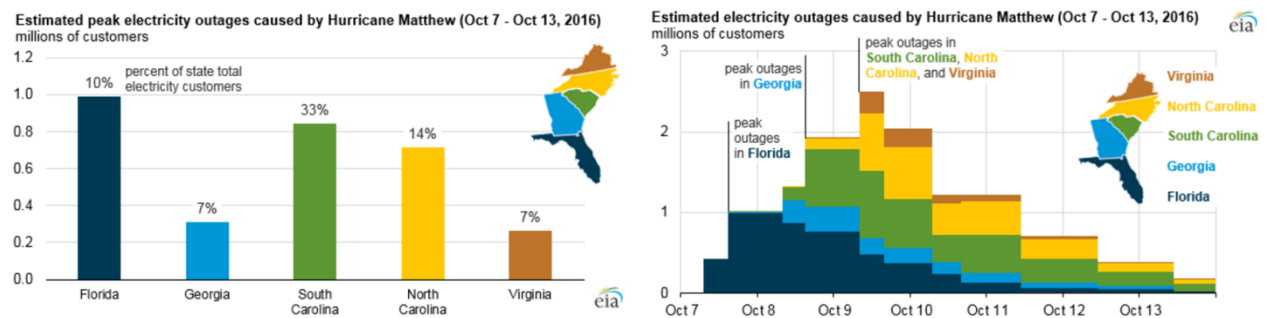
Duke Energy substation, Whiteville, NC (Source: Duke Energy)

Florida Power and Light Company, the largest energy provider affected by Hurricane Matthew, spent almost USD317 million repairing over 250 miles (400 kilometers) of wire, more than 900 transformers, and more than 400 poles. Additional costs were incurred by the company due to the large amount of vegetation that had to be cleared to facilitate these repairs. All of the major energy providers impacted noted that there were delays to power restorations and additional costs incurred as the result of severe vegetation damage.

Across Florida and the Carolinas Duke Energy expected to spend USD200 million to repair damage incurred to its infrastructure. Duke Energy's CEO Lynne Good said that *"storm has swamped Duke's 2016 storm-repair fund of $40 million. The company will be asking regulators in the three states to allow the company to recover those costs from customers".* Duke Energy reported damage to more than 115 substations, 800 transformers, 58 transmission towers, almost 2,000 utility poles, and several miles of power lines throughout North and South Carolina. Floodwaters also prompted a 50-foot (15-meter) breach in a cooling pond dam at H.F. Lee Plant, near Goldsboro, North Carolina.

Georgia Power reported damage to approximately 1,000 power poles and almost 80 miles (130 kilometers) of wire. Additionally they noted that more than 1,800 trees caused damage to their infrastructure.

The highest absolute number of power outages was recorded in Florida. The state Division of Emergency Management (FDEM) reported that on October 7 at 8:47 PM local time, 1,134,981 customers in the state were left without power: this comprised 11 percent of all customers. The highest numbers of customers affected by power outages were reported in Volusia, Duval, and Brevard counties. The counties with the highest percentages of customers left without power were the coastal counties of Flagler (99%), Volusia (90%), and St. Johns (90%).

County	Power Outages (Customers)	Power Outages (Percentage of Total)
Volusia	255,048	90%
Duval	215,748	52%
Brevard	159,298	52%
St. Johns	78,610	90%
Seminole	64,606	31%
Flagler	58,536	99%
Orange	50,877	9%
St. Lucie	41,149	27%
Indian River	41,000	47%
Clay	28,214	20%

Petroleum ports

Across Florida, 29 out of 37 petroleum product terminals in five ports were closed on the morning of Friday, October 7, including all terminals on Florida's Atlantic Coast. Eight terminals in the Tampa area were operating on October 7, while seven terminals in Savannah, Georgia (four) and Charleston, South Carolina (three) were closed. By the morning of October 8, the terminal in Wilmington, North Carolina was also closed while the Hampton Roads terminal, Virginia was operating with restrictions. By that evening, Hampton Roads was also closed and by the morning of October 9 all ports in Florida were operating as normal. Charleston and Wilmington ports were operating with restrictions by the morning of October 10 while Hampton Roads fully reopened by the afternoon of October 11. By midday on October 12 all of the affected ports were operating with no restrictions.
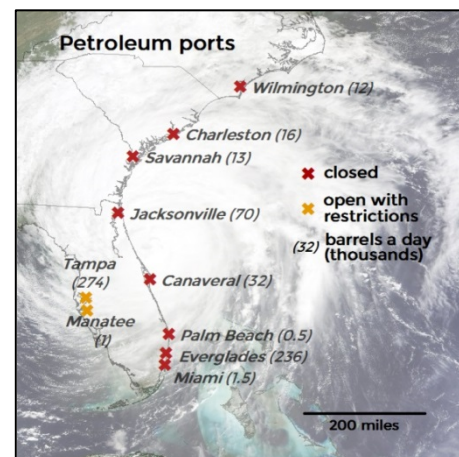
Source: Department of Energy, NASA

In total, eight main petroleum-importing ports on the East coast, distributing around 381,000 barrels per day, were closed during Matthew's passage due to high waves and storm surge. The disruption to petroleum imports affected the product's availability across Florida; in total, 775 gas stations reported severe shortages.

State	Total Gas Stations	No Fuel (October 10)	No Fuel (% of Total)
Florida	7,107	775	11%
Georgia	6,024	19	<1%
South Carolina	2,957	25	<1%
North Carolina	5,276	21	<1%
Virginia	3,771	2	<1%

Transportation Impacts

Airports & Airlines

Hurricane Matthew led to thousands of flight cancellations throughout its lifecycle. The first airport closures and flight cancellations began in the Caribbean as airports on the Windward Islands – including Grenada, St. Lucia, and Dominica – were temporarily closed as tropical storm-force winds were threatening safe aviation to the islands. Service was eventually stopped in Jamaica at both Montego Bay (Sangster International Airport) and Kingston (Norman Manley International Airport) once hurricane watches and warnings were initiated. In Haiti, both international airports on the island were closed in Port-au-Prince and Cap-Haitien. Further closures were reported in Cuba at the local airports in Holguin and Camaguey. Despite the flight cancellations and temporary airport closures in the Caribbean, there were no reports of any major structural damage to terminals and runways.

Grand Bahama Int'l Airport (Source: The Bahamas Weekly)

The Department of Civil Aviation in the Bahamas reported that all but one airport on the archipelago were temporarily closed but re-opened soon after Matthew's exit. On Grand Bahama, there was flood damage to the domestic terminal at Grand Bahama International Airport that left the airport operating at reduced capacity until the end of November 2016. Officials reported that the floods were due to storm surge from the north shore that swept across runways. Significant debris additionally covered the runways, and in the immediate aftermath of the event, the airport was used for relief supply deliveries to the island.

Matthew's arrival in the United States led to nearly 5,000 flight cancellations from October 5 to 9; most of which were associated with flights to the Southeast. Airports with the most cancellations included Orlando International Airport, FL, Miami International Airport, FL, Jacksonville International Airport, FL, Hilton Head International Airport (Savannah), GA, and Charleston International Airport, SC. The most significant US airport impact came in North Carolina, where the Pitt-Greenville Airport was severely flooded after the Tar River overflowed its banks. The facility was closed until October 19.

Roadways

Severe storm surge that inundated the east coast of Florida caused substantial infrastructural damage. A 1.3-mile long section of A1A highway that runs parallel to the coast was severely damaged and became impassable or narrowed to only one lane after large chunks of soil and asphalt were torn off by the waves. The bulk of the damage was sustained in Flagler Beach, Flagler County. In late October 2016, a USD4.0 million temporary repair project began. These repairs were meant to ensure availability of the road for traffic in both directions. The road was reopened in mid-November, while Florida's Department of Transportation was preparing the final restoration project.

A1A Highway in Flagler County, Florida (Source: Miami Herald)

Traffic disruption was widespread in all impacted US states. The South Carolina Department of Transportation (SCDoT) reported, that on October 10, 446 roads and 35 bridges were closed across the state. By the end of November, SCDoT had reopened the majority of these, while 21 roads and four bridges still remained closed due to washout or partial collapse, including two primary roads. Some 925,578 cubic yards of debris was removed from state roads. Shortly after Matthew's passage, the federal Department of Transportation (DoT) announced the immediate availability of USD1.0 million for initial repairs of roads and bridges in the state.

In North Carolina, traffic on several interstates, including I-95 and I-40 was interrupted on multiple locations on October 10 and detoured along minor roads. Multiple main state roads were closed as well. Interstate-95 and Interstate-16 were also closed in Georgia. The DoT announced that it had made USD5.0 million available for emergency repairs of roads and bridges in North Carolina.

Railways

The railroad network in North Carolina also suffered as the result of the flooding generated by Hurricane Matthew: the State Department of Transportation earmarked millions of dollars to repair damaged tracks in the aftermath of the storm. The Rail Division reported that bridge damage and track washouts were observed on the North Carolina and Virginia, Carolina Coastal, Clinton Terminal, and RJ Corman Carolina track lines.

