NATIONAL HURRICANE CENTER ANNUAL SUMMARY

2016 ATLANTIC HURRICANE SEASON

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VIIRS visible image of Hurricane Matthew at 1830 UTC 30 September from the Suomi-NPP satellite courtesy of NRL Monterey.

ABSTRACT

The 2016 Atlantic hurricane season featured above normal activity, with 15 tropical storms and 7 hurricanes, with 4 reaching major hurricane strength (category 3 or higher on the Saffir-Simpson Hurricane Wind Scale). The amount of activity was well above that seen during the 2013-2015 hurricane seasons.

Most of the 2016 cyclones affected land. Matthew was the strongest, deadliest, and most destructive cyclone of the season, with its impacts reaching from the eastern Caribbean Sea across Haiti, Cuba, and the Bahamas to the southeastern United States. Earl, Hermine, and Otto also made landfall at hurricane strength, while Nicole affected Bermuda as a hurricane.

OVERVIEW

Tropical cyclone activity in the Atlantic basin during the 2016 season was above the 1981-2010 long-term average and well above that seen during the 2013-15 hurricane seasons. Fifteen tropical storms formed, of which seven became hurricanes, and four reached major hurricane strength (category 3 or higher on the Saffir-Simpson Hurricane Wind Scale). There was also one tropical depression that did not reach tropical storm strength. By comparison, the 1981-2010 averages are 12 tropical storms, 6 hurricanes, and 3 major hurricanes. The Accumulated Cyclone Energy (ACE) index, a measure that takes into account the strength, duration, and frequency of the season's tropical storms and hurricanes, was 140% of the long-term median value. Figure 1 depicts the tracks of the 2016 Atlantic tropical storms and hurricanes.

The 2016 season had an unusually early start when Alex formed from a non-tropical low in January. Three storms also formed from late May to late June, which is above the climatological average. The rest of the season's activity was more climatological, with four storms forming in August, five in September, and one each in October and November. African easterly waves provided a preferred mechanism of genesis in August and September over the central and eastern tropical Atlantic, where favorable large-scale upper-level divergent conditions existed (Figure 2). A secondary preferred area for tropical cyclogenesis was over the Atlantic and Gulf of Mexico waters near the southeastern United States. Figure 2 also shows that while unfavorable upper-level convergence existed over the western Atlantic and Caribbean Sea during August and September, these conditions changed to a more favorable pattern in October which likely aided the formation of Hurricane Matthew. This change was probably due to the influence of a developing La Niña episode during that time (Bell et al 2017).

Most of the 2016 cyclones had impacts on land areas. The season's most devastating hurricane was Matthew, which left a long trail of destruction from the Lesser Antilles across Haiti, eastern Cuba, and the Bahamas to the southeastern United States. Earl caused significant damage as it made landfall as a hurricane in Belize, and it produced additional damage in southeastern Mexico. Hermine made landfall as a hurricane along the Florida Gulf coast, while Nicole brought hurricane conditions to Bermuda. The season's last cyclone, Otto, made landfall as a major hurricane in southeastern Nicaragua, crossed northern Costa Rica, and emerged over the eastern Pacific, becoming a rare Atlantic-to-Pacific basin-crossing tropical cyclone. In addition, Julia reached tropical storm strength over northeastern Florida, Colin made landfall as a tropical storm over the northwestern Florida Peninsula, Danielle moved into eastern Mexico as a tropical storm, and Karl caused tropical storm conditions on Bermuda. Finally, the Azores were affected by Alex as a tropical storm and Gaston as a post-tropical cyclone.

The following section summarizes those hurricanes that affected land. More detailed information on the tropical cyclones of 2016 can be found at http://www.nhc.noaa.gov/data/tcr/index.php?season=2016&basin=atl.

SELECTED STORM SUMMARIES

Hurricane Earl

The tropical wave that led to the formation of Earl moved off of the west coast of Africa on 26 July. The disturbance moved rapidly westward across the tropical Atlantic at speeds of 25-30 kt for the next several days, producing limited deep convection until it reached the Lesser Antilles on 30 July. As the wave moved across the eastern and central Caribbean Sea on 31 July-1 August, a combination of decreased forward speed and decreasing vertical wind shear allowed the associated thunderstorm activity to increase and become better organized along the wave axis. On 1 August, ship reports and scatterometer surface wind data indicated that tropical-storm-force winds were already occurring in the northern and eastern portions of the fast-moving disturbance. Early on 2 August, a strong burst of deep convection developed along the wave axis and it is estimated that a tropical storm formed around 0600 UTC that day when the system was located about 100 n mi south of Jamaica.

