2017 North Atlantic Hurricane Season Review

RMS REPORT

Executive Summary

THE 2017 NORTH ATLANTIC HURRICANE SEASON will be remembered as one of the most active, damaging, and costliest seasons on record. The 2017 season saw 17 named storms, with 10 of these storms (Franklin through Ophelia) reaching hurricane strength and occurring consecutively within a hyperactive period between August and October. The season will be remembered for its six major hurricanes and specifically for the impacts of three of these storms: Harvey, Irma, and Maria.

Hurricane Harvey, the first U.S. major hurricane (Category 3 or greater on the Saffir-Simpson Hurricane Wind Scale) to make landfall since Hurricane Wilma in 2005, made landfall near Rockport, Texas, as a Category 4 storm in late August, thus ending the contiguous U.S. major hurricane landfall drought at 4,323 days. Harvey brought record-breaking rainfall to southeast Texas that resulted in widespread catastrophic and unprecedented inland flooding across the Houston metropolitan area, damaging more than 300,000 structures. The RMS best estimate is that the insured loss from Hurricane Harvey will likely be between US$25 and US$35 billion. This estimate represents the insured loss associated with wind, storm surge, and inland flood damage across Texas and Louisiana.

Florida saw its first Category 4 hurricane landfall since 2004 when Hurricane Irma made landfall over the Florida Keys in mid-September. The system later came ashore near Naples, Florida as a Category 3 storm, causing widespread wind damage and flooding across the state. Before impacting Florida, Irma tracked through the Caribbean as a Category 5 hurricane and caused extensive devastation on many islands, ultimately ranking as the strongest hurricane on record to impact the Leeward Islands. RMS estimates that the insured losses from Hurricane Irma will be between US$35 and US$55 billion, representing wind, storm surge, and inland flood loss across Florida and the southeast U.S., as well as insured loss associated with wind and storm surge in the Caribbean.

Following soon after Irma, Hurricane Maria caused catastrophic damage in parts of the Caribbean, including in Dominica, the U.S. Virgin Islands, and most notably in Puerto Rico, where Maria made landfall as a Category 4 major hurricane. Most buildings in San Juan did not sustain significant damage, though buildings with wood roofs and light metal were extensively damaged. Across Puerto Rico, power plants and pharmaceutical facilities sustained only minor damage; however, significant transmission, distribution, and infrastructure failures led to prolonged suspension of these facilities' normal operations. Maria most severely impacted power and telecommunication systems. The RMS best estimate is that the insured loss in the Caribbean associated with wind damage from Hurricane Maria will be between US$15 and US$30 billion, with a vast majority of loss originating from Puerto Rico.

In all, the contiguous U.S. suffered three hurricane landfalls (Harvey, Irma, and Nate) and two tropical storm landfalls (Cindy and Emily). The season marked the first time on record that two Category 4 or greater hurricanes made landfall over the mainland U.S. in a single season.

Looking ahead to the 2018 hurricane season, early forecasts by Tropical Storm Risk (TSR) predict the 2018 season will be slightly above-average, but not at the levels attained during 2017, although forecast skill at this lead time is poor. The scientific community will monitor the state of North Atlantic sea surface temperatures and the phase of the El Nino-Southern Oscillation (ENSO) as key indicators of 2018 hurricane activity.

The information within this report is based on the National Hurricane Center (NHC) preliminary operational data and tropical cyclone reports available as of March 9, 2018. Tropical Cyclone Reports for several storms have yet to be released, and the NHC may adjust storm parameters based on reanalyses.

Overview of the 2017 North Atlantic Hurricane Season

In many respects, the 2017 season was the most active since the record-breaking season of 2005. Seventeen named storms formed in 2017, above the 1950-2016 average[1] (11.6 named storms) and above the 1996-2016 average[2] (14.4). Ten hurricanes formed in 2017, above both the 1950-2016 average (6.2 hurricanes) and 1996-2016 average (7.2). There were six major hurricanes (Category 3 or greater) during the 2017 season, which lies above the average of 1950-2016 (2.5 major hurricanes and 1996-2016 (3.3). The 2017 season was seventh season since 1950 to have at least six major hurricanes.

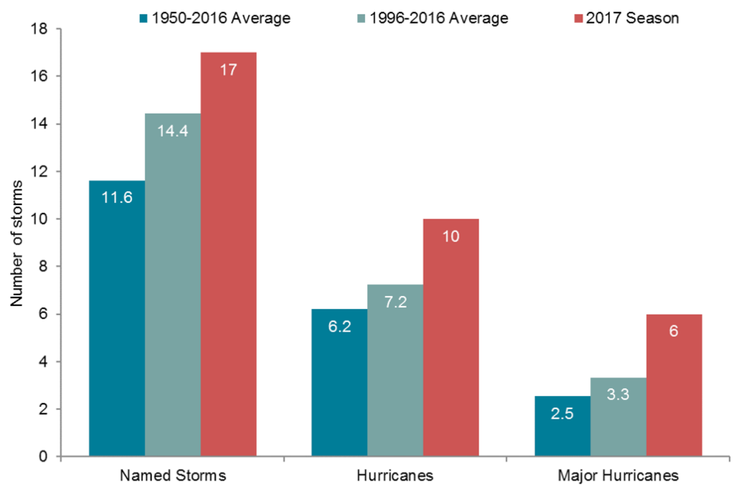

Figure 1: Comparison of the 2017 North Atlantic hurricane season storms to the 1950-2016 and 1996-2016 averages. (Data from the National Oceanic and Atmospheric Administration Hurricane Research Division, 2018).

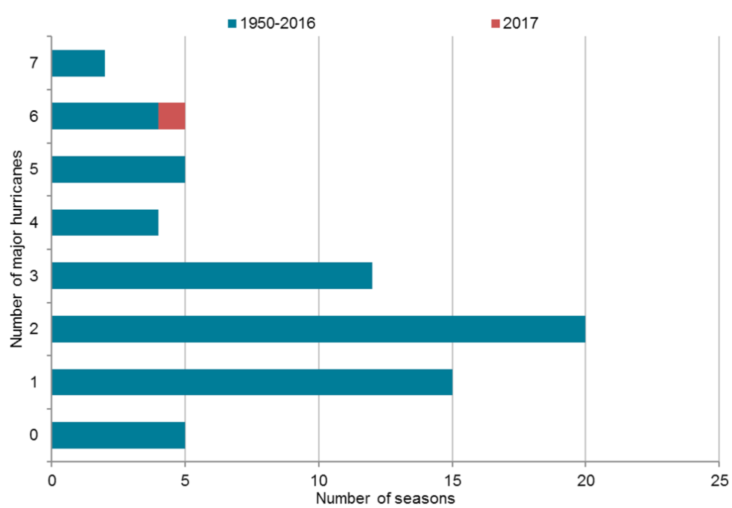

Figure 2: Historical frequency of major hurricanes in a season. (Data from the National Oceanic and Atmospheric Administration Hurricane Research Division, 2018).

[1] The historical database for landfalling hurricanes worldwide is generally agreed to be complete since 1900. However, the record of hurricane activity in the Atlantic Basin itself is generally agreed to be complete only from 1950 onward, following the increases in aircraft reconnaissance and the onset of satellite technology

[2] It is widely recognized that the Atlantic Basin entered a period of elevated activity from 1996, compared to the long-term historical average, driven by a positive phase in the Atlantic Multidecadal Oscillation (AMO)

The Accumulated Cyclone Energy (ACE) index[3] provides an alternative assessment of hurricane activity that is based on intensity and duration. The 2017 ACE index total of 226 was well above both the 1950-2016 (101 ACE) and 1996-2016 (124 ACE) averages. The season's ACE total ranks as the fourth largest since 1950 and is on-par with the active 1995 (228 ACE) and 2004 (227 ACE) seasons. The 2017 season ACE was the largest since 2005. Figure 3 illustrates the historical ACE activity, along with the 2017 season total.

The largest contributors to the season's total ACE were Irma, Jose, and Maria, which combined contributed 68 percent of the overall total. Irma, the season's largest ACE contributor, generated 67.5 ACE units, the second-largest[4] ACE total for a single storm in the Atlantic during the satellite era (since 1966)[5]. Irma alone generated enough ACE to meet NOAA's Atlantic hurricane season definition of a near-normal season[6] (66 ACE). Figure 4 shows ACE values for all storms in the 2017 season.

Atlantic basin cyclones occurring in September produced 155.4 ACE units, surpassing September 2004 to become the most active calendar month in the Atlantic on record. Furthermore, September 8 generated more ACE than any other calendar day in the Atlantic basin on record, contributed by Hurricanes Irma, Jose, and Katia. Figure 5 shows the ACE totals for each month of the 2017 season.

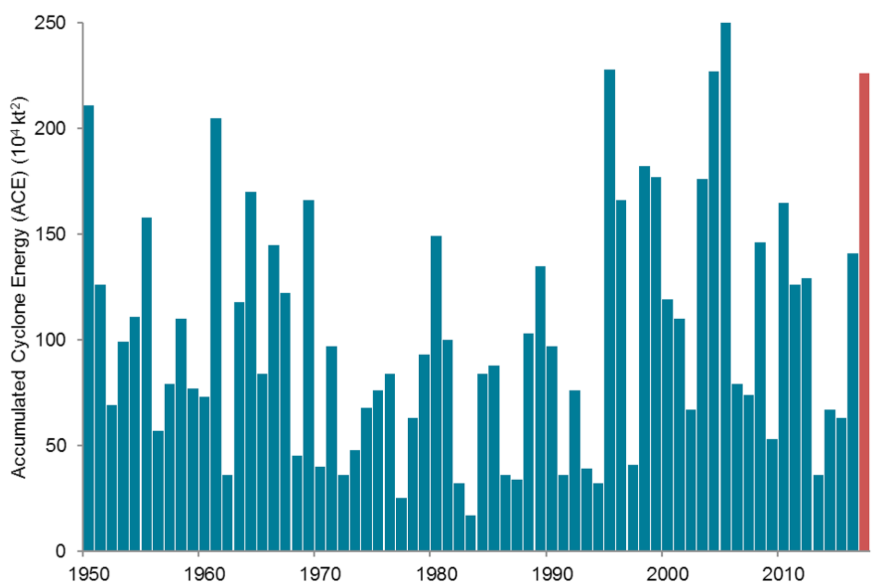

Figure 3: North Atlantic hurricane season Accumulated Cyclone Energy (ACE) (104 kt²) totals 1950-2017. (Data from the National Oceanic and Atmospheric Administration Hurricane Research Division, 2018).