Track washout near Clinton, NC
(Source: The Sampson Weekly)

Officials awarded an additional USD10 million to the Freight Rail and Rail Crossing Safety Improvement program for the fiscal year 2017 due to the widespread damage. (The total fund stood at almost USD14 million at the time of this writing). The most pressing projects to benefit from the fund were: the re-instatement of tracks between Chadbourn and Whiteville in Columbus County and other track upgrades from Chadbourn to Tabor City (USD7.3 million); the upgrade of several bridges and more than 31 miles of tracks in Wake, Johnston, Nash, Wilson, and Beaufort Counties (USD1.7 million); the replacement of five culverts and repair of 29 miles of track in Currituck, Camden, and Pasquotank Counties (USD725,000); and the construction of a new transload facility and the reinforcement of eight miles of tracks in Cumberland and Hoke Counties (USD393,600).

Marine Industry

The Association of Bahamas Marinas reported that all 31 of its marina members and 16 allied members had escaped significant damage. A handful of docks on Exuma and Grand Bahama were impacted, but were not damaged severely and did not cause any business closures. The agency cited strong building codes for the marinas being able to withstand the Category 3 and 4 impacts of Matthew as it traversed the archipelago.

Impacts to the marine industry in the United States were considerable, but not historically significant. Reports by local communities indicated that at least a combined USD100 million in damage had been incurred to marinas and other coastal marine facilities due to storm surge and high waves. A separate study by the Boat Owners Association of the United States reported that damage to recreational boats along four coastal states (Florida, Georgia, South Carolina, North Carolina) was at least USD110 million. For comparison, the most recent notable US tropical cyclone was Sandy in 2012. That storm damaged more than 65,000 recreational boats at a cost of USD650 million.

Environmental Impacts

Coastal Erosion

Hurricanes and severe storms can generate vast storm surges and large waves, often eroding beaches and dunes, and reshaping the coastal landscape. This not only has an environmental toll but also an economic one, as these changes can incur structural damage to property or compromise development potential and the tourism industry.

Surges and waves can erode beaches and dunes and/or they can overwash them and transport the sand particles further inland, where they are deposited. These deposits can bury homes and roads or damage coastal vegetation and crops. Water can also breach the coastal dunes and create new islands or inlets.

Hurricane Matthew impacted a vast swath of US East Coast. According to a report by the United States Geological Survey (USGS), Matthew's storm surge and waves overwashed about 15 percent of the sand dunes on Florida's Atlantic coast, 30 percent along Georgia's coastline, and 42 percent of dunes on South Carolina's sandy beaches as the powerful storm brushed past the Southeastern states.

The USGS compiled an extensive database of more than 24,000 oblique aerial photos documenting the coastal change in Florida, Georgia, and the Carolinas. They show extensive alteration of the coast due to erosion and overwash in all four states. Near St Augustine, Florida, a new inlet was created between the Atlantic and the Matanzas River, stripping away a 3.7-meter (12.0-foot) high dune and depositing sand in the estuary. At Flagler Beach, waves washed away a significant portion of the A1A State Road while at Vilano Beach a five-meter (16.0-foot) high dune was eroded, destroying parts of the oceanfront homes.

New inlet near St Augustine, FL (Source: USGS)

Damaged houses in Vilano Beach, FL (Source: USGS)

Flora & Fauna

Hurricane Matthew caused damage to protected sea turtle nests along the coast of Florida. According to a report by Ecological Associates Inc., an environment monitoring company based in Jensen Beach, Florida, many of the nests were wiped out by waves and storm surge on Treasure Coast. In Archie Carr National Wildlife Refuge, about 800 nests were lost while 250 more were thought to be lost in Canaveral National Seashore. Fortunately, Matthew arrived at the end of the sea turtle nesting season, which lasts from March to October and most of the turtles had already hatched.
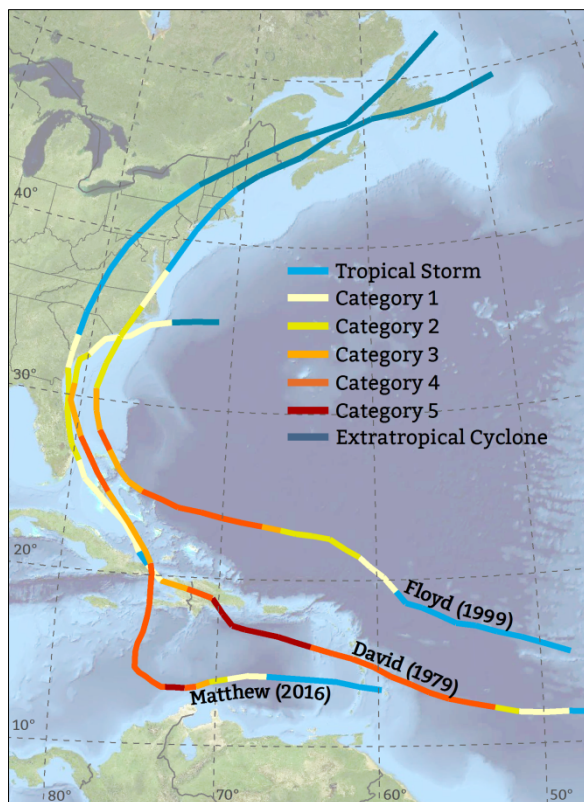
Comparison: Matthew vs. David (1979) & Floyd (1999)

Matthew was not the first hurricane to parallel the East Coast of the United States. Hurricanes David (1979) and Floyd (1999) both followed a path similar to Matthew's. All three of these hurricanes caused widespread damage in coastal US states, while David and Matthew also devastated portions of the Caribbean.

Hurricane David (1979) underwent rapid intensification after being declared a hurricane on August 26, approximately 1,000 miles (1,600 kilometers) east of the Windward Islands. The storm devastated Dominica and hit Hispaniola at full strength, after attaining Category 5 status. After passing the eastern tip of Cuba in almost the same place as Matthew did in 2016 (near Baracoa), it weakened to Category 1, and caused minor damage in the Bahamas before re-intensifying to Category 2 status prior to making landfall in Florida, near Palm City, on September 3 with sustained winds of 100 mph (160 kph). It then paralleled the US East Coast and made its final landfall just south of Savannah, GA the following day.

Hurricane Floyd (1999) avoided the Caribbean and became a hurricane on September 10 while located about 250 miles (400 kilometers) northeast of Guadeloupe. Floyd paralleled the Lesser and Greater Antilles chain at a distance of a few hundreds of miles to the north. It remained just below Category 5 intensity while crossing the Bahamas before undergoing an eyewall replacement cycle.

Tracks of David, Floyd, and Matthew (Source: NHC, NASA)

Floyd then paralleled the Floridian coastline, staying approximately 110 miles (180 kilometers) offshore. Floyd made landfall at Cape Fear, NC on September 16 as a Category 2 strength hurricane with sustained wind speeds of 105 mph (170 kph). It briefly re-entered the Atlantic Ocean near Norfolk, Virginia and reached Long Island, New York on September 17.

Storm	Minimum Pressure	Maximum Winds	Fatalities	Economic Loss (Actual USD)	Insured Loss (Actual USD)
Matthew (2016)	934 mb	165 mph	604+	15.0 billion	4.5 billion
Floyd (1999)	921 mb	155 mph	58	6.9 billion	2.5 billion
David (1979)	924 mb	175 mph	2,068	1.6 billion	800 million

Details

Damage inflicted by all three aforementioned hurricanes was widespread. However, the actual mechanisms that caused the bulk of the damage were different in each case.

Hurricane David caused absolute devastation on Dominica, mainly due to a serious underestimation of the hurricane's effects and unpreparedness. At least 56 people died and three quarters of the population were left homeless as the catastrophe prompted a vast influx of foreign aid. The entire agricultural sector, which comprised mainly banana plantations, was destroyed. Similar damage was inflicted in 2016 after the passage of Matthew on several Caribbean islands. These examples show how vulnerable the Caribbean agricultural sectors are.

David killed over 2,000 people in the Dominican Republic and caused major flooding in Puerto Rico, where it dumped more than 20 inches (500 millimeters) of rain. Storm surge, wind, and flood damage losses in the US reached USD320 million, including USD95 million in Florida alone. In total, 400,000 people were evacuated in the US. Rainfall associated with David in the US was not exceptional and no major flooding occurred.
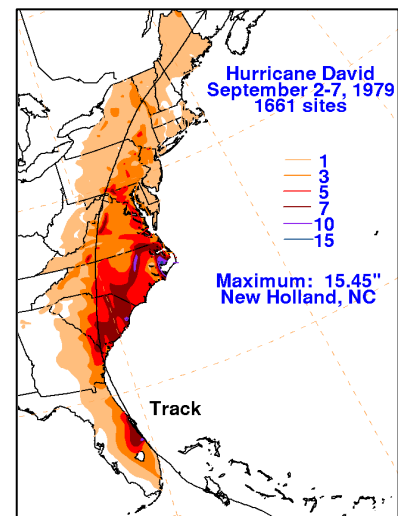
Hurricane David rainfall totals (Source: NHC)

Hurricane Floyd was initially forecast to track westward and make a direct hit on Florida, which would have had catastrophic consequences, given the storm's intensity. This led to massive evacuations, which were later extended to Georgia and the Carolinas. Approximately 2.6 million residents were evacuated in total as well as NASA's Cape Canaveral facility.