Earl moved generally west-northwestward for the next three days along the southern periphery of a strong deep-layer ridge that extended from the central Atlantic Ocean westward across Florida, the Gulf of Mexico, and into mainland Mexico. Under the influence of light shear and 30^{O}C waters, the tropical cyclone steadily intensified, becoming a hurricane around 1800 UTC 3 August. Reconnaissance data indicate that Earl reached its peak intensity of 75 kt by 0400 UTC 4 August, just before the hurricane made landfall on the Belize island of Turnleffe Caye. The hurricane made a second landfall at the same intensity 2 h later along the coast of Belize just south of Belize City. After landfall, Earl weakened to a tropical storm over extreme northeastern Guatemala, and it maintained tropical storm status while it moved slowly west-northwestward across southeastern Mexico and into the southern Bay of Campeche. Upon emerging over water. Earl re-strengthened to an intensity of 50 kt before making its third and final landfall around 0230 UTC 6 August, along the eastern coast of mainland Mexico to the southeast of Veracruz near Salinas.

Remaining under the influence of the strong ridge to its north, Earl moved inland and encountered the rugged terrain of central Mexico, quickly weakening to a tropical depression by 1200 UTC and dissipating later on 6 August near Mexico City. Earl's remnants turned westward and moved across central Mexico and emerged over the eastern North Pacific Ocean a few days later, triggering the formation of Tropical Storm Javier in that basin.

Earl brought hurricane conditions to portions of Belize and the southeastern portion of the Yucatan Peninsula of Mexico, with tropical storm conditions occurring in other portions of southeastern and eastern Mexico near the track of the center. The maximum reported sustained winds were 63 kt with a gust of 90 kt at Xcalak in Quintana Roo state in Mexico. Storm surges of 4-6 ft above normal tide levels occurred along the coast of Belize in the landfall area. The cyclone produced storm total rainfalls of up to 8 inches in eastern Mexico.

Earl was responsible for 81 direct[1] deaths, all in Mexico. An additional 13 deaths were reported in the Dominican Republic when Earl's precursor disturbance passed over that country. Media reports and information from emergency management agencies indicate that torrential rains and strong winds associated with Hurricane Earl caused considerable damage across portions of the northern Caribbean Islands, Central America, and Mexico.

Hurricane Hermine

Hermine formed from a tropical wave that moved off the west coast of Africa late on 16 August and early on 17 August. After moving across the tropical Atlantic, the system spread heavy rains over portions of the Leeward Islands late on 23 August. These rains continued to spread across the Leeward Islands and Greater Antilles on 24-25 August, with the wave axis continuing quickly westward. While gale-force winds occurred north of the Greater Antilles, there was no closed circulation at this time. On 26 August, the northern portion of the tropical wave split off to the north of the Greater Antilles, and the disturbance's forward speed slowed considerably. However, the system also approached an upper-level trough that extended across the western Bahamas, and the resulting increased deep-layer shear caused the convection to lose organization and the maximum surface winds to decrease below gale force. Showers and thunderstorms remained displaced east of the wave axis for another day or two while the wave moved between Cuba and the Bahamas. The system finally developed a well-defined center of circulation on 28 August, and since the deep convection had sufficient organization at the time, it is estimated that a tropical depression formed by 1800 UTC that day in the Straits of Florida about 50 n mi south-southeast of Key West, Florida.

The depression was located to the south of a mid-level high pressure system centered over the Appalachian Mountains, which caused the cyclone to move slowly westward across the southeastern Gulf of Mexico through 30 August. Despite 30°C sea surface temperatures, persistent northwesterly shear prevented intensification for a couple of days. Early on 31 August, a break developed in the ridge over the southeastern United States, and the cyclone slowly turned toward the north and north-northeast. Upper-level winds also decreased, and the depression strengthened to a tropical storm by 0600 UTC that day while centered about 345 n mi west of Key West, Florida. Steady strengthening commenced at that time, with Hermine moving north-northeastward and northeastward over the warm waters of the eastern Gulf of Mexico around the western periphery of a low- to mid-level western Atlantic ridge. Still, upper-level winds remained strong enough to give the tropical storm an asymmetric structure, with most of the cloudiness and deep convection located east of the center in an elongated band that extended from the Yucatan Peninsula to Florida.