[3] ACE is calculated as the square of the sum of the maximum sustained wind speed (in knots) at 6-hour intervals for the duration of the storm at tropical storm status or greater (sustained wind speeds of 35 knots or higher). The unit of ACE is 10^4 kt^2
[4] Hurricane Ivan (2004) holds the record for the most ACE generated in the Atlantic basin with 70.4
[5] CSU defines the satellite era as 1966 onwards: https://tropical.colostate.edu/media/sites/111/2017/11/2017-11.pdf
[6] NOAA's Atlantic hurricane season classification: http://www.cpc.ncep.noaa.gov/products/outlooks/background_information.shtml

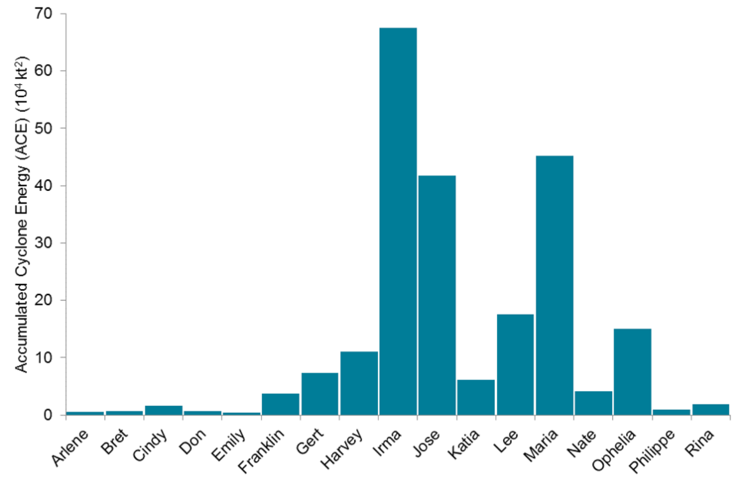

Figure 4: Accumulated Cyclone Energy (ACE) values for storms in the 2017 season. (Data from the National Oceanic and Atmospheric Administration Hurricane Research Division, 2018).

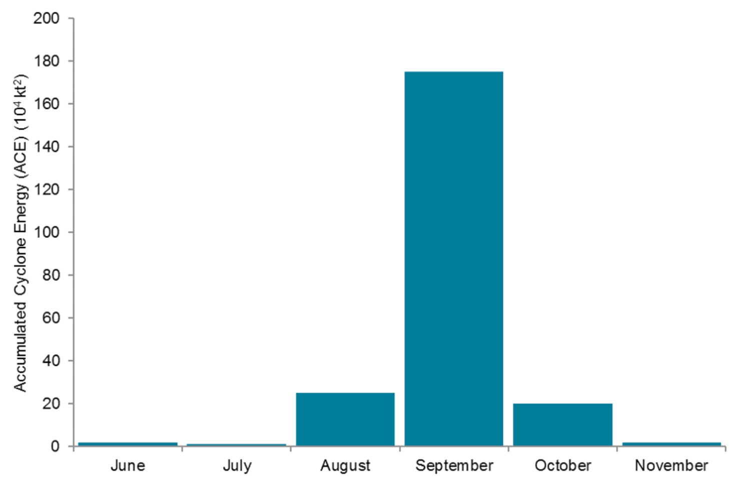

Figure 5: Accumulated Cyclone Energy (ACE) values for June to November 2017. (Data from the National Oceanic and Atmospheric Administration Hurricane Research Division, 2018).

Additionally, seasonal hurricane activity can be measured by the recently developed Track Integrated Kinetic Energy (TIKE) metric[7]. TIKE is calculated by accumulating the integrated kinetic energy[8] of each tropical cyclone's wind field in six-hour intervals throughout a hurricane season. As such, TIKE is influenced by the size and strength of each storm, rather than solely focusing on maximum intensity without consideration for storm structure, as is done when calculating ACE.

Initial estimates based on operationally reported wind radii indicate that the 2017 season accumulated nearly 10,500 Terajoules (TJs) of TIKE. Driven by Hurricanes Jose, Maria, and Irma – long-lived storms with wide, strong wind fields – the 2017 season TIKE total was approximately 25 percent higher than the annual mean calculated from 1990 onward. 2017 marks the second

[7] https://journals.ametsoc.org/doi/abs/10.1175/MWR-D-12-00349.1
[8] https://journals.ametsoc.org/doi/abs/10.1175/BAMS-88-4-513

consecutive season with above average North Atlantic TIKE: the 2016 season posted nearly identical levels of TIKE as 2017, driven in large part by Hurricanes Matthew and Nicole. Prior to that, the notably inactive 2013-15 hurricane seasons generated less combined TIKE than the single TIKE value generated in 2017 alone.

The TIKE generated in 2017 falls short of several notable recent seasons. The active 2004-05 seasons each accumulated more than 12,000 TJs, and the nineteen storms of the 2012 season, which included the historically large Hurricane Sandy, accumulated nearly 15,000 TJs. The 1995 Atlantic hurricane season remains the most active season in terms of TIKE in the last three decades, with more than 20,000 TJs accumulated that year.

The 2017 North Atlantic Storms and Their Impacts

In many respects, the 2017 season was the most active since the record-breaking season of 2005, with 17 named storms, 10 hurricanes, and six major hurricanes. Ten of the 17 named storms made direct landfall in countries and territories across the Atlantic basin, while a further three tracked close enough to impact land.

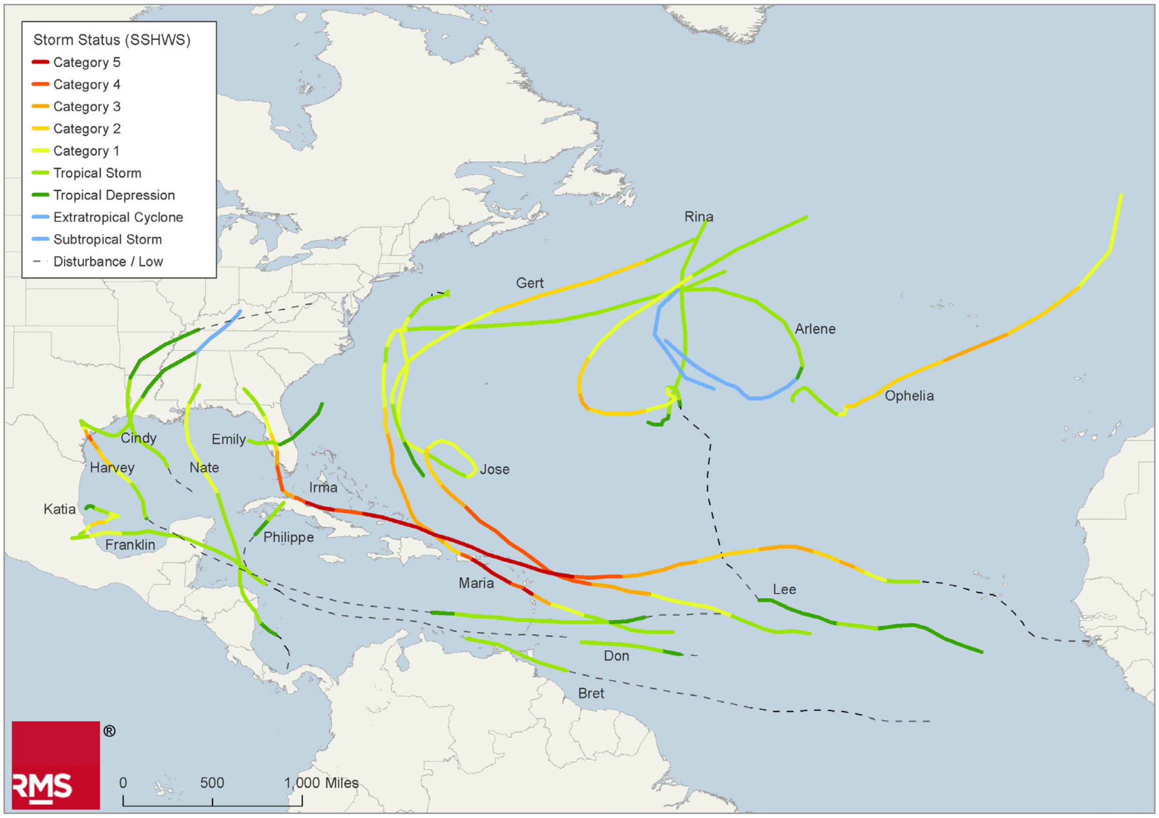

Figure 6: The 2017 North Atlantic storm tracks and intensities. (Data from the National Hurricane Center, 2018)

Six named storms made landfall in the U.S. (mainland and overseas territories), including three major hurricanes (Harvey, Irma, and Maria), one hurricane (Nate), and two tropical storms (Cindy and Emily). All five of the U.S. mainland landfalls occurred from within, or adjacent to, the Gulf of Mexico, with the eastern U.S. coast not experiencing a direct landfall from a tropical cyclone in 2017. Harvey was the first major hurricane to make landfall in the continental U.S. since Wilma in 2005 and ended the country's record-breaking major hurricane landfall drought at 4,323 days. Irma's landfall in Florida in September marked the first time on record that two Category 4 major hurricanes had made landfall in the continental U.S. in a single year.

Two Category 1 hurricanes, Franklin and Katia, made landfall in Veracruz State, Mexico. In the Caribbean, Cuba was impacted by two landfalling systems (Irma and Philippe), while the northeast Windward Islands experienced a record three major hurricanes (Irma, Jose, and Maria). The lower Windward Islands experienced three storms at tropical storm strength (Bret, Don, and Harvey). Ophelia became the easternmost major hurricane in the Atlantic basin on record, and underwent extratropical transition as it impacted Ireland and the United Kingdom in mid-October.

Tropical Storm Arlene

The first named storm of the 2017 season, Tropical Storm Arlene, developed from a subtropical depression in the central Atlantic on April 20, becoming only the second tropical storm on record[9] to form in the month of April, since Ana in 2003. It marked the third consecutive year that a storm has been named before the official start of the hurricane season on June 1.

Arlene meandered over the central Atlantic Ocean for several days under the influence of a larger extratropical low. The system began to lose its tropical characteristics shortly after attaining its peak intensity on April 21. Arlene was short lived and dissipated on April 22.

Tropical Storm Bret

On June 19, a tropical wave gained sufficient organization and a well-defined circulation center to be considered a tropical storm and was named Bret. The system became the earliest named storm to form in the main development region (MDR)[10] on record, surpassing the record of Tropical Storm Ana in 1979, and it became the lowest latitude named storm in the month of June, since 1933.