Ultimately Florida was spared and Floyd hit the outer islands of the Bahamas and the Carolinas. Unlike in 2016, the vast majority of damage in the US was caused by inland flooding. A two-month long one-in-500 year flood event in North Carolina was the result of the combined effects of Hurricanes Dennis, Floyd, and Irene, which brought
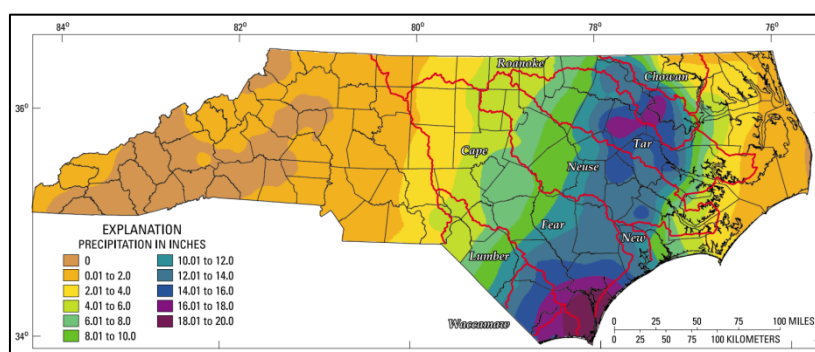
Rainfall in North Carolina brought by Hurricane Floyd (Source: NHC)

and Irene, which brought unprecedented amounts of rainfall in September and October 1999, surpassing 30 inches (762 millimeters) in some places, and saturating river basins in the state. Additionally, storm surge and severe winds destroyed hundreds of houses on the coast. In North Carolina alone, economic losses due to Floyd reached USD6.0 billion.

The highest rainfall generated by Matthew in the US was recorded near Evergreen, North Carolina, and was measured at 18.95 inches (481.3 millimeters). Although rainfall totals were not quite as high as those recorded in 1999, many rivers still broke historical peak crest records and widespread flooding devastated North Carolina. The Neuse River peaked in Kinston at 28.31 feet (8.63 meters), surpassing the record set by Floyd by one foot. Both hurricanes impacted the eastern half of North Carolina. During the floods in 1999, drought conditions prevailed in the western part of the state.

What drives the trend of increasing hurricane losses?

Hurricane damage in the US is generally expected to increase in the coming decades. It is not simple to determine what drives the anticipated increase. The problem in its complexity provides a variety of explanations that have been addressed by extensive research. Generally, climate change will influence hurricane activity to a certain degree. There are also several important socio-economic factors.

- Climate Change – Climate change will increase ocean temperatures and raise ocean levels. Its impact on tropical cyclone activity has been heavily researched and there is no proof of any significant trends in the number of tropical cyclones worldwide, however, there is some evidence that the number of intense Atlantic hurricanes is increasing.

- Population Increase & Migration Patterns – The concentration of people and residential property in coastal areas is growing at an alarming rate and may likely result in further increase of damage in the coming years. This problem is particularly significant in Florida. Massive coastal development in Florida and elsewhere may also have serious consequences as the transportation routes can be overwhelmed in case of massive evacuations of coastal communities. Therefore, increasing population density can compromise preparedness efforts.

- Economic Growth & Increased Exposures – Hand in hand with population, economies of coastal, hurricane-exposed areas have been steadily growing and continue to do so. For example, the nominal GDP of Florida has increased ninefold in the last 35 years since Hurricane David. The concentration of businesses in coastal counties increases the total exposure significantly. Wind, surge, or flood damage to business property itself is not the sole problem. Other factors have to be considered, such as business interruption, power outages, infrastructure, and distribution network damage etc.

Trends of selected socio-economic indexes for four coastal states impacted by David, Floyd and Matthew are shown below (Source: US census):
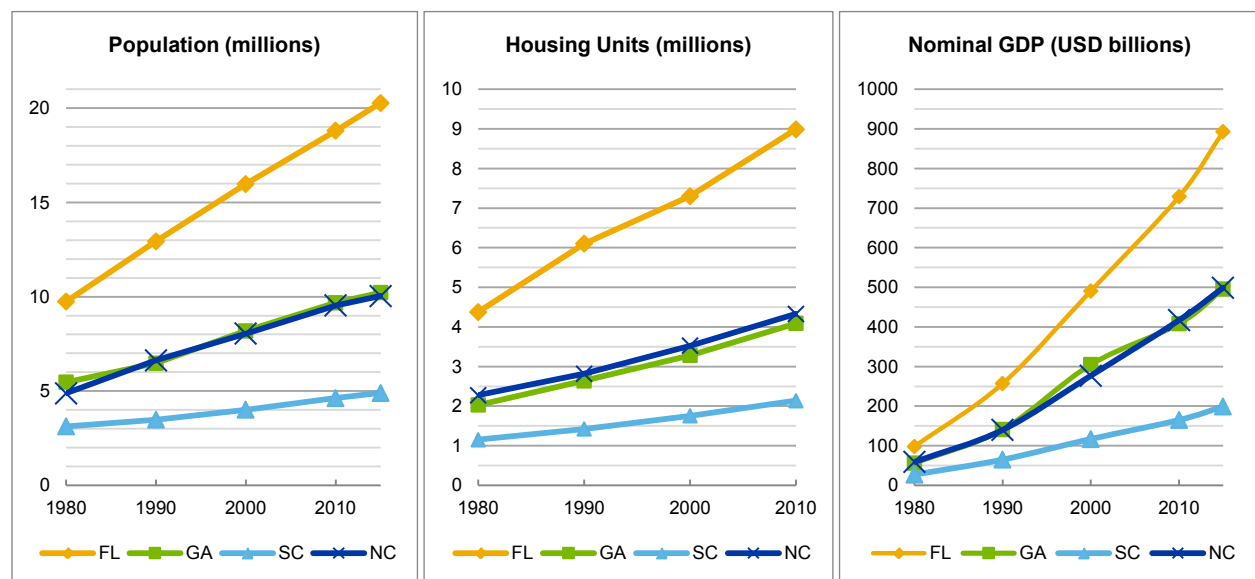
Final Thoughts

Matthew's devastation in the Caribbean showed that the island nations are still not well prepared for such catastrophes, although some progress is visible in some countries, such as Dominica, the Dominican Republic and the Bahamas. The Caribbean risk insurance facility and other insurance projects are very important for small, vulnerable countries' governments, but overall market penetration remains very low. The international community also recognizes its role in helping developing countries, which was the case with such devastating events like David and Matthew.

Significant population increase and business growth along the coastal US will only further increase total exposure and vulnerabilities in the years to come. Because of this, there will be an increasing need – and demand – for more accurate and earlier forecasting. As more people live in these high-risk areas, it will be imperative to improve awareness and communication channels given that early warnings can save lives. Evacuation plans must be well prepared and followed.

In addition, every hurricane is unique. Even a small change in the storm's track can result in a significant change of the amount of damage incurred. David's and Matthew's tracks were very close while paralleling Florida: David sustained its winds at about 100 mph as it rode along the Florida coast while Matthew remained a bit farther offshore but its winds were at least 20 mph higher at the same latitude at all times. However, total damage sustained in Florida during Matthew's passage was about 20 times higher than damage incurred by David in 1979.

Impact Forecasting: Modeled US Results

Storm Surge

The importance of coastal and inland flood driving a larger portion of loss than wind from Matthew highlights the need to be able to effectively model storm surge – both for post-loss risk assessment, and as part of a pre-loss stochastic evaluation of portfolio risk. In order to do this, Impact Forecasting has implemented the SLOSH methodology into its stochastic modeling platform, ELEMENTS.

What is SLOSH?

According to the National Hurricane Center, the **S**ea, **L**ake and **O**verland **S**urges from **H**urricanes (SLOSH) model is a computerized numerical model developed by the National Weather Service (NWS) to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account atmospheric pressure, size, forward speed, and track data. These parameters are used to create a model of the wind field which drives the storm surge. The SLOSH model consists of a set of physics equations which are applied to a specific locale's shoreline, incorporating unique bay and river configurations, water depths, bridges, roads, levees, and other physical features.