A central cluster of deep convection developed separate from the elongated cloud band early on 1 September, and a ragged eye became evident in visible imagery later that day. Hermine reached hurricane intensity by 1800 UTC while it was centered about 115 n mi south-

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[1] Deaths occurring as a direct result of the forces of the tropical cyclone are referred to as "direct" deaths. These would include those persons who drowned in storm surge, rough seas, rip currents, and freshwater floods. Direct deaths also include casualties resulting from lightning and wind-related events (e.g., collapsing structures). Deaths occurring from such factors as heart attacks, house fires, electrocutions from downed power lines, vehicle accidents on wet roads, etc., are considered "indirect" deaths.

southwest of Apalachicola, Florida, and it strengthened a little more, to a peak intensity of 70 kt, by 0000 UTC 2 September. Hermine maintained that intensity until landfall along the Florida Big Bend coast just east of St. Marks, Florida, at 0530 UTC 2 September. The cyclone weakened quickly once it moved inland, and became a tropical storm by 0800 UTC over the Florida Panhandle about 25 n mi east-northeast of Tallahassee.

As a tropical storm, Hermine moved northeastward just inland over coastal portions of Georgia, South Carolina, and North Carolina on 2-3 September with maximum sustained winds of 50 kt. During that time, Hermine began to develop frontal boundaries, which caused the convective structure to become increasingly asymmetric. Hermine became extratropical by 1200 UTC 3 September while centered near Oregon Inlet, North Carolina, while baroclinic forcing caused the cyclone's maximum winds to increase to 60 kt. The extratropical cyclone moved generally eastward over the Atlantic Ocean away from the coast, maintaining 60-kt winds until early on 5 September. The low then occluded and began to steadily weaken, and it turned northwestward and westward on 5 and 6 September, moving closer to the mid-Atlantic coast. Now cut off from the mid-latitude westerlies, the occluded low meandered offshore of New Jersey and Long Island on 7 September with its winds dropping below gale force by 1200 UTC. The weak low then moved northeastward on 8 September and dissipated soon after 1800 UTC near Chatham, Massachusetts.

Hermine produced hurricane conditions over a small portion of the coast of the Florida Big Bend, and a private weather station at Bald Point State Park measured a sustained wind of 53 kt and a gust to 68 kt while within Hermine's western eyewall. During Hermine's extratropical phase, the National Ocean Service station in Duck, North Carolina, measured a sustained wind of 62 kt, and a WeatherFlow station on the Alligator River Bridge (near the town of East Lake), North Carolina, measured a sustained wind of 60 kt. A storm surge of 7.5 ft above normal tide levels was reported at Cedar Key, Florida, with storm surges of 4 ft common elsewhere from Florida to North Carolina. A storm total rainfall of 22.36 inches was measured near Tarpon Springs, Florida, and rainfall totals exceeded 10 inches in other places in the southeastern United States. Hermine produced 10 total tornadoes: 5 in Florida, 2 in Georgia, and 3 in North Carolina.

Hermine was directly responsible for one death in Florida when it was a tropical cyclone, and it caused a second death in North Carolina after becoming extratropical. Property damage in the United States is estimated at $550 million.

Hurricane Matthew

Matthew, the first category 5 hurricane in the Atlantic since Felix in 2007, formed from a vigorous tropical wave that exited the west coast of Africa early on 23 September. The fast-moving, low-latitude disturbance generally remained south of 10^{O} N latitude until 26 September when it slowed down and turned toward the west-northwest. By 27 September, the system had tropical storm force winds, although a U.S. Air Force Reserve Unit reconnaissance aircraft was unable to close off a surface circulation during an investigative mission. Increased convective organization was seen early on 28 September when the system was passing just north of Barbados, and another Air Force Reserve Hurricane Hunter aircraft found a closed circulation and 50-kt surface winds around 1400 UTC that day. Based on the aircraft wind data and microwave satellite imagery, it is estimated that a tropical storm formed around 1200 UTC 28 September about 15 n mi west-northwest of Barbados.