Bret made landfall over southern Trinidad and Tobago on June 20, bringing tropical storm force winds and prolonged intense rainfall to the island. Hundreds of homes sustained wind damage and were inundated by floodwater up to 4 ft (1.2 m) deep. In Venezuela, heavy rainfall associated with the storm generated several large mudslides, which damaged hundreds of residential buildings. Localized flooding was also reported along coastal areas, with minor wind damage limited to coastal areas in the northeast.

The system encountered strong southerly wind shear over the southeastern Caribbean Sea and degenerated to a tropical wave on June 20.

Tropical Storm Cindy

A broad area of low pressure that had formed over the northwestern Caribbean Sea tracked into the Gulf of Mexico in mid-June and developed into Cindy, the third named storm of the season on June 20. Despite encountering strong wind shear and an abundance of dry air, the system strengthened and attained a peak intensity of 58 mph (93 km/hr) on June 21.

Cindy tracked northeast across the Gulf of Mexico but weakened as it approached the northern Gulf of Mexico coastline as its deepest convection, which was displaced to the far northeast of the low-level center, moved inland. The low-level circulation center of Cindy made landfall near the Texas-Louisiana state border on June 22.

The system's impacts extended several hundred miles to the east of the landfall location. Rain bands associated with Cindy remained over the same areas for several days, leading to widespread rainfall accumulations of 7 to 10 inches (178-254 mm), with an isolated maximum of 18.7 inches (474 mm) recorded at Ocean Springs, Mississippi. The persistent heavy rain led to minor flooding along several rivers including the Biloxi River in Mississippi.

[9] Storms like Arlene would have been difficult to detect prior to the satellite era (since 1966)
[10] The main development region (MDR) spans the tropical Atlantic Ocean and the Caribbean Sea between 10°N–20°N, 20°W–80°W

A storm surge of up to 6 feet (1.8 meters) above normal tide levels was observed at Shell Beach, Louisiana. A surge of 4 feet (1.2 meters) was widely observed along the Louisiana-Mississippi coastline. Some coastal areas of Louisiana and Mississippi experienced tidal flooding.

Cindy's broader circulation interacted with a cold front and produced several tornadic outbreaks from Florida to Pennsylvania, including a damaging EF-1 tornado in Fairfield, Alabama.

The remnants of Cindy brought strong winds and flash flooding to parts northern U.S., causing power outages and damaging several properties.

The combined presence of Tropical Storms Bret and Cindy in the Atlantic on June 20 marked the first time in 49 years, and only the third time on record, that two named storms co-existed in the Atlantic prior to July 1.

Tropical Storm Don

A tropical wave that tracked across the central tropical Atlantic in early July developed into Tropical Storm Don on July 17, approximately 630 miles (1,000 km) east-southeast of Barbados. The system gradually strengthened, reaching a peak intensity of 52 mph (83 km/hr) on July 18. Don battled dry air aloft and increasing westerly wind shear as it approached the southern Windward Islands and weakened back into a tropical wave before progressing into the eastern Caribbean Sea. Don brought heavy showers and thunderstorms to the southern Windward Islands, which led to localized flash flooding in Port of Spain, Trinidad and Tobago. The system dissipated on July 18.

Tropical Storm Emily

On July 30, showers began organizing within a small area of low pressure embedded within a dissipating stationary cold front that extended from mainland U.S. into the northern Gulf of Mexico.

The system rapidly developed and was designated as a tropical storm during the morning of July 31, located approximately 75 miles (120 km) west of Tampa, Florida. The system quickly tracked east and made landfall as a weak tropical storm over Anna Maria Island, west of Bradenton, Florida, with maximum sustained wind speeds of around 45 mph (72 km/hr). The system had formed, intensified into a tropical storm, and made landfall within approximately five hours.

Emily brought tropical storm force wind gusts to the Collier County, Florida coastline, causing some minor damage to several homes. The system triggered several rounds of thunderstorms across Miami-Dade County, with rainfall intensities of up to 7 in/hr (177 mm/hr). The intense rainfall coincided with high tide and localized power outages which overwhelmed the flood pumps and led to significant flooding in Miami Beach and within the city of Miami. Some downtown areas experienced floodwaters of up to 2 feet (0.6 meters), which inundated dozens of properties. Emily also spawned an EF-0 tornado, with estimated maximum winds of 80 mph (129 km/hr), which damaged several homes near Bradenton. A state of emergency was declared in 31 counties in central and southern Florida.

The system degenerated as is tracked across Florida into the western Atlantic. It later accelerated northeast and became embedded within an existing frontal zone on August 2.

Hurricane Franklin

A broad area of low pressure over the northwestern Caribbean Sea developed into the sixth named tropical storm of the season on August 7. Despite high wind shear, Franklin intensified to a moderate-strength tropical storm before making its first landfall on August 8 along the east coast of the Yucatan Peninsula near Pulticub, Mexico.

The system weakened as it tracked across the peninsula but retained a well-defined inner core. The storm exploited favorable environmental conditions over the Bay of Campeche and gradually intensified to become the first hurricane of 2017. Franklin achieved its peak intensity of 85 mph (140 km/hr) shortly before making landfall on August 8 as a Category 1 hurricane near Emilio Carranza, Veracruz state. Franklin was the first hurricane to make landfall in the state of Veracruz since Karl in 2010.

In Veracruz state, hurricane force winds damaged dozens of homes, with heavy rains triggering several landslides and mudslides. Power outages impacted more than 300,000. In Guatemala, localized flash flooding was also reported due to prolonged intense rainfall, with hundreds of homes inundated by floodwaters.

Franklin rapidly weakened over the mountainous terrain of central Mexico and the surface circulation dissipated shortly afterwards. However, the remnants of Franklin crossed Mexico and re-developed into a new named storm, Tropical Storm Jova, on August 12 in the eastern Pacific.

Hurricane Gert

Gert developed from an area of low pressure located around 350 miles (560 km) northeast of the Bahamas on August 13. With Gert's development, 2017 became only the fourth year on record to have observed seven or more tropical storms by August 13.[11]

The system intensified within favorable environmental conditions to become the second hurricane of the season. Gert tracked north-northwest before turning and accelerating north-northeast as it became embedded within the mid-latitude westerlies. The system attained a peak intensity of 104 mph (167 km/hr) on August 17 before rapidly weakening as it passed over cooler sea surface temperatures.

Although Gert remained well off the U.S. east coast, swells generated by the system affected areas from the Outer Banks of North Carolina to southeastern New England, killing two people.

Major Hurricane Harvey

Harvey, the eighth named storm of the 2017 hurricane season, developed from a tropical wave approximately 95 miles (155 km) east of Barbados on August 17. The system passed over Barbados and St. Vincent and the Grenadines as a weak tropical storm, with maximum sustained wind speeds of 46 mph (74 km/hr). Minor damage from flash flooding was reported in Barbados. Environmental conditions in the central Caribbean Sea were unfavorable, with northerly wind shear, and Harvey degenerated back into a tropical wave on August 19.

[11] The three other years to have seven or more named storms by August 13 are 1936, 1995, and 2005

However, the National Hurricane Center (NHC) continued to monitor signs of redevelopment as the remnants tracked through the western Caribbean Sea and over the Yucatan Peninsula.

The system's structure improved considerably as it emerged into the Bay of Campeche in the far southwestern Gulf of Mexico, and Harvey was re-designated as a tropical storm on August 23. Environmental conditions were highly favorable and over the next 48 hours Harvey underwent a period of rapid intensification from a tropical depression to a Category 4 hurricane.

Harvey made landfall on August 24 on the northern end of San Jose Island near Rockport, Texas as a Category 4 hurricane. Harvey made a second landfall on mainland Texas between Port Aransas and Port O'Connor around three hours later. At landfall, Harvey had maximum sustained wind speeds of 131 mph (215 km/hr), according to the RMS HWind real-time service. Harvey was the first major hurricane (Category 3 or greater) to make landfall in the U.S. since Hurricane Wilma in 2005, and the first Category 4 hurricane to make landfall in the U.S. since Hurricane Charley in 2004.

Harvey's wind field was quite compact. RMS HWind analysis on August 26 at 03:00 UTC indicated that hurricane force winds were confined to an area within 40 miles of its center. At this time, Harvey had approximately 27 terajoules of integrated kinetic energy (IKE), which was a fraction of the IKE found in the much larger wind field of Hurricane Ike that affected Texas in 2008.

The small size of the storm helped to confine wind damage to a narrow swath and limit storm surge along the Texas coastline. However, significant damage was reported near the landfall location in Port Aransas, Aransas Pass, and Rockport, with many residential buildings sustaining significant brick veneer failure, roof damage, or total roof failure. Elsewhere, wind damage was reported in Fulton, Portland, City-By-The-Sea, Falman-County Acres, Mustang Island, Holiday Beach, Victoria, Ingleside, Ingleside by the Bay, and Flour Bluff. Minimal damage was reported in Corpus Christi.

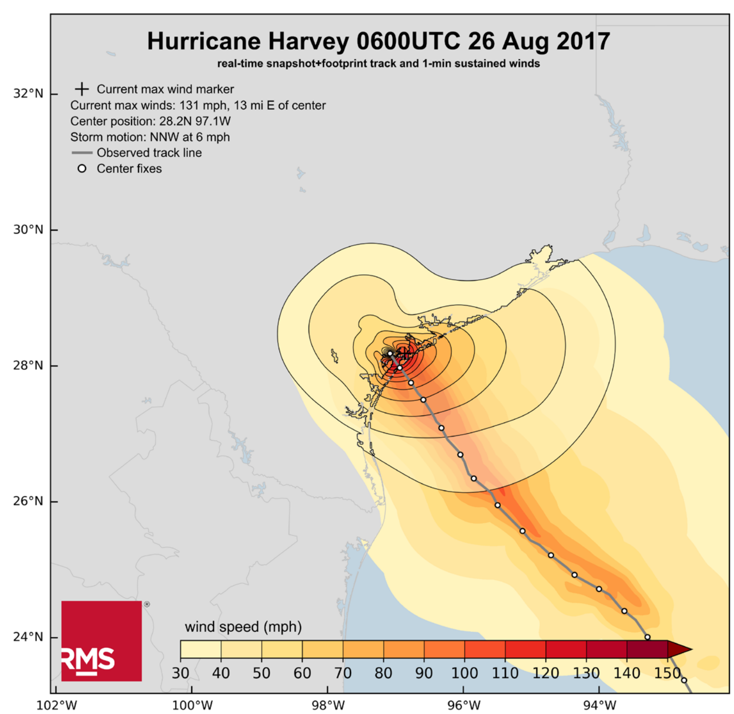

Figure 7: RMS HWind Real-Time snapshot and footprint track of Major Hurricane Harvey at 06:00 UTC on August 26, 2017

Overall, the severity of the wind damage was less than anticipated. Local media reported extensive storm surge damage along the waterfront and shipping channel of Port Aransas, along with damage to the interior components of several coastal hotels and apartment complexes.