Impact Forecasting Storm Tide Heights Using SLOSH

The table below indicates that the Impact Forecasting implementation of SLOSH for Matthew showed varying levels of performance with actual observed storm tide inundation above mean sea level values (using NOAA's NAVD datum), with the average absolute difference around 18 percent. The averages were solely based on the seven selected storm tide heights at coastal locations which sustained the most significant losses. This in turn translated into a more accurate assessment of the losses. For reference, the overall accuracy of the Impact Forecasting implementation of SLOSH for all hurricanes is about 15%.

Gauge Location	State	Storm Tide Actual (feet)	IF Modeled Results (feet)	% Difference
Mayport	Florida	5.2	6.1	+17%
Fernandina Beach	Florida	7.0	7.5	+7%
Fort Pulaski	Georgia	8.5	8.3	-2%
Charleston	South Carolina	6.2	9.2	+48%
Myrtle Beach	South Carolina	5.2	8.2	+58%
Wrightsville Beach	North Carolina	4.4	5.4	+23%
Beaufort	North Carolina	3.6	2.5	-31%
Average of Selected Locations		**5.7**	**6.7**	**+18%**

Observed and modeled storm tide heights from selected locations (Source: NOAA; USGS; Impact Forecasting)

Impact Forecasting has a suite of catastrophe models that analyze the financial implications of catastrophic events so that our clients achieve a greater understanding of their risks. To estimate the insured losses for Hurricane Matthew, presented in the next section of this report, Impact Forecasting used this implementation of SLOSH, as well as its hurricane wind model and riverine and pluvial inland flood model, through its in-house ELEMENTS software platform.

The following two maps show predicted inundation along the Florida, Georgia, South Carolina and North Carolina coastlines. The estimates are based on actual parameters from Matthew, including official height data as measured by the National Oceanic and Atmospheric Administration (NOAA) and the USGS.

Modeled inundation footprint (Source: Impact Forecasting)
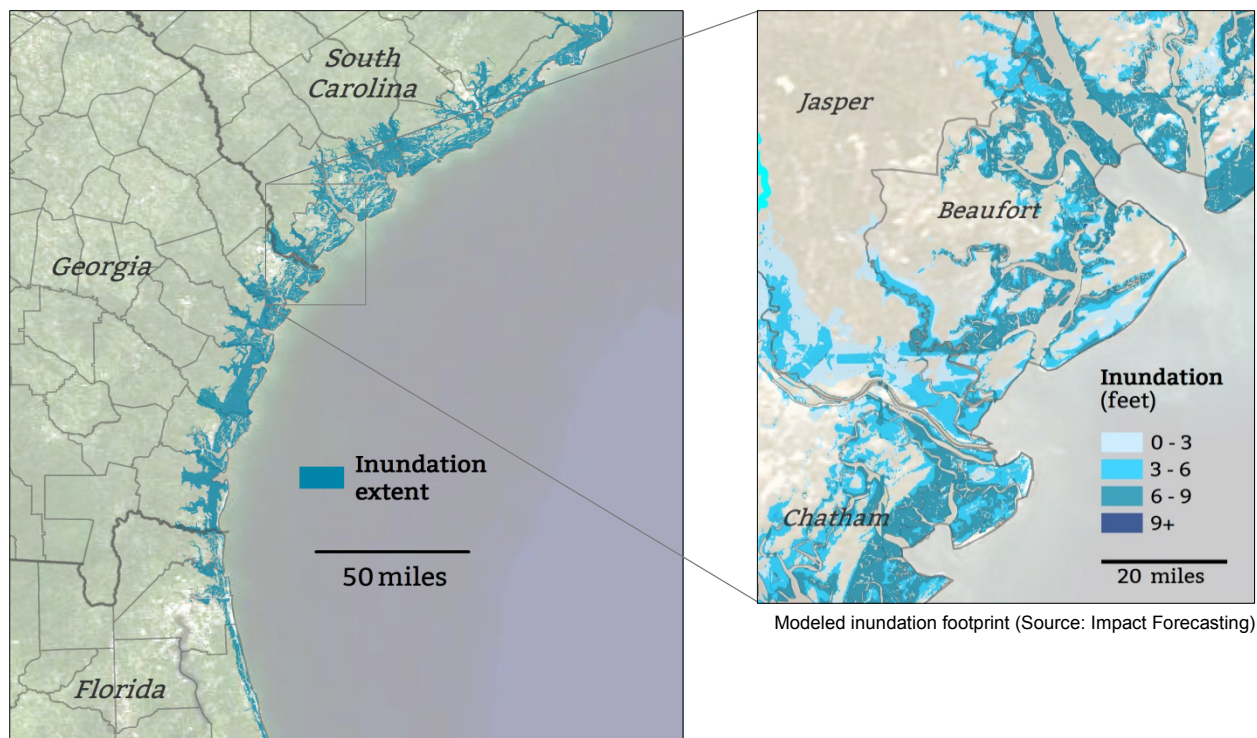
A representation of the full Impact Forecasting's inundation footprint can be found in Appendix D. As a reminder, data used for storm tide is water height above the North American Vertical Datum of 1988 (NAVD88). Note that this is different from inundation, which is the measured water height above ground level after high tide that occurs as a result of the storm tide. To see a full glossary of tropical cyclone-related terms see Appendix E.

Wind

The full track of Hurricane Matthew was reconstructed using the preliminary best-track data from the National Hurricane Center's Automated Tropical Cyclone Forecasting system (ATCF). The ATCF, developed by the US Naval Research Laboratory, is a computer based application designed to automate and optimize the forecasting process of tropical cyclones. The NHC and the Joint Typhoon Warning Center (JTWC), among other institutes, are the operational users of the ATCF.

The parameters utilized in the reconstruction included the position of hurricane eye (latitude and longitude), minimum central pressure, forward speed, heading angle, and radius of maximum winds that were reported in 6-hour increments. These hurricane parameters were imported into the wind field and the storm surge models to calculate wind speeds and surge heights. These wind speeds and surge heights were next used in Impact Forecasting's ELEMENTS software program to estimate the potential economic losses caused by the hurricane.

Modeled wind footprint (Source: Impact Forecasting)
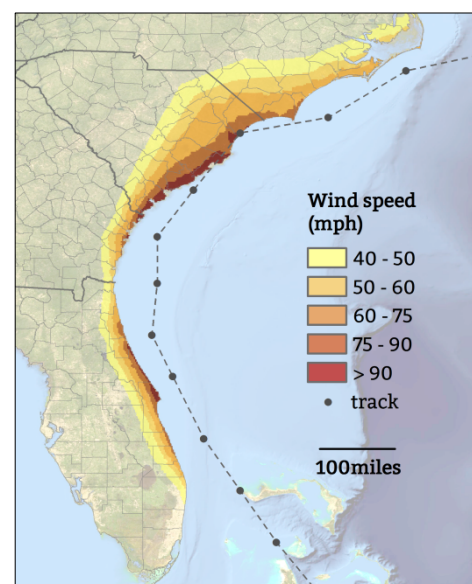
The Impact Forecasting wind field model is a spectral-based parametric model that solves equations of motion by using the finite difference method. The wind field model has been calibrated, both spatially and temporally, to the surface winds. The wind speed footprint, as modeled by Impact Forecasting, for Hurricane Matthew is presented on the previous page. This footprint has general agreements with the wind speed swath from the NHC and other models such as H*Wind; which is a product from NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML).

Inland Flood (Riverine & Flash Flood)

Given the substantial rainfall associated with the outer bands of Matthew, Impact Forecasting additionally ran its inland flood model. The inland flood results show areas impacted by both pluvial (flash flood) and fluvial (riverine) flooding and was constructed using Impact Forecasting's 1D riverine and 2D hydrodynamic rainfall-runoff model. In order to run the model, real-time stream gauge discharge observations were collected for the impacted regions from October 4-12, 2016. Due to a number of stream gauges failing during the peak of the event, corrections were made in order to include them in the calibration process.

Some areas recorded rainfall rates with an estimated return period ranging as high as 1-in-1,000 years. (This means that there was a 0.1 percent chance that the recorded rainfall would occur at any given location in any year.) Given the rainfall rates, Impact Forecasting used pre-calculated return period flash flood events to cover the Matthew rainfall extent. The final inland flood extents are shown below.
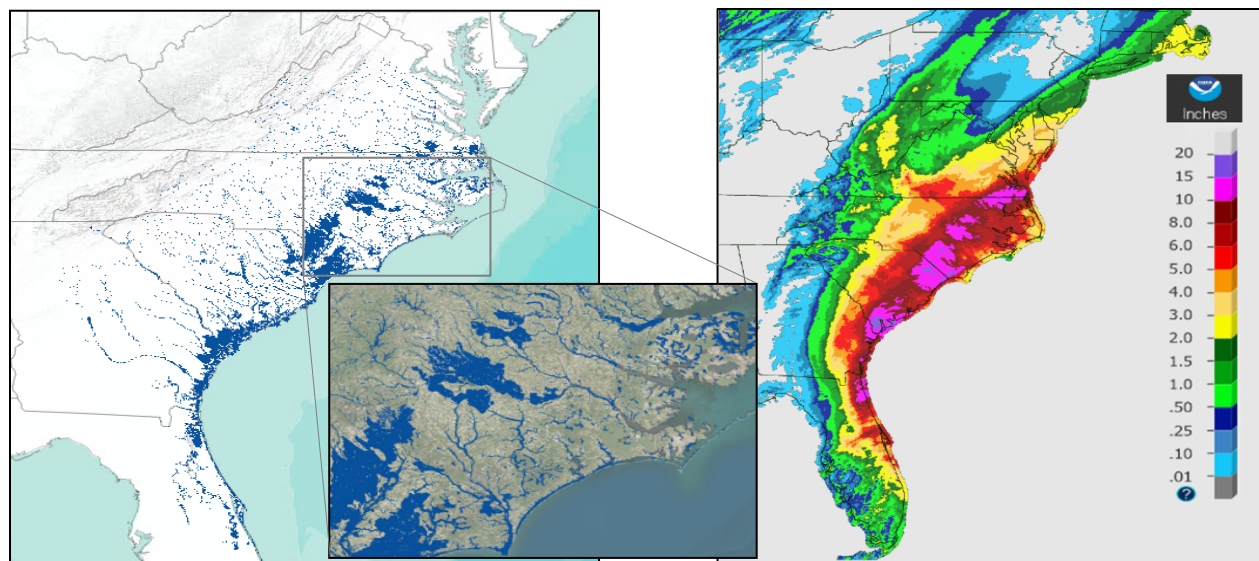
Modeled inland flood results (Source: Impact Forecasting)

7-Day Rainfall Ending Oct. 11, 2016 (Source: NOAA)

## Impact Forecasting Modeled Loss Results

Based on the modeled results of Impact Forecasting's wind, storm surge, and inland flood models from its initial near real-time runs in October 2016, it was determined that economic losses resulting from Hurricane Matthew in the United States would range between USD10 and 16 billion. The specific breakout is as follows:

Wind: USD2.0 to 4.0 billion
Storm Surge: USD4.0 to 6.0 billion
Inland Flood: USD4.0 to 6.0 billion

Financial Impact

Hurricane Matthew is expected to have an overall economic impact approaching USD15 billion. This includes physical damage to residential and commercial properties, vehicles, infrastructure, agriculture, and others. It also assumes direct business interruption losses. A majority of the economic losses were incurred in the United States (roughly estimated around USD10 billion). Other damage totals included Haiti (USD2.8 billion), the Bahamas (USD600 million to USD1.0 billion), Canada (USD150 million), and Cuba (minimally estimated at USD100 million; likely much higher, with unconfirmed media reports suggesting USD billions). Other economies in some of the small Caribbean Islands – such as St. Lucia and St. Vincent & the Grenadines – cited costly impacts to local crops (such as bananas) and tourism.

Source: Aon Benfield
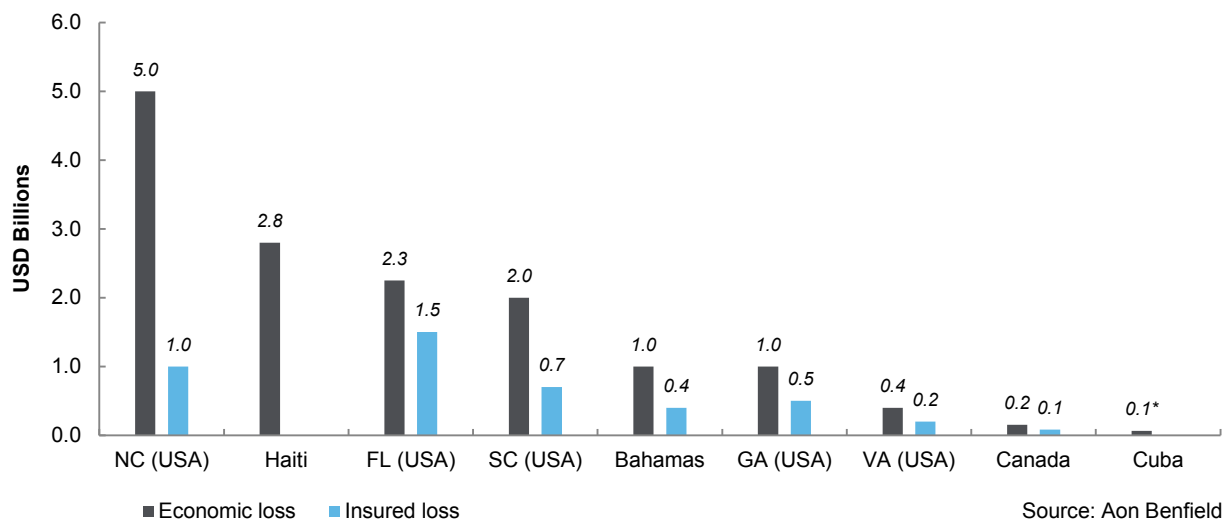
Insurance losses resulting from Matthew were significantly less than the overall economic cost. At roughly USD4.5 billion, this meant that only 30 percent of the financial cost was covered by public and private insurers. Most of the insured losses – approximately USD4.0 billion – occurred in the United States. This meant that about 60 percent of the overall loss total went uninsured; a higher than normal percentage for tropical cyclone events. This was almost entirely due to most of the damage resulting from coastal storm surge or inland riverine flood, as opposed to wind. In the state of North Carolina, the most prolific flood damage occurred well inland where the vast majority of residents did not own National Flood Insurance Program (NFIP) policies.

CCRIF Payouts per Policy
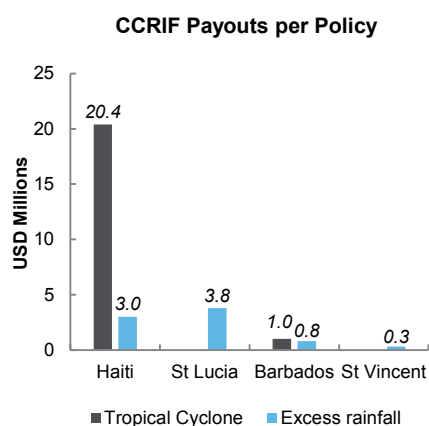
Outside of the United States, the most significant insurance losses were recorded in the Bahamas. At a minimum of USD400 million, this was the costliest event for the Bahamian insurance industry. In Canada, insurers noted payouts exceeding USD80 million.

The governments of several Caribbean nations participate in a parametric insurance scheme brokered by Caribbean Catastrophe Risk Insurance Facility (CCRIF), which is intended to help them deal with immediate needs in the aftermath of disasters. Through this scheme, four Caribbean nations received payouts totaling USD29.2 million due to damage from Matthew.

Appendix A
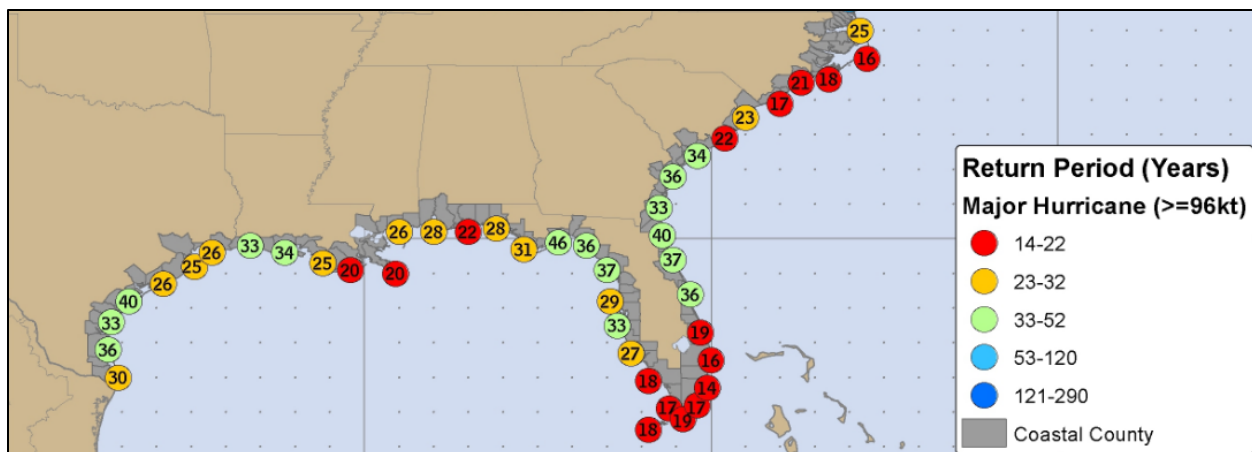
United States Hurricane Landfall Return Periods

Below are maps from the National Hurricane Center (NHC) that provide tropical cyclone return periods for areas along the United States coastline located south of the North Carolina border.