Tide and surge impacts were limited and restricted to near-coastal localities, with inundation amounts of 6 to 10 feet (1.8-3.0 meters) related to surge flood damage in Calhoun County, Texas.

Embedded within weak steering currents, Harvey's forward speed slowed as it tracked inland and the system became near-stationary for around 24 hours, before completing a cyclonic loop. The system had stalled approximately 85 miles (137 km) inland from the central-Texas coastline: close enough to the Gulf of Mexico for a significant portion of its circulation to remain over water.

Several intense rain bands, fed by a continual and abundant supply of moisture from the Gulf of Mexico, led to record-breaking rainfall totals in southeast Texas in and around the Houston metropolitan area. According to the National Weather Service (NWS), Harvey produced widespread rainfall totals of 40 to 50 inches (1,016-1,270 mm), with Cedar Bayou recording the maximum of 51.88 inches (1,318 mm). This set a new continental U.S. record for rainfall from a tropical cyclone.

The intensity and accumulation of rainfall resulted in widespread catastrophic and unprecedented inland flooding in the Houston metropolitan area. More than 60 river forecast points in southeast Texas (approximately 90 percent) reached flood stage, with 46 river forecast points (69 percent) reaching major flood stage. In total, 31 of the 67 river forecast points in the region (46 percent) set new all-time records.[12]

Around one-third of Harris County, which includes the city of Houston within and north of Interstate 610, was inundated by floodwater. In total, more than 300,000 structures and 500,000 cars were damaged. Over 160,000 structures were damaged in Harris and Galveston counties alone, with over 110,000 structures flooded in Jefferson, Orange, Hardin, and Tyler Counties.

Harvey remained over Texas for a record-breaking 60 hours and re-emerged into the Gulf of Mexico on August 28. The system re-strengthened and reached an intensity of 52 mph (83 km/hr) on August 29. Under the influence of a subtropical ridge over the Gulf of Mexico, the system began to track east-northeast before turning north-northeast and making another landfall in the U.S. just west of Cameron, Louisiana, on August 30 as a tropical storm. The cyclone weakened as it tracked further inland and dissipated over northern Kentucky on September 1.

According to the Louisiana Governor's Office of Homeland Security, damage from Harvey in Louisiana was minimal.

Harvey remained at tropical storm strength or greater for 117 hours after making its first landfall in Texas, thereby becoming the most enduring named storm after making landfall as a hurricane in Texas on record. It also became the first named storm to make two landfalls in the Gulf of Mexico more than 60 hours apart – Harvey's landfall in Louisiana came around 100 hours after its first landfall in Texas.

The RMS best estimate is that the insured loss from Hurricane Harvey will be between US$25 and US$35 billion, with an upper limit of US$40 billion. The insured losses for the industry are only a fraction of the total economic losses, which are estimated to be US$70 to US$90 billion. The significant gap between the economic losses and the insured losses reflects the lack of comprehensive flood coverage and penetration within many sectors of the industry.

[12] River forecast point statistics from NWS Houston/Galveston's cyclone report

Inland flood contributes a significant portion of the insured losses impact of this event, at between US$21 and US$36.5 billion. The median estimate of the economic inland-flood loss is US$75 billion, which when combined with the wind and surge losses, is in the middle of the US$70 to US$90 billion total economic loss range. RMS estimates that the gross losses accrued in the NFIP will be between US$7 and US$10 billion; about 40 percent of those claims are expected to come from Harris County alone. The best estimate of insured wind and storm surge loss is between US$1.5 and US$3.0 billion.

Major Hurricane Irma

A tropical wave that moved off the west coast of Africa quickly developed into Irma in the far eastern Atlantic on August 30. Over the following five days, the system took advantage of favorable environmental conditions in the central tropical Atlantic and strengthened to a Category 4 hurricane. As Irma approached the Leeward Islands, it underwent a period of rapid intensification and became the first Category 5 hurricane of the 2017 North Atlantic hurricane season, and the first in the basin since Matthew in October 2016. It was also the first in the tropical Atlantic[13] since Hugo in 1989.

Irma was the strongest hurricane to impact the Leeward Islands on record. On September 6, Irma made its first landfall in the Caribbean over Barbuda as a Category 5 hurricane, with maximum sustained wind speeds of 185 mph (295 km/hr). Catastrophic damage was reported on the island, with around 90 percent of building stock (~1,100 buildings) on the island severely damaged or destroyed, and around 90 percent of the electricity infrastructure was damaged, with significant damage to the island's water supply.

Irma maintained its Category 5 intensity as it tracked over the islands of Saint-Martin/Sint Maarten and Anguilla. Most buildings sustained serious or catastrophic damage in the French territory of Saint-Martin, with a large percentage of buildings destroyed, including government offices. On the Dutch side of the island, Sint Maarten, damage was described as catastrophic, with at least at least 70 percent of buildings destroyed. The island's Princess Juliana International Airport was also severely damaged. The British Overseas Territory of Anguilla sustained critical damage, with around 90 percent of all buildings damaged to varying degrees.

Irma's landfall over the British Virgin Islands marked the third such instance in less than 12 hours. Reports from Tortola described severe wind and storm surge damage. Many homes, businesses, and public buildings were destroyed. Communications systems were impacted across the territory.

Damage on the neighboring U.S. Virgin Islands of St. Thomas and St. John was substantial, with large parts destroyed. Many buildings were structurally damaged or lost their roof, and power and telecommunications were destroyed.

Although Irma bypassed Puerto Rico, the Dominican Republic, and Haiti around 60 miles (100 km) offshore, the countries were impacted by strong winds, heavy rains, and some storm surge. In Puerto Rico, damaging winds and storm surge damaged several hundred homes, and more than 1 million households were without power. Several thousand structures were damaged to varying degrees in the Dominican Republic, and hundreds of homes were damaged by flooding and mudslides in Haiti.

[13] The Tropical Atlantic is defined as 7.5-20°N, 60-20°W

On September 8, the system bypassed the Turks and Caicos Islands and tracked over the far southeastern Bahaman islands of Little Inagua. It was the closest approach of a Category 5 hurricane to the Turks and Caicos Islands on record, and the first Category 5 landfall in the Bahamas since Andrew in 1992. Wind and storm surge damaged approximately 80 to 90 percent of buildings in South Caicos, with significant damage to schools, government buildings, infrastructure, utilities, and communication networks.

As Irma tracked away from Little Inagua, it underwent an eyewall replacement cycle and briefly weakened to a Category 4 hurricane. Irma had spent over three consecutive days (78 hours) as a Category 5 hurricane, setting a record for the longest lifetime of a Category 5 hurricane in the Atlantic during the satellite era.

Not only was Irma an intense storm, but it also had a large wind field. Late on September 8 as Irma approached Cuba's northern shore, RMS HWind analyses showed that tropical storm force winds extended nearly 250 miles (400 km) from its center. This large and intense wind field contained nearly 125 terajoules of integrated kinetic energy (IKE), which was more than five times the maximum amount found in Hurricane Harvey earlier in the year, and nearly eight times that of Hurricane Andrew as it made landfall South Florida in 1992. More notably, Irma contained more IKE at this point, than did Hurricanes Katrina, Ivan, and Ike when they made landfall in the U.S. in past seasons as similarly large storms.

The following day, on September 9, Irma re-strengthened to a Category 5 hurricane and made landfall on the Camaguey Archipelago of Cuba, becoming the first Category 5 hurricane to make landfall in Cuba since 1924. According to the United Nations (UN), more than 150,000 homes were destroyed or damaged to varying degrees. Storm surge floodwaters inundated hundreds of miles of coastline as well as parts of Havana.

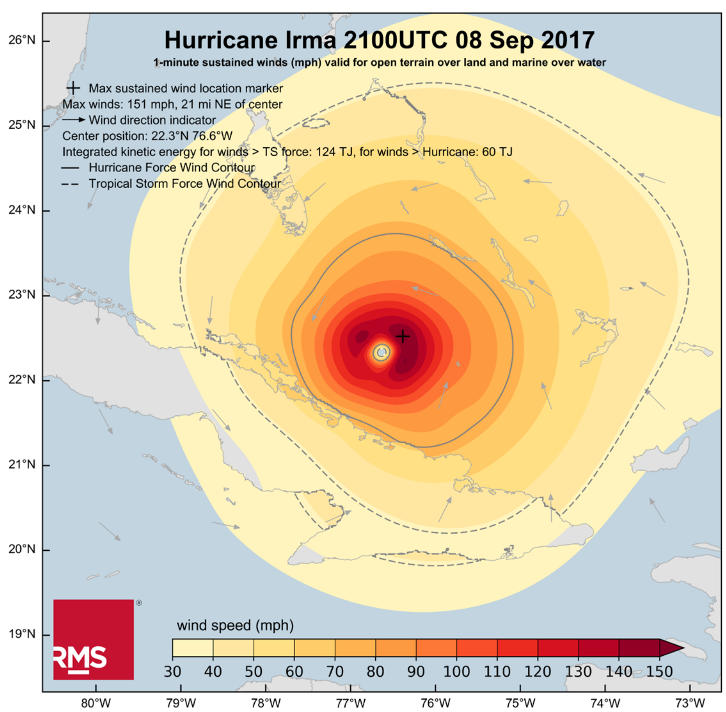

Figure 8: RMS HWind Real-Time snapshot of Major Hurricane Irma at 21:00 UTC on September 8, 2017.

The interaction of Irma's circulation with the northern coast of Cuba resulted in the weakening of the system to a Category 3 hurricane. As Irma's circulation moved off land, it began to round the southwestern portion of a subtropical high and the system turned north toward Florida. Irma re-strengthened over the warm waters of the Straits of Florida into a Category 4 hurricane as it approached the Florida Keys.

Although Irma's inner core weakened before reaching the Florida coastline, its large size remained. Irma made its first U.S. landfall at Cudjoe Key in the Lower Florida Keys on September 10 as a Category 4 hurricane, with maximum sustained wind speeds of 130 mph (210 km/hr), and more than 100 terajoules of IKE in its wind field according to RMS HWind analyses.

It made a second landfall a few hours later over Marco Island, near Naples, as a Category 3 hurricane with maximum sustained wind speeds of 115 mph (185 km/hr). Gusts up to 130 mph (210 km/hr) were reported by the NHC. Irma was the first Category 4 hurricane to make landfall in Florida since Charley in 2004. It also marked the first time on record that two Category 4 or greater hurricanes made landfall over the mainland U.S. in a single season, following Hurricane Harvey.

Hurricane force winds were experienced over a large area of southwest Florida, including Tampa and Naples. In the Florida Keys, photographs showed storm surge covering cars and even reaching the tops of palm trees in some locations. Storm surge damaged most homes that were not elevated, including some homes elevated 8 to 10 feet (2.4-3.0 meters). According to the director of the Federal Emergency Management Agency (FEMA), around 90 percent of the archipelago's homes were damaged to some degree with up to 25 percent of homes in the Florida Keys being destroyed. Tidal gauges in selected locations around the Keys registered storm surge depths of up to 3 feet (0.9 meters). In the Naples area, where Irma made its second Florida landfall, storm surge depths of 4 to 5 feet (1.2-1.5 meters) were observed. The city of Naples appeared to have suffered severe flood inundation as drone footage showed suburban areas under water. Large areas of Miami, where a tidal gauge observed a storm surge depth of 4 feet (1.2 meters), were flooded by storm surge inundation.

Observations showed damaging levels of storm surge along the southeast U.S. coastline, including Georgia and South Carolina. Gauge measurements in the region ranged between 5-9 feet (1.5-2.7 meters). In Charleston, South Carolina, approximately 6 inches (152 mm) of rain fell in a 24-hour period, which added to the storm surge and caused the most severe surge flooding in the city since Hugo in 1989.

In Florida, Irma broke several river records, with the St. John's River in Jacksonville surpassing the previous record set during Dora in 1964. This flooding caused damage in the downtown area near the river, with water reaching 5 to 6 feet (1.5-1.8 meters) above ground in some locations. In southwest Florida, flooding of 4 to 6 feet (1.2-1.8 meters) reportedly caused significant damage in Bonita Springs, with standing water still present a week after the event. On the east coast of Florida, flooding of 4 to 5 feet (1.2-1.5 meters) was reported in downtown St. Augustine. Homes were damaged in Daytona Beach near the coast from floodwaters of approximately 2 feet (0.6 meters) above ground, although the flooding was not widespread.

Irma tracked north-northwest through Florida and weakened to a Category 2 storm on September 11 approximately 45 mi (70 km) west of Lake Okeechobee. Six hours later, the NHC downgraded the system to Category 1 strength, and by Monday September 11 Irma had weakened to a tropical storm, approximately 80 miles (130 km) southwest of Jacksonville. By Tuesday September 12 Irma was classed as a tropical depression.

The RMS best estimate is that the insured loss from Hurricane Irma will be between US$35 and US$55 billion. This estimate represents insured loss associated with wind, storm surge, and inland flood damage across Florida and the southeast U.S., as well as insured loss associated with wind and storm surge in the Caribbean.

For the U.S., the RMS best estimate ranges from US$25 to US$35 billion. This estimate, which includes wind, storm surge, and inland flood losses, is based on analysis of RMS ensemble footprints (hazard reconstructions of Irma's wind field and storm surge). This figure also includes estimated losses to the National Flood Insurance Program (NFIP), which RMS expects to reach between US$2.5 and US$5.5 billion. RMS estimates significant insured wind losses for the Caribbean of between US$10 and US$20 billion.

Major Hurricane Jose

Deep convection associated with a disturbance in the central tropical Atlantic gradually organized and became the 10th named storm of the season, Jose, on September 5. The system tracked west to west-northwest for several days across the Atlantic along the southern periphery of the Azores-Bermuda high. Environmental conditions in the tropical Atlantic were highly favorable for intensification, with very warm sea surface temperatures, low vertical wind shear, and an abundant supply of mid-level moisture. Jose intensified into a hurricane on September 6 and the following day the system underwent a phase of explosive intensification and reached major hurricane status. With Irma tracking through the Caribbean as a Category 5 hurricane, it marked the first time in seven years that were simultaneous major hurricanes in the Atlantic basin.

Jose continued to intensify and attained its peak intensity of 155 mph (250 km/hr) on September 9, located around 160 mi (260 km) east of Guadeloupe. As it neared the northern Leeward Islands the system turned northwest and bypassed around 55 mi (90 km) northeast of Barbuda as a Category 4 major hurricane. Although hurricane force winds did not impact land, some of the islands left devastated by Hurricane Irma such as Barbuda, Anguilla, Saint-Martin and Sint Maarten, experienced tropical storm force winds. Strong winds and heavy rainfall significantly hampered humanitarian and aid relief efforts on those islands.

Jose maintained Category 4 intensity for several days as it tracked northwest around a mid- and upper-level high and progressed into the central western Atlantic. Despite the system remaining over warm sea surface temperatures, increased north to northeasterly shear led to a weakening trend back to a tropical storm. As Jose's steering influences weakened, its forward speed slowed, and the system executed a slow cyclonic loop over open water in the eastern Atlantic well east of the Bahamas. Jose produced a large swell field that affected much of the southwestern Atlantic basin, generating rough surf and rip conditions.

As Jose completed its loop, the wind shear relaxed as the system began to show signs of reorganization and restrengthening. As the system began rounding the western periphery of a subtropical ridge on September 15, it regained hurricane status. Jose maintained Category 1 hurricane intensity as it tracked north. The cooler waters of the Gulf Stream and the unfavorable upper-level conditions weakened the system back to a tropical storm as it started to turn north-northeast. Jose became embedded with the mid-latitude southwesterly flow but the development of a ridge to the north blocked the motion of the system and it stalled offshore of the U.S. east coast. Jose meandered off the New England coast for several days until its structure deteriorated and transitioned to a post-tropical cyclone on September 21. The remnants of Jose looped back towards the U.S. coastline before the system dissipated off the coast of Maine.

Hurricane Katia

A broad area of low pressure in the Bay of Campeche developed a well-defined low-level circulation and was designated a tropical depression on September 5. The depression became more organized in favorable environmental conditions and was designated a tropical storm the following day. Under the influence of a ridge of high pressure over the north Gulf of Mexico, Katia began to track west-southwest towards Veracruz, Mexico. The system continued to develop, reaching a peak intensity of 104 mph (167 km/hr), equivalent to a Category 2 hurricane, on September 8.

With Irma, Jose, and Katia all at hurricane strength, it was the first time since 2010 that three hurricanes were active in the basin at the same time, and September 8 marked the second time on record that there had been three Category 2 or stronger hurricanes at the same time.

The system began to weaken as it interacted with land and made landfall near Tecolutla, Mexico, on September 9 as a Category 1 storm. Katia brought intense rainfall that led to hundreds of mudslides and landslips across eastern Mexico. Although it did not cause vast wind damage, at least 53 municipalities reported some damage.

Katia dissipated on September 9 over the mountainous terrain of eastern Mexico. After passing over central Mexico, the mid-level remnants of Katia emerged over the Pacific Ocean and developed into Hurricane Otis on September 11.

Major Hurricane Lee

Convection associated with a tropical wave quickly developed into the twelfth named storm of the season, Lee, on September 16. However, the system encountered high vertical wind shear and gradually weakened back to a depression the following day, before degenerating on September 18.

The remnants of Lee's mid-level circulation tracked northward and a new low-level center developed four days later, on September 22. The system became better organized and was re-classified as tropical storm later that day. Lee gradually strengthened to a Category 1 hurricane as it completed a tight anticyclonic loop over the central Atlantic.

Lee continued to organize within highly favorable upper-level wind patterns. Following an eyewall replacement cycle on September 27, the storm strengthened to a Category 3 major hurricane, with estimated maximum sustained wind speeds of 115 mph (185 km/hr). Lee became the fifth major hurricane of the 2017 Atlantic hurricane season.

The system tracked around the western periphery of the subtropical ridge in the central Atlantic and accelerated northeast before becoming embedded within the mid-latitude westerlies. Lee gradually weakened until it dissipated over the far north-central Atlantic on September 30.

Major Hurricane Maria

An area of low pressure located several hundred miles east of the Lesser Antilles became better organized and established a low-level center of circulation and was classified as a tropical storm on September 16. Maria was located within a favorable environment for rapid intensification, with low wind shear, high moisture content, and warm sea surface temperatures in excess of 29°C (84°F). The system organized and intensified to become a hurricane early on September 18, and underwent an 18-hour period of explosive and rapid intensification as it approached the Lesser Antilles to become a Category 5 major hurricane, with maximum sustained wind speeds of 161 mph (259 km/hr).

Maria made its first landfall in the Caribbean over Dominica on September 19 as a Category 5 hurricane, a first for the island nation. The RMS HWind real-time service estimated 1-minute maximum sustained winds of 159 mph (256 km/h) at landfall. The system damaged or destroyed approximately 90 percent of structures on Dominica, with around 95 percent of buildings sustaining roof damage. All communication systems were downed, and water and electricity supplies were severely damaged.

Land interaction briefly weakened the storm, but it quickly regained intensity and strengthened to its lifetime maximum intensity of 173 mph (278 km/hr) as it crossed the far eastern Caribbean Sea, passing within a short distance of Guadeloupe, Martinique, and the U.S. Virgin Islands. In the U.S. Virgin Islands, dozens of buildings on St. Croix sustained structural damage or roof failure. Although St. Thomas was spared major wind damage, several low-lying regions suffered flooding damage. Guadeloupe sustained minor damage, with severe impacts to the island's banana plantations. Martinique also suffered extensive power failure due to Maria.

Similar to Irma, Hurricane Maria had a large wind field. At peak intensity on September 20, RMS HWind operational analyses indicated that hurricane force winds extended out nearly 100 miles (160 km) from its center, and the wind field as a whole had more than 75 terajoules of IKE.

Maria weakened slightly during an eyewall replacement cycle as it approached Puerto Rico and made landfall near Yabucoa on September 20 as a Category 4 hurricane. RMS HWind real-time analysis estimated 1-minute maximum sustained winds of 130 mph (209 km/h), making it the most intense landfalling hurricane for the island since the 1928 San Felipe Segundo Hurricane, and the first Category 4 landfalling storm since the San Ciprian Hurricane of 1932.