The first map shows regions at greatest risk of hurricanes tracking within 50 nautical miles (57 miles (93 kilometers)) of a particular location along the coastline. Historical data shows that the southern tip of Florida, Louisiana, and the outer banks of North Carolina are areas that typically record a hurricane every five to seven years. Matthew's official landfall came in rural coastal South Carolina, which has a return period for such an event every 8 or 9 years.
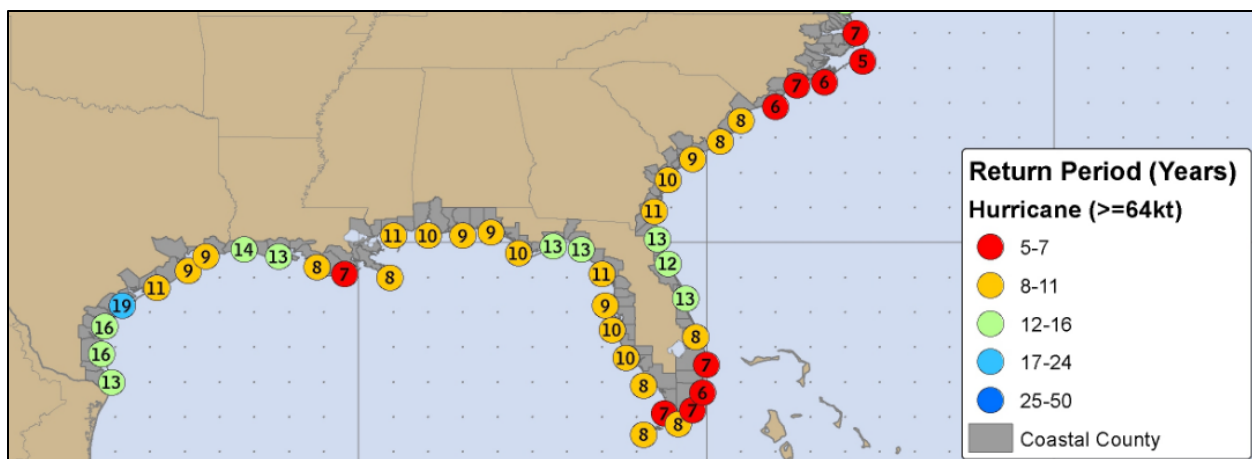
Hurricane landfall return period (Source: NHC)

The second map shows regions at greatest risk of major hurricanes within 50 nautical miles (57 miles (93 kilometers)) of a particular location along the coastline. Historical data shows, unsurprisingly, that there are longer return periods for stronger storms. Areas with greatest historical frequency include south Florida, the Florida panhandle, Louisiana, South Carolina, and North Carolina. Had Matthew not slightly wobbled to the east and north while tracking through the Caribbean, it is entirely possible that the storm may have neared the Florida coast at major hurricane intensity. It would have been the first such event in Florida and the United States since Hurricane Wilma in 2005.

Major hurricane landfall return period (Source: NHC)

In terms of tropical cyclone development, the official Atlantic Hurricane season runs from June 1 to November 30 – though tropical cyclones have been known to develop during any month. As seen in the graphics below, the most likely months for cyclogenesis are during the peak months of August, September, and October. During these months, atmospheric and oceanic conditions are climatologically the most conducive for cyclones being influenced and/or steered by a strong Atlantic ridge of high pressure and/or by the advancement of strong troughs that dig into the central and eastern United States.
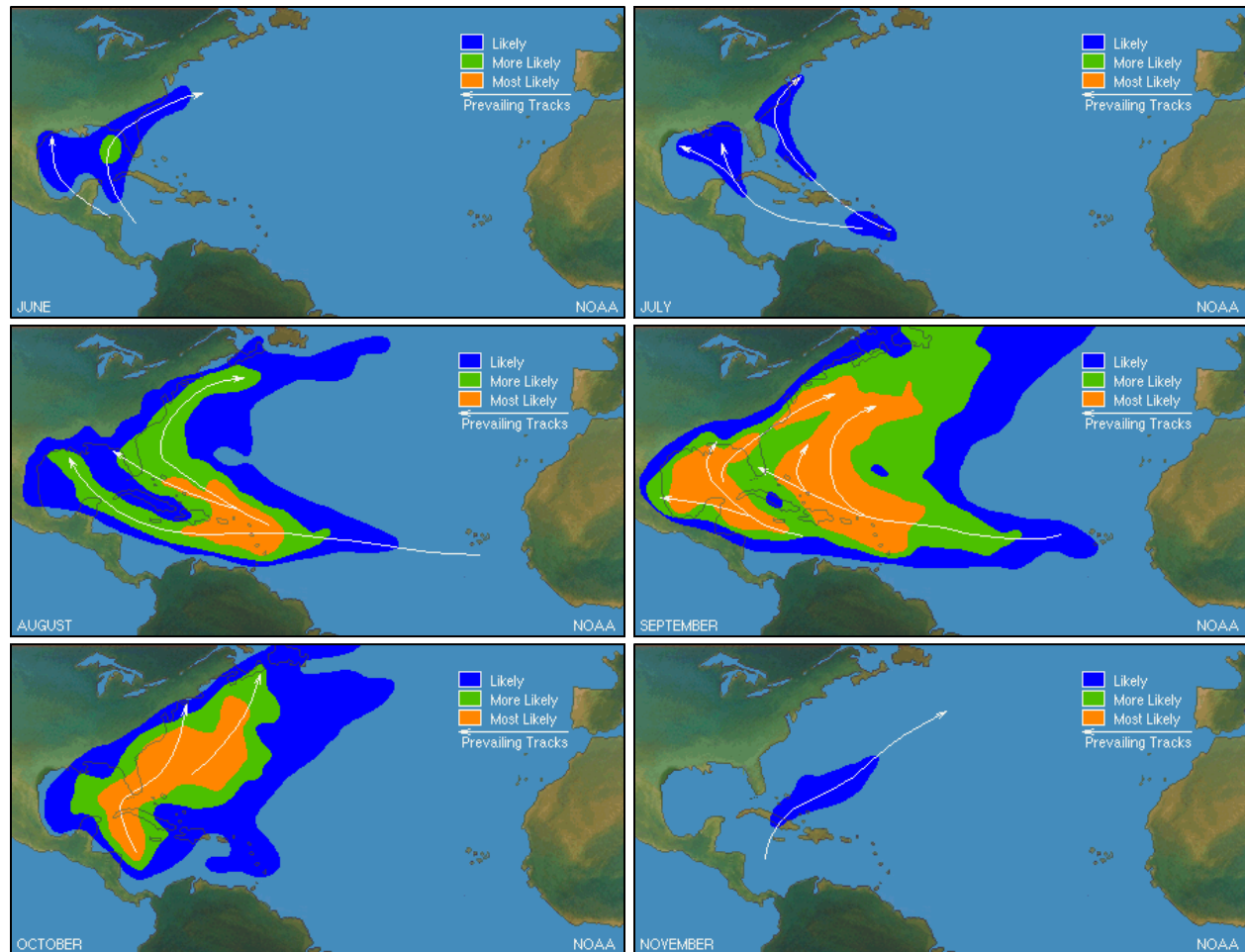
The caveat to cyclogenesis is, of course, the eventual track of storms that do develop. While greater frequency of storms increases the chance of US landfall, the reality is that it only takes one landfalling storm to entirely change the perception of how active a season is to the general public – regardless of how many storms actually make landfall in a single season.

Appendix B

Costliest Atlantic Basin and United States Hurricanes

Atlantic Basin

Rank	Storm Name	Affected Locations	Economic Loss[1] (2017 USD)	Insured Loss[2] (2017 USD)
1	HU Katrina (2005)	Gulf Coast, Southeast	153 billion	82 billion
2	HU Sandy (2012)	US, Caribbean, Hispaniola, Bahamas	74 billion	31 billion
3	HU Andrew (1992)	US, Bahamas	46 billion	27 billion
4	HU Ike (2008)	US, Jamaica, Hispaniola, Cuba	41 billion	17 billion
5	HU Wilma (2005)	US, Jamaica, Haiti, Mexico, Cuba	33 billion	15 billion
6	HU Ivan (2004)	US, Hispaniola, Caribbean, Bahamas	30 billion	13 billion
7	HU Rita (2005)	US, Caribbean	23 billion	7.4 billion
8	HU Charley (2004)	US, Caribbean, Cayman Islands	22 billion	9.5 billion
9	HU Hugo (1989)	US, Caribbean	18 billion	10 billion
10	HU Matthew (2016)	US, Caribbean	15 billion	4.5 billion

United States

Rank	Storm Name	Affected Locations	Economic Loss[1] (2017 USD)	Insured Loss[2] (2017 USD)
1	HU Katrina (2005)	Gulf Coast, Southeast	153 billion	82 billion
2	HU Sandy (2012)	Northeast, Mid-Atlantic, Ohio Valley, Midwest	71 billion	31 billion
3	HU Andrew (1992)	US, Bahamas	46 billion	27 billion
4	HU Ike (2008)	Texas, Midwest, Northeast	33 billion	17 billion
5	HU Ivan (2004)	Southeast, Mid-Atlantic, Northeast	26 billion	11 billion
6	HU Wilma (2005)	Florida	23 billion	13 billion
7	HU Rita (2005)	Southeast, Plains	22 billion	7.4 billion
8	HU Charley (2004)	Southeast	21 billion	9.5 billion
9	HU Hugo (1989)	US, Caribbean	18 billion	10 billion
10	HU Irene (2011)	Mid-Atlantic, Northeast	14 billion	5.9 billion

[1] Economic losses included those sustained to residential and commercial properties, automobiles, infrastructure, electrical grids, public buildings, business interruption, etc.