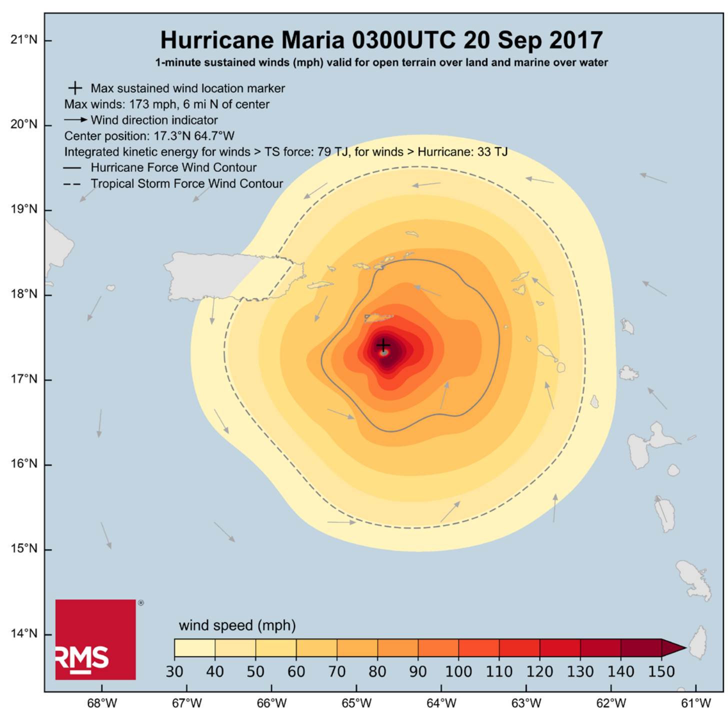

Figure 9: RMS HWind Real-Time snapshot of Major Hurricane Maria at 03:00 UTC on September 20, 2017

RMS reconnaissance within a few days of landfall noted that most buildings in the greater San Juan area did not sustain significant damage, though buildings with wood roofs and light metal were extensively affected. Substantial roof damage was observed in Palmas Del Mar and Guayama. Only tile roofs sustained noticeable damage at large resorts such as Rio Grande. Damage in Fajardo and Caguas was mostly minor, with only light metal roofs and siding damaged. In Arecibo, weak structures, including light metal and wood roofs, suffered heavy damage but reinforced concrete buildings with concrete roofs sustained little visible damage. Near Yabucoa, RMS reconnaissance noted most residential buildings, which were constructed of reinforced concrete walls with concrete roofs, did not seem to have any significant structural damage. All trees in this region were stripped of their leaves and branches.

Some roofs of pharmaceutical plants in the Humacao area sustained visible damage. Across Puerto Rico, power plants and pharmaceutical facilities sustained only minor damage; however, significant transmission, distribution, and infrastructure failures led to prolonged suspension of normal operations. Maria most severely impacted power and telecommunication systems. Significant damage was observed to several large wind turbines, with all but one turbine losing at least one blade and the remaining blades also significantly damaged. Maria also destroyed one weather radar on the island and disabled another.

Rainfall-driven flooding proved to be a major cause of infrastructure damage across Puerto Rico, with many roads and bridges washed out. In addition, excessive inflows caused partial failure of the Guajataca Dam. River and flash flooding inundated parts of San Juan with around 4 feet (1.2 m) of floodwater, with maximum flood inundation of around 8 feet (2.4 m).

Interaction with Puerto Rico's mountainous terrain significantly weakened the system. Maria emerged off the northern coastline as a disorganized Category 2 hurricane with two wind maxima and two concentric eyewalls. Favorable environmental conditions aided the system's reorganization and the system restrengthened to into a Category 3 hurricane on September 21 as it pulled away from the island.

Hurricane Jose had weakened the ridge to the north, which allowed Maria to turn to the north-northwest. As the system recurved and tracked back into the Atlantic, Maria's outermost winds brushed the northern coastline of the Dominican Republic. Several hundred homes were damaged or destroyed by strong winds and flash flooding, mainly in coastal areas. Maria bypassed to the east of the Turks and Caicos Islands on September 22, causing extensive damage to areas previously impacted by Hurricane Irma.

Maria maintained this large size for several days and despite decreasing peak winds later in its lifecycle, its wind field expanded further as it turned and accelerated to the north over the western Atlantic. Despite nearing the coastline of North Carolina, the storm had no measurable impact on the U.S. mainland except for large waves and rip currents.

On September 28, the system accelerated to the northeast as it became embedded in the mid-latitude westerlies and transitioned into an extratropical cyclone.

The RMS best estimate is that the insured loss from Major Hurricane Maria will be between US$15 and US$30 billion. This estimate represents insured loss in the Caribbean associated with wind damage, as modeled by RMS ensemble footprints, and inland flood damage. RMS expects that the vast majority of insured losses will be driven by wind damage with well over 85 percent of the insured losses being sustained by Puerto Rico alone. Accounting for uninsured wind and flood losses in the region, RMS expects the economic loss from Hurricane Maria to fall between US$30 and US$60 billion.

Hurricane Nate

The fourteenth named storm of the 2017 season developed in the far southwestern Caribbean Sea out of an area of low pressure associated with the Central American gyre that was situated over the western Caribbean Sea.

Nate tracked north-northwest under the influence of a ridge located over the southwestern Atlantic. The system was generally disorganized but developed a partial eye before making landfall as a tropical storm over Nicaragua on October 5. The system passed over the border into eastern Honduras and re-entered the western Caribbean Sea on October 6.

Heavy rainfall from the gyre and tropical system brought flooding rain and landslides to parts of Central America. Extensive property and infrastructure damage was reported in Nicaragua, Honduras, and Costa Rica.

Back over the warm waters of the western Caribbean Sea, Nate began to gradually organize and re-strengthen, and the system accelerated north-northwest between the large cyclonic gyre located across southern Mexico and the mid-level ridge located over the southwestern Atlantic. Shortly after entering the Gulf of Mexico, Nate had sufficiently strengthened to be classified as a Category 1 hurricane, becoming the ninth hurricane of the season.

Nate's 28 mph (45 km/hr) forward speed was the fastest recorded motion of a hurricane in the Gulf of Mexico. The system attained its peak intensity over the central Gulf of Mexico of 92 mph (148 km/hr) on October 7. Strong vertical wind shear displaced the storm's most vigorous convection and strong winds to the northeast quadrant as it approached the northern Gulf coastline.

Nate made its first U.S. landfall near the mouth of the Mississippi River on October 8 as a Category 1 hurricane, with maximum sustained wind speeds of 85 mph (140 km/hr). The system made a second landfall a few hours later at a similar intensity near Biloxi, Mississippi. Nate was the fourth hurricane to make landfall in the U.S. (including mainland and overseas territories) in 45 days, and the first hurricane to make landfall in Louisiana since Hurricane Katrina in 2005.

Peak gusts of up to 75 mph (120 km/hr) were observed along the Mississippi and Alabama coastline. Wind damage was limited to downed trees and electricity poles damaging buildings, with minor roof damage reported in parts of Mississippi and Alabama.

The system rapidly weakened as it tracked inland and spawned at least ten tornadoes from Alabama to North Carolina, including at least two EF-2 rated systems. One of these damaged more than two dozen homes in Pickens County, South Carolina. Additional isolated instances of tornadic roof damage were reported across South Carolina.

Storm surge flooding was reported along the northern Gulf Coast. A surge of 6.3 feet (1.9 meters) was observed in Pascagoula, Mississippi, the highest measured anywhere along the Gulf Coast. Surge inundation of up to 5.5 feet (1.7 meters) above normal high tide impacted coastal areas of Alabama, with inundation levels of up to 4.5 feet (1.4 meters) recorded in Louisiana. Surge inundated several beach front commercial buildings.

RMS expects that the insured U.S. loss associated with wind and coastal flooding from Hurricane Nate will not exceed US$500 million.

Hurricane Ophelia

A well-defined low-pressure system over the eastern Atlantic, located several hundred miles to the southwest of the Azores, gained sufficient convection on October 9 to become the fifteenth named storm of the 2017 North Atlantic hurricane season.

Ophelia was located within a weak steering flow and meandered in the eastern Atlantic for several days. Despite fluctuations in its intensity, the system strengthened to hurricane status on October 11. In strengthening to a hurricane, 2017 became the first year since 1893, and only the fourth on record, to have 10 consecutive storms attain hurricane status.[14]

By October 12, the system had become almost stationary, but it steadily organized and intensified into a Category 2 hurricane. Embedded within the mid-latitude westerlies, Ophelia began to accelerate towards the east-northeast on October 13 ahead of a mid-latitude trough. Despite tracking over sea surface temperatures less than 25°C (77°F), cooler-than-normal upper-level temperatures helped create sufficient instability to drive convection and the development of the system, and Ophelia attained major hurricane status on October 14. The system achieved its peak intensity of 115 mph (185 km/hr) as its center bypassed approximately 100 miles (162 km) southeast of the Azores. Ophelia was the sixth major hurricane of 2017 and became the easternmost Category 3 hurricane in the Atlantic basin on record.

Increasing vertical wind shear and the intrusion of dry air led to the gradual weakening of the system, and by October 16, it had weakened to a post-tropical cyclone near the Celtic Sea of the British Isles. Ophelia remained a powerful post-tropical cyclone as it impacted Ireland and the United Kingdom. A peak representative onshore gust of up to 97 mph (156 km/hr) was recorded at Roches Point, at the southeastern tip of Cork Harbour, Ireland. Damage reports indicated the system caused minor damage to property, affected power lines and downed trees across the British Isles, with only a few isolated reports of major property damage.

Tropical Storm Philippe

The interaction of a tropical wave with the Central American Gyre led to the development of a broad area of low pressure in the western Caribbean Sea in late October. This disturbance became better organized, with increased convection and a defined low-level circulation center, and was designated a tropical storm near the southwestern tip of Cuba on October 28.

Philippe accelerated northeast ahead of a large mid-latitude trough and made landfall as a weak tropical storm over Cuba's Zapata Peninsula. Land interaction and strong southwesterly shear caused the system to quickly dissipate, though the remnants continued to accelerate northeast into the Straits of Florida.

Simultaneously, a new non-tropical low developed near the coast of southern Florida in the morning of October 29. This system brought gale-force winds to the southern Florida coastline and spawned several tornadoes which damaged several homes in Boynton Beach.

The remnants of the non-tropical low merged with a cold front and were later drawn into a much broader extratropical low-pressure system that developed near the outer banks of North Carolina.

[14] As these years occurred before the introduction of satellites in 1966, weak depressions or tropical storms that may have formed between hurricanes may have been missed within the record

This extratropical low-pressure system caused damaging winds and isolated flash flooding in northeastern U.S.