[2] Insured losses include those sustained by private industry and government entities such as the US National Flood Insurance Program.

Appendix C

United States Emergency Declarations

Florida

Emergency Declaration made on 10/05/2016.

Counties: Baker, Brevard, Broward, Citrus, Clay, Duval, Flagler, Glades, Hendry, Hernando, Highlands, Indian River, Lake, Marion, Martin, Miami-Dade, Monroe, Nassau, Okeechobee, Orange, Osceola, Palm Beach, Putnam, Polk, Seminole, St. Johns, St. Lucie, and Volusia.

Georgia

Emergency Declaration made on 10/07/2016.

Counties: Appling, Atkinson, Bacon, Brantley, Bryan, Bulloch, Burke, Camden, Candler, Charlton, Chatham, Clinch, Coffee, Echols, Effingham, Emanuel, Evans, Glynn, Jeff Davis, Jenkins, Liberty, Long, McIntosh, Pierce, Screven, Tattnall, Toombs, Treutlen, Ware, and Wayne.

South Carolina

Emergency Declaration made on 10/07/2016.

Counties: Abbeville, Aiken, Allendale, Anderson, Bamberg, Barnwell, Beaufort, Berkeley, Calhoun, Charleston, Cherokee, Chester, Chesterfield, Clarendon, Colleton, Darlington, Dillon, Dorchester, Edgefield, Fairfield, Florence, Georgetown, Greenville, Greenwood, Hampton, Horry, Jasper, Kershaw, Lancaster, Laurens, Lee, Lexington, Marion, Marlboro, McCormick, Newberry, Oconee, Orangeburg, Pickens, Richland, Saluda, Spartanburg, Sumter, Union, Williamsburg, and York.

North Carolina

Emergency Declaration made on 10/07/2016.

Counties: Alamance, Anson, Beaufort, Bertie, Bladen, Brunswick, Camden, Carteret, Caswell, Chatham, Chowan, Columbus, Craven, Cumberland, Currituck, Dare, Davidson, Davie, Duplin, Durham, Edgecombe, Franklin, Forsyth, Gates, Granville, Greene, Guilford, Halifax, Harnett, Hertford, Hoke, Hyde, Johnston, Jones, Lee, Lenoir, Martin, Montgomery, Moore, Nash, New Hanover, Northampton, Onslow, Orange, Pamlico, Pender, Perquimans, Person, Pitt, Randolph, Richmond, Robeson, Rockingham, Sampson, Scotland, Stokes, Surry, Tyrell, Vance, Wake, Warren, Washington, Wayne, Wilson, and Yadkin.

United States Major Disaster Declarations

Florida

Major Disaster Declaration made on 10/08/2016.

Counties: Bradford, Brevard, Broward, Clay, Duval, Flagler, Indian River, Lake, Martin, Nassau, Orange, Osceola, Palm Beach, Putnam, Seminole, St. Johns, St. Lucie, and Volusia.

Georgia

Major Disaster Declaration made on 10/08/2016.

Counties: Brantley, Bryan, Bulloch, Camden, Candler, Chatham, Effingham, Emanuel, Evans, Glynn, Jenkins, Liberty, Long, McIntosh, Pierce, Screven, Tattnall, Toombs, Ware, and Wayne.

South Carolina

Major Disaster Declaration made on 10/11/2016.

Counties: Allendale, Bamberg, Barnwell, Beaufort, Berkeley, Calhoun, Charleston, Chesterfield, Clarendon, Colleton, Darlington, Dillon, Dorchester, Florence, Georgetown, Hampton, Horry, Jasper, Kershaw, Lee, Marion, Marlboro, Orangeburg, Richland, Sumter, and Williamsburg.

Source: FEMA, NASA

North Carolina

Major Disaster Declaration made on 10/10/2016.

Counties: Anson, Beaufort, Bertie, Bladen, Brunswick, Camden, Carteret, Chatham, Chowan, Columbus, Craven, Cumberland, Currituck, Dare, Duplin, Edgecombe, Franklin, Gates, Greene, Halifax, Harnett, Hertford, Hoke, Hyde, Johnston, Jones, Lee, Lenoir, Martin, Montgomery, Moore, Nash, New Hanover, Northampton, Onslow, Pamlico, Pender, Perquimans, Pitt, Richmond, Robeson, Sampson, Scotland, Tyrell, Wake, Warren, Washington, Wayne, and Wilson.

Virginia

Major Disaster Declaration made on 11/02/2016.
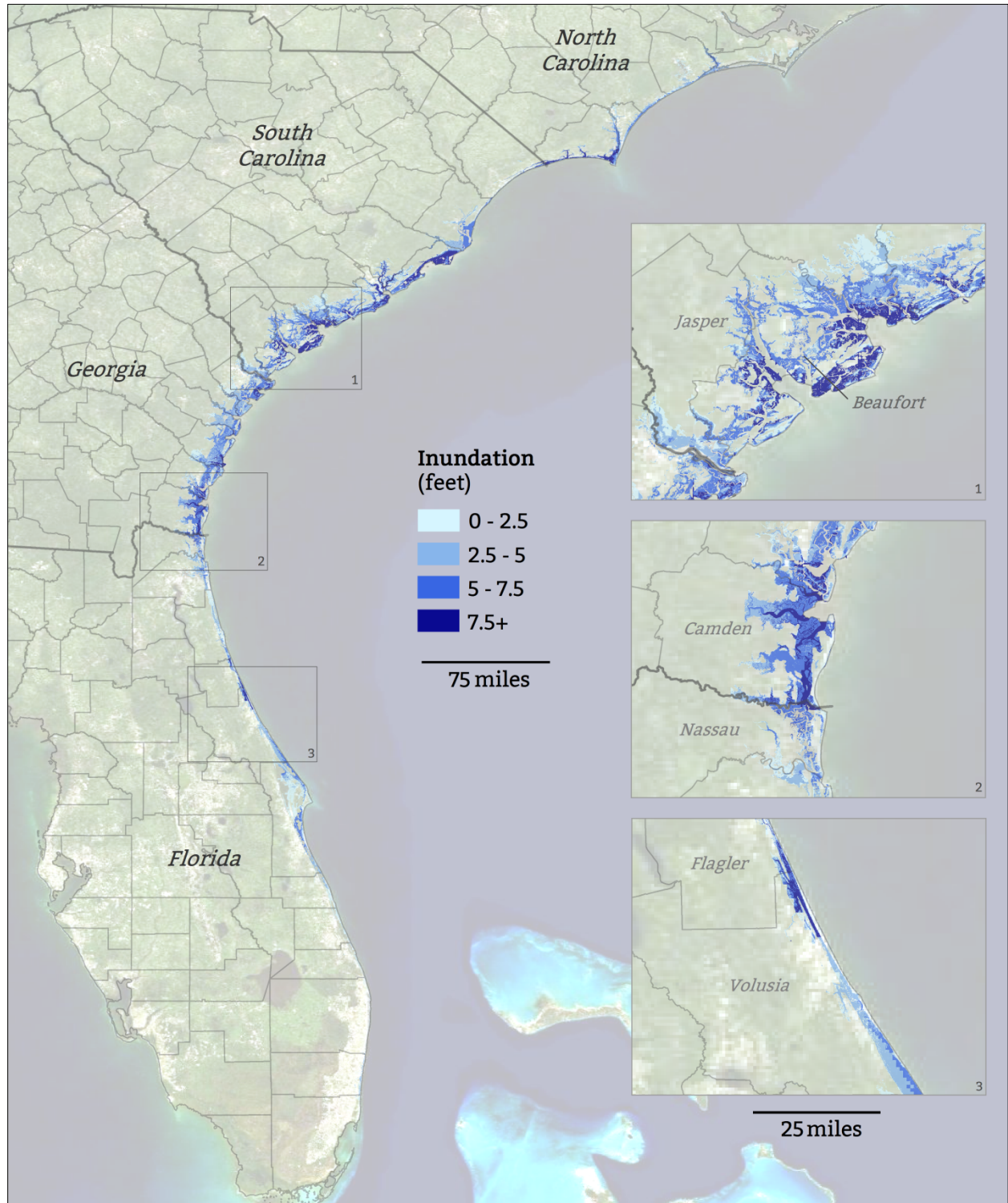
Counties: Chesapeake, Isle of Wight, Newport News, Norfolk, Southampton, Suffolk, and Virginia Beach.
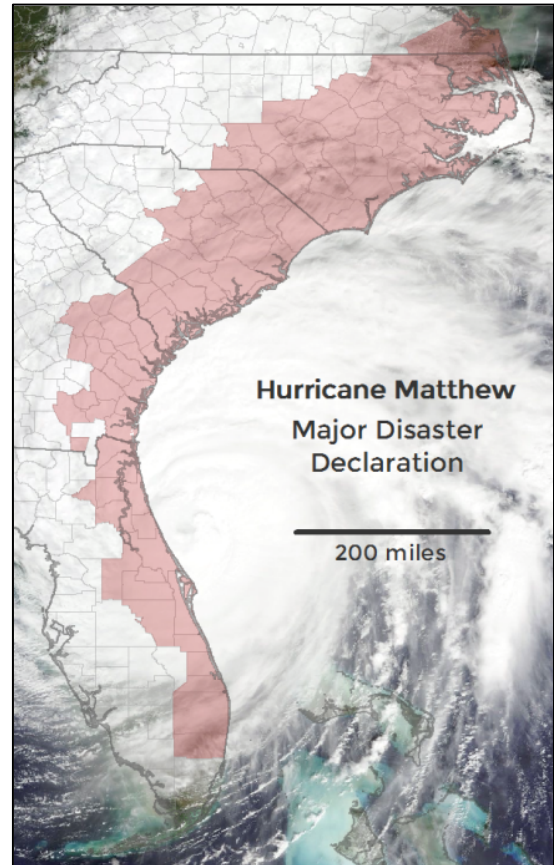
Appendix D