The NHC's Tropical Cyclone Report on Philippe, published on January 31, 2018, determined that the system had dissipated over Cuba and did not pass over southeastern Florida as a tropical storm as had been reported operationally. Philippe's peak intensity was also revised down to 40 mph (65 km/hr).

Tropical Storm Rina

Convection associated with an area of low pressure in the central Atlantic became better organized and was designated as a tropical storm on November 6. Rina, the seventeenth, and final named storm on the season, tracked north along the western periphery of a strong mid-level ridge. Despite increased wind shear, dry air, and cool sea surface temperatures, Rina strengthened into a strong tropical storm, reaching a peak intensity of 60 mph (95 km/hr). High wind shear separated Rina's convection from its low-level center and the system began to weaken. Rina became post-tropical over the cold waters of the far north Atlantic before merging with a complex extratropical low pressure area.

Review of the 2017 Season Forecasts

The consensus amongst pre-season forecasts, issued between April and June, called for near- to above-average activity, but few forecasts predicted the season's outcome of 17 named storms, 10 hurricanes, six major hurricanes, and an ACE index value of 226. In fact, no pre-season forecast predicted the number of major hurricanes or ACE index value observed in 2017.

Prior to the hurricane season's official start (June 1), the three main seasonal Atlantic hurricane forecast agencies - National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA CPC), Colorado State University (CSU), and Tropical Storm Risk (TSR) - predicted average to slightly above-average activity. These agencies cited the El Niño-Southern Oscillation (ENSO), sea surface temperatures in the central tropical Atlantic, and vertical wind shear across the main development region, to be the key drivers of activity in 2017.

Table 1 provides the seasonal forecasts at the time the RMS North Atlantic Hurricane Season Outlook was published in June 2017, along with the final numbers for the 2017 season.

Forecast Group	Tropical Storms	Hurricanes	Major Hurricanes	ACE Index (10^4 kt^2)
NOAA CPC[15] (May 25)	11–17	5–9	2–4	-
CSU[16] (June 1)	14 (10–18)	6 (4–8)	2 (1–3)	100 (52–148)
TSR (May 26)	14 (±4)	6 (±3)	3 (±2)	98 (±48)
U.K. Met Office[17] (June 1)	13 (10–16)[18]	8 (6–10)	-	145 (92–198)
N. Carolina State University (April 18)	11–15	4–6	1–3	-
Penn State University (April 25)	15 (11–20)	-	-	-
AccuWeather (May 31)	10	5	3	-
The Weather Company (May 20)	14	7	3	-
Weather Tiger (April)	14	7	2-3	110
WeatherBELL Analytics (May 12)	11–13	4–6	1–2	75–95
All Forecast Groups	10–17 (10–20)	4-9 (3–10)	1–4 (1–5)	75–145 (50–198)
2017 Season	**17**	**10**	**6**	**226**

Table 1: Summary of the 2017 North Atlantic pre-season forecasts, and the 2017 storm totals

[15] NOAA CPC does not issue a single-figure best estimate.

[16] CSU's forecast ranges derived as one standard deviating from its best estimate forecast. CSU expects to see two-thirds of its forecasts verify within one standard deviation of observed values, with 95 percent verifying within two standard deviations of observed values.

[17] Forecast ranges have a 70 percent probability of occurrence.

[18] Tropical Storm Arlene occurred in April 2017 and is therefore outside the period covered by this Met Office prediction (June–November).

Role of the Ocean and Atmosphere in the 2017 Season Activity

The 2017 season surpassed most, if not all, pre-season forecasts and expectations, especially for estimates of major hurricanes and ACE. The question must be asked, then: why was the 2017 North Atlantic hurricane season so active?

The season was characterized by phases of oceanic and atmospheric influences that promoted above-average hurricane activity in the Atlantic. During a period between late-August and late-September, these factors reinforced the hurricane-conducive conditions to establish an environment capable of sustaining highly elevated levels of hurricane activity. The main factors that promoted cyclogenesis and intensification were:

- The transition of the El Niño-Southern Oscillation (ENSO) to a La Niña phase by mid-summer, which reduced vertical wind shear in the main development region
- Above-average sea surface temperatures and high ocean heat content in the tropical Atlantic throughout the peak months of the season
- Enhanced lower-tropospheric convergence across the western Atlantic and Gulf of Mexico

While these factors created a favorable environment for hurricane development, a large-scale synoptic pattern created a predominant steering flow towards land and turned an active season into a damaging season.

The following subsections discuss in more detail the oceanic and meteorological factors that contributed to the extremely active hurricane season.

El Niño-Southern Oscillation

One of the foremost drivers of inter-annual hurricane activity is the El Niño-Southern Oscillation (ENSO), a coupled ocean-atmosphere climate fluctuation over the tropical Pacific that transitions between warmer (El Niño) and cooler (La Niña) phases, typically over a two- to seven-year period. La Niña events characteristically enhance Atlantic hurricane activity via teleconnections that decrease vertical wind shear over the main development region of the tropical Atlantic, with the reverse true for El Niño events. Vertical wind shear, a change in wind direction or speed with height, is a major inhibitor of cyclogenesis and tropical cyclone intensification.

Through the first half of 2017, the central equatorial Pacific Ocean warmed out of the La Niña phase observed in winter 2016-17 to borderline El Niño conditions. At the official start of the hurricane season in June, operational ENSO guidance indicated an equal probability of warm-neutral or weak El Niño conditions through the peak months of the hurricane season. In the absence of other atmospheric conditions, this scenario would have typically led to near-average to lower-than-average activity.

But, in fact, neither of these scenarios materialized. Instead, tropical Pacific Ocean sea surface temperatures and upper ocean heat content cooled rapidly, and ENSO quickly transitioned toward La Niña conditions by mid-summer. Sea surface temperature declines of this magnitude (around 1°C (1.8°F) in the four months between April and August) are highly unusual and normally only occur following strong winter El Niño events.

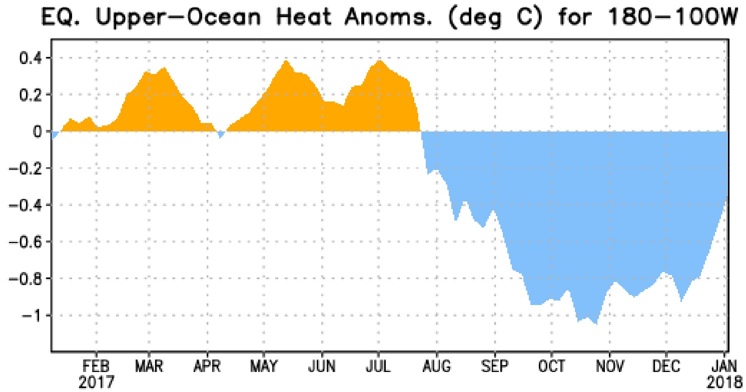

Figure 10: Area-averaged equatorial upper-ocean heat content anomaly (°C) in the central Pacific. (Data: National Weather Service (NWS) Climate Prediction Center (CPC) El Niño/Southern Oscillation (ENSO) Diagnostic Discussion, January 11, 2018.)

Atlantic Vertical Wind Shear

The transition toward La Niña conditions was reflected in the overall North American weather pattern during the summer, leading to a reduction in the vertical wind shear in the tropical Atlantic. This reduction was particularly apparent across the Atlantic main development region and eastern Caribbean Sea between late August and late September.

Atlantic Sea Surface Temperatures

In the basin's main development region, sea surface temperatures reached their third warmest September temperature on record, and the warmest level since 2010.

Warm sea surface temperatures act to increase atmospheric instability in the overlying lower troposphere, leading to the low-level convergence of winds, moisture, and latent heat. These conditions, combined with the decrease in vertical wind shear, provided a highly favorable set of atmospheric and ocean conditions for developing systems to rapidly intensify and sustain a strong intensity for extended periods of time.

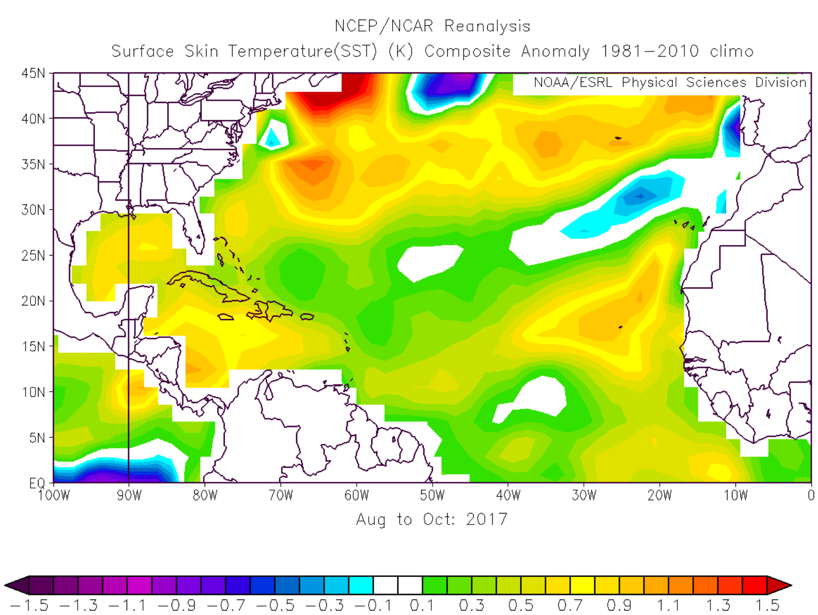

Figure 11: Atlantic sea surface temperature anomalies (°K) for the period through August to October. (Data: NOAA/ESRL Physical Sciences Division, 2018).

The timing of the Atlantic Basin's record warmth coincided with the rapidly evolving shift of ENSO toward La Niña conditions, resulting in a marked rise in cyclogenesis and intensification that included the hurricanes Irma, Jose, and Maria.

Low-level Convergence

The peak months of the 2017 hurricane season were characterized by enhanced lower-tropospheric convergence across the western Atlantic and Gulf of Mexico, which tends to favor cyclogenesis. The most well-defined area of enhanced low-level convergence was centered over the Gulf of Mexico. This, combined with low wind shear and a warm eddy of high oceanic heat content in the western Gulf of Mexico, aided the rapid intensification of Harvey from tropical storm strength to a Category 4 major hurricane in less than 24 hours as it approached the Texas coastline.