Impact Forecasting Modelled Inundation Footprint

Appendix E

Glossary: Terms as defined by the National Hurricane Center

Advisory:

Official information issued by tropical cyclone warning centers describing all tropical cyclone watches and warnings in effect along with details concerning tropical cyclone locations, intensity and movement, and precautions that should be taken.

Best Track:

A subjectively-smoothed representation of a tropical cyclone's location and intensity over its lifetime. The best track contains the cyclone's latitude, longitude, maximum sustained surface winds, and minimum sea-level pressure at 6-hourly intervals. Best track positions and intensities, which are based on a post-storm assessment of all available data, may differ from values contained in storm advisories.

Direct Hit:

A close approach of a tropical cyclone to a particular location. For locations on the left-hand side of a tropical cyclone's track, a direct hit occurs when the cyclone passes to within a distance equal to the cyclone's radius of maximum wind. For locations on the right-hand side of the track, a direct hit occurs when the cyclone passes to within a distance equal to twice the radius of maximum wind.

Eye:

The roughly circular area of comparatively light winds that encompasses the center of a severe tropical cyclone. The eye is either completely or partially surrounded by the eyewall cloud.

Eyewall:

An organized band or ring of cumulonimbus clouds that surround the eye, or light-wind center of a tropical cyclone.

Extratropical:

A term used in advisories and tropical summaries to indicate that a cyclone has lost its "tropical" characteristics. The term implies both northward displacement of the cyclone and the conversion of the cyclone's primary energy source from the release of latent heat of condensation to baroclinic (the temperature contrast between warm and cold air masses) processes. Cyclones can become extratropical and still retain winds of hurricane or tropical storm force.

Extratropical Cyclone:

A cyclone of any intensity for which the primary energy source is baroclinic, that is, results from the temperature contrast between warm and cold air masses.

Gale Warning:

A warning of 1-minute sustained surface winds in the range 34 knots (39 mph (63 kph)) to 47 knots (54 mph (87 kph)) inclusive, either predicted or occurring and not directly associated with tropical cyclones.

High Wind Warning:

A high wind warning is defined as 1-minute average surface winds of 35 knots (40 mph (64 kph)) or greater lasting for 1 hour or longer, or winds gusting to 50 knots (58 mph (93 kph)) or greater regardless of duration that are either expected or observed over land.

Hurricane:

A tropical cyclone in which the maximum sustained surface wind (using the US 1-minute average) is 64 knots (74 mph (119 kph) or more.

Hurricane Warning:

An announcement that hurricane conditions (sustained winds of 74 mph (119 kph) or higher) are *expected* somewhere within the specified area of a tropical, subtropical or post-tropical cyclone. The warning can remain in effect when high water or a combination of high water and waves continue, even though winds may be less than hurricane-force.

Hurricane Watch:

An announcement that hurricane conditions (sustained winds of 74 mph (119 kph) or higher) are *possible* within the specified area of a tropical, subtropical or post-tropical cyclone.

Indirect Hit:

Generally refers to locations that do not experience a direct hit from a tropical cyclone, but do experience hurricane force winds (either sustained or gusts) or tides of at least 4.0 feet above normal.

Inundation:

The total water level that occurs on normally dry ground as a result of the storm tide, and is expressed in terms of height above ground level.

Invest:

A weather system for which a tropical cyclone forecast center is interested in collecting specialized data sets and/or running model guidance. The designation of a system as an invest does not correspond to any particular likelihood of development of the system into a tropical cyclone.

Landfall:

The intersection of the surface center of a tropical cyclone with a coastline. Because the strongest winds in a tropical cyclone are not located precisely at the center, it is possible for a cyclone's strongest winds to be experienced over land even if landfall does not occur. Similarly, it is possible for a tropical cyclone to make landfall and have its strongest winds remain over the water.

Major Hurricane:

A hurricane that is classified as Category 3 or higher on the Saffir-Simpson Hurricane Wind Scale.

Post-Tropical Cyclone:

This term describes a cyclone that no longer possesses sufficient tropical characteristics to be considered a tropical cyclone. Post-tropical cyclones can continue carrying heavy rains and high winds. Former tropical cyclones that have become fully extratropical or remnant lows are two classes of post-tropical cyclones.

Radius of Maximum Winds:

The distance from the center of a tropical cyclone to the location of the cyclone's maximum winds. In well-developed hurricanes, the radius of maximum winds is generally found at the inner edge of the eyewall.

Rapid Intensification:

An increase in the maximum sustained winds of a tropical cyclone of at least 30 knots (35 mph (55 kph)) in a 24-hour period.

Remnant Low:

A post-tropical cyclone that no longer possesses the convective organization required of a tropical cyclone, and has maximum sustained winds of less than 34 knots (39 mph (63 kph)).

Storm Surge:

An abnormal rise in sea level accompanying a hurricane or other intense storm, and whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone. Storm surge is usually estimated by subtracting the normal or astronomic high tide from the observed storm tide.

Storm Tide:

The actual level of sea water resulting from the astronomic tide combined with the storm surge.

Storm Warning:

A warning of 1-minute sustained surface winds of 48 knots (55 mph (88 kph)) or greater, predicted or occurring, not directly associated with tropical cyclones.

Subtropical Cyclone:

A non-frontal low-pressure system that has characteristics of both tropical and extratropical cyclones. Like tropical cyclones, they are non-frontal, synoptic-scale cyclones that originate over tropical or subtropical waters, and have a closed surface wind circulation with a well-defined center. Unlike tropical cyclones, subtropical cyclones derive a significant proportion of their energy from baroclinic sources, and are generally cold-core in the upper troposphere, often being associated with an upper-level low or trough. In comparison to tropical cyclones, these systems generally have a radius of maximum winds occurring relatively far from the center and generally have a less symmetric wind field and distribution of convection.

Subtropical Depression:

A subtropical cyclone in which the maximum sustained surface wind speed (using the US 1-minute average) is 33 knots (38 mph (62 kph)) or less.

Subtropical Storm:

A subtropical cyclone in which the maximum sustained surface wind speed (using the US 1-minute average) is 34 knots (39 mph (63 kph)) or more.

Tropical Cyclone:

A warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center. Once formed, a tropical cyclone is maintained by the extraction of heat energy from the ocean at high temperature and heat export at the low temperatures of the upper troposphere.

Tropical Depression:

A tropical cyclone in which the maximum sustained surface wind speed (using the US 1-minute average) is 33 knots (38 mph (62 kph)) or less.

Tropical Disturbance:

A discrete tropical weather system of apparently organized convection originating in the tropics or subtropics, having a non-frontal migratory character, and maintaining its identity for 24 hours or more.

Tropical Storm:

A tropical cyclone in which the maximum sustained surface wind speed (using the US 1-minute average) ranges from 34 knots (39 mph (63 kph)) to 63 knots (73 mph (118 kph)).

Tropical Storm Warning:

An announcement that tropical storm conditions (sustained winds of 39 to 73 mph) are *expected* somewhere within the specified area within 36 hours in association with a tropical, subtropical or post-tropical cyclone.

Tropical Storm Watch:

An announcement that tropical storm conditions (sustained winds of 39 to 73 mph) are *possible* within the specified area within 48 hours in association with a tropical, subtropical or post-tropical cyclone.

Tropical Wave:

A trough or cyclonic curvature maximum in the trade-wind easterlies. The wave may reach maximum amplitude in the lower middle troposphere.

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