This enhanced low-level convergence also contributed to the intensification of other landfalling hurricanes in the Gulf of Mexico, including Katia, which made an early September landfall as a Category 1 hurricane in Mexico in early September, and Nate, which made an early October landfall as a Category 1 hurricane over Louisiana and Mississippi. In fact, Nate's peak intensity was limited by its record-breaking forward speed; a slower track across the Gulf of Mexico could have allowed the storm to strengthen into a more significant hurricane.

Tropical Atlantic Moisture

Moist air in the low and mid-levels of the atmosphere is critical for tropical cyclone development. Dry air can hinder development and intensification of tropical cyclones by suppressing deep convection.

The far western Atlantic, Caribbean Sea, and Gulf of Mexico were anomalously moist throughout the peak months of the hurricane season. This was particularly the case during September, which featured storms such as Irma, Jose, and Maria. The mid-level dry moisture anomaly over the central and eastern Atlantic observed in Figure 12 is distorted by a strong early- and mid-August dry anomaly in the same region; during the peak weeks of activity in 2017 much of the basin had above-average moisture content, offering a preferential environment for cyclone development and intensification.

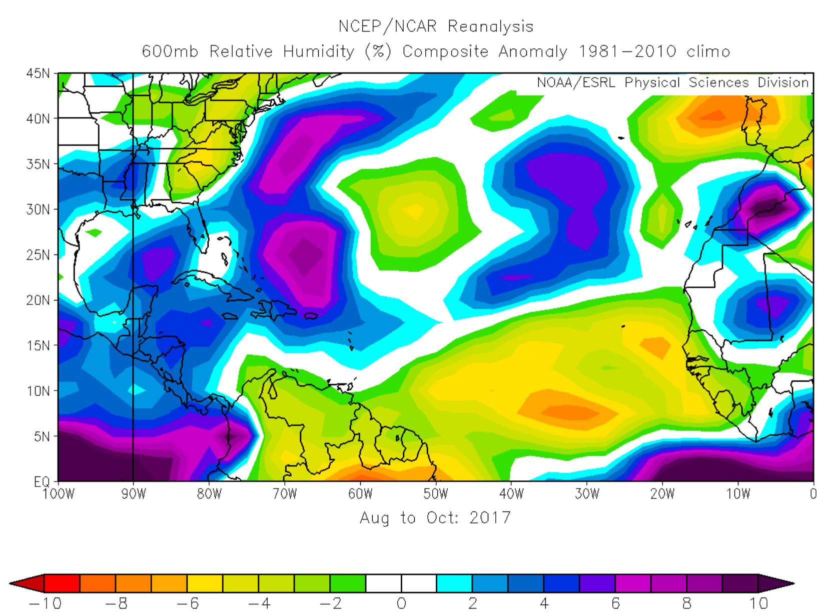

Figure 12: 600mb relative humidity (%) moisture anomalies for the period through August to October. (Data: NOAA/ESRL Physical Sciences Division, 2018).

Tropical Atlantic Sea Level Pressure

Tropical cyclone activity in the North Atlantic basin can be enhanced by lower sea level pressure due to increased instability and increased low-level moisture. Conversely, higher sea level pressure can reduce cyclone activity.

In general, the 2017 hurricane season experienced below average sea level pressures across the western Atlantic, Gulf of Mexico, and Caribbean Sea. Part of this pattern could be associated with the season's most intense storms, although individual storms are represented only coarsely within the NCEP/NCAR Reanalysis data.

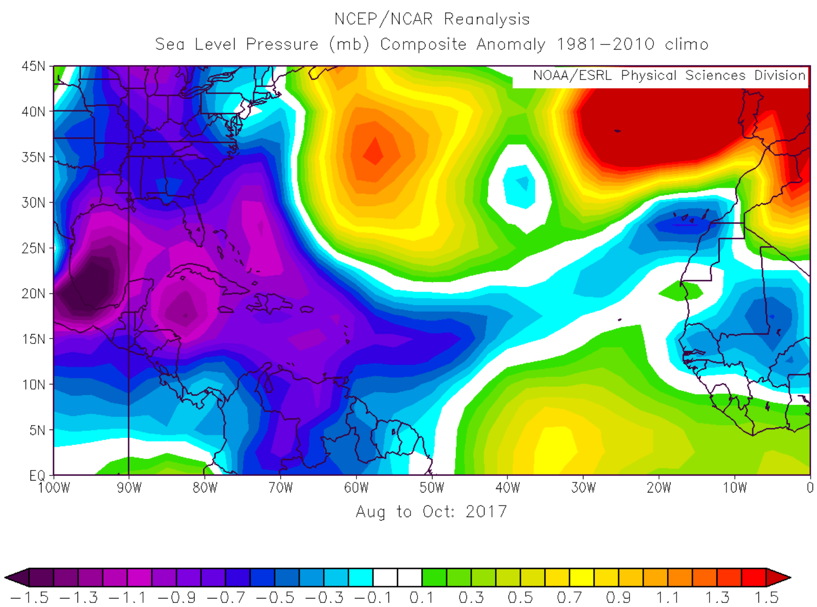

Figure 13: August to October sea surface pressure (mb) anomalies. (Data: NOAA/ESRL Physical Sciences Division, 2018).

Madden-Julian Oscillation

The Madden Julian Oscillation (MJO), an intraseasonal, eastward propagating area of enhanced and suppressed tropical convection, is known to modulate tropical cyclone development and activity in the Atlantic basin, especially for the strongest storms, by providing a large-scale environment that is favorable or unfavorable for development.

The MJO was relatively weak and disorganized during the peak months of the 2017 Atlantic hurricane season, with no significant influence on tropical development. Despite largely favorable large-scale synoptic and environmental conditions throughout October, activity in the Atlantic was, in part, suppressed by an amplified MJO phase over the maritime continent and western Pacific.

Steering Patterns

Highly favorable environmental conditions can cause active hurricane seasons. However, to turn an active season into a damaging season, the proper steering patterns must be in place. The Atlantic subtropical high extended much further west in 2017 than it has done during the past decade, leading to a large-scale synoptic pattern that created a predominant steering flow towards land.

This position of the subtropical high prevented storms, particularly the season's most intense hurricanes, from recurving into the mid-latitudes and directed them on a westward trajectory through the Caribbean Sea and toward the southeast U.S. It was this pattern, along with the quick succession of intense hurricanes forming, that led to significant damage throughout the Caribbean and parts of southeast U.S. during September and October.

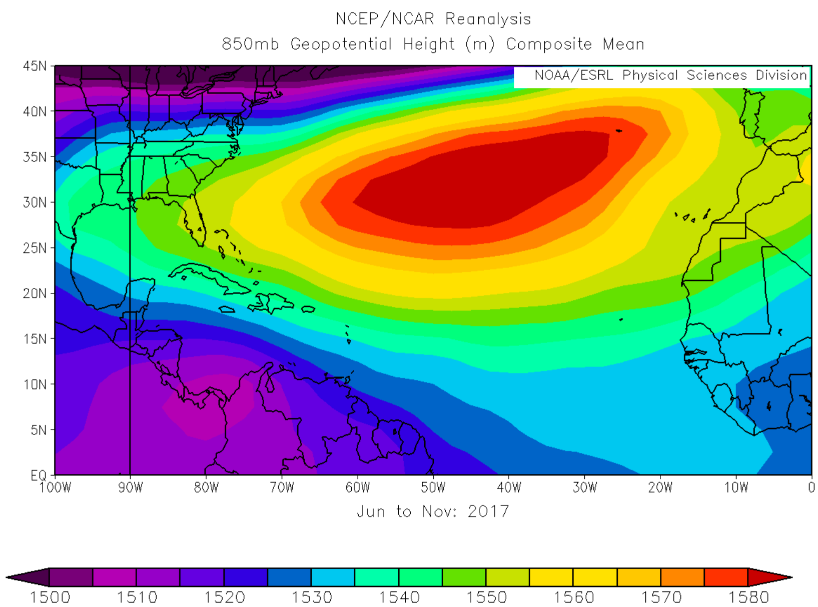

Figure 14: 850mb Geopotential Height (m) composite mean for the period June to November 2017. (Image from NOAA ESRL Physical Sciences Division, 2018)

Outlook for the 2018 North Atlantic Hurricane Season

As many of the factors that influence hurricane activity cannot be predicted with significant lead time, it is difficult at this time to forecast with skill the activity levels of the 2018 North Atlantic hurricane season. However, Tropical Storm Risk (TSR) and Colorado State University (CSU) issued extended forecasts in December 2017 to provide an early glimpse as to what may be in store.

TSR issued its first forecast for the 2018 hurricane season on December 7 and anticipates a slightly above-average season with 15 (±4) tropical storms, 7 (±3) hurricanes, and 3 (±2) major hurricanes. TSR forecast that the 2018 ACE index will be 117 (±60), with a 47 percent probability that the index will be above the 1950-2017 average and a 32 percent probability that it will be near average. One of the main contributors to the TSR extended forecast is the forecast July-September trade wind speed over the Caribbean Sea and the tropical Atlantic, which influences cyclonic vorticity and wind shear in the main development region. TSR anticipates this wind speed to be slightly lower than average, which typically results in enhanced hurricane activity. The agency reports that the precision of its forecast at this lead time based on activity between 2008 and 2017 is low, with the average forecast skill at this lead time around 7 percent for tropical storms, 9 percent for hurricanes, 19 percent for major hurricanes, and 17 percent for ACE.

On December 13, CSU issued a qualitative discussion of the features likely to affect activity during the 2018 North Atlantic hurricane season, rather than a specific quantitative forecast. According to CSU, activity in the upcoming season will be primarily determined by sea surface temperatures in the North Atlantic and the phase of ENSO. Temperatures in the North Atlantic remain above-average, though there is some uncertainty regarding the phase of the Atlantic Multidecadal Oscillation (AMO) due to cooler waters in the far north Atlantic. The tropical Pacific remains in a La Niña phase and forecast models are indicating a trend toward ENSO-neutral conditions in the boreal spring. The development of these two influences will be monitored in the coming months.

As in previous years, NOAA does not release a seasonal forecast prior to late May.

The number of storms that will make landfall on an Atlantic coastline of the U.S. or over the Caribbean in 2018 will be determined by the weather patterns and steering currents throughout the season, which cannot be predicted this far in advance.

RMS will provide an in-depth review of the seasonal forecasts and the oceanic and atmospheric conditions for the 2018 hurricane season in June 2018, alongside a detailed overview of RMS Event Response and RMS HWind offerings for the 2018 season.

RMS solutions help insurers, financial markets, corporations, and public agencies evaluate and manage risks throughout the world, promoting resilient societies and a sustainable global economy.

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