Under the influence of a strong deep-layer ridge to its north, Matthew turned westward and moved across the Windward Islands, passing midway between St. Lucia and St. Vincent around 1800 UTC 28 September, and moved into the eastern Caribbean Sea 6 h later. As Matthew passed over the deep, warm waters of the Caribbean Sea, the tropical cyclone gradually strengthened within an environment of west-southwesterly vertical wind shear, reaching hurricane status by 1800 UTC 29 September about 165 n mi northeast of Curaçao.

Over the next 48 h, ridging increased to the north and west of Matthew, forcing the hurricane towards the west-southwest. Despite moderate vertical wind shear, Matthew underwent a 24-h period of rapid intensification between 0000 UTC 30 September and 0000 UTC 1 October, during which time the hurricane strengthened an extraordinary 75 kt, reaching an estimated peak intensity of 145 kt at 0000 UTC 1 October when the cyclone was located less than 80 n mi north of Punta Gallinas, Colombia. This intensity made Matthew the southernmost category 5 hurricane in the Atlantic basin, surpassing a record previously set by Hurricane Ivan in 2004.

Almost immediately after Matthew reached its peak intensity, the powerful hurricane began a slow weakening trend. Reconnaissance aircraft wind data indicated that a secondary wind maximum did not develop and that the weakening was likely not due to an eyewall replacement cycle. However, cold water upwelling seen in both satellite-derived sea-surface temperature data and data from NOAA buoy 42058 may have contributed to the weakening.

The western portion of the subtropical ridge across Cuba and Hispaniola weakened early on 2 October, and the hurricane made a small counter-clockwise loop and turned slowly northwestward within weak steering currents. During that time, Matthew weakened to an estimated intensity of 125 kt by 0600 UTC 2 October when the cyclone was located about 300 n mi south-southwest of Port-au-Prince, Haiti.

After the weakening, Matthew re-intensified between 0600 UTC and 1800 UTC on 2 October as it moved northward around the western periphery of a broad deep-layer ridge located over the central subtropical Atlantic. Matthew reached a secondary peak intensity of 135 kt by 1800 UTC 2 October when the powerful category 4 hurricane was located about 105 n mi south of Tiburon, Haiti. Over the next 12 h, Matthew moved slightly east of due north with some fluctuations in intensity, and it was at an intensity of 130 kt when the center made landfall along the southwestern coast of Haiti near Les Anglais around 1100 UTC 4 October. Matthew was the first category 4 hurricane to strike Haiti since Cleo of 1964.

Matthew continued moving northward across the western end of Haiti's Tiburon Peninsula and into the western Gulf of Gonâve by 1800 UTC. Land interaction caused the maximum sustained winds to decrease to 115 kt when the category 4 hurricane made landfall near Juaco, Cuba, around 0000 UTC 5 October. While an upper-level trough lifted out to the northeast, the ridge to the north of Matthew built westward, forcing the hurricane on a northwestward track across the eastern end of Cuba and into the Atlantic Ocean between Cuba and the Bahamas early on 5 October. Additional disruption by the mountainous terrain of eastern Cuba caused the hurricane to weaken to category 3 status. A slow increase in intensity occurred during the next 36 h as Matthew moved through the southeastern Bahamas. However, late on 6 October Matthew began a slow but steady weakening trend due to an eyewall replacement, increasing vertical wind shear, and decreasing mid-level moisture ahead of an approaching mid-latitude trough. Matthew's eyewall passed over the extreme western portion of New Providence Island, bringing hurricane-force winds and flooding rains to most of the central and northwestern Bahamas. Continuing on a northwestward track, the category 4 hurricane made landfall near West End, Grand Bahama Island, around 0000 UTC 7 October, bringing Category 3 winds to that area.

A broad, eastward-moving mid-latitude trough located over the central United States gradually eroded the ridge to the north and east of Matthew, allowing the major hurricane to turn toward the north-northwest on 7 October. Over the next 24 h, Mathew completed an eyewall replacement cycle, causing the eye diameter to increase to 30-40 n mi. Remaining about 30 n mi offshore of the Florida east coast, the western edge of Matthew's eyewall barely clipped NASA's Cape Canaveral launch facility. Matthew weakened to a category 3 hurricane around 0600 UTC 7 October about 35 n mi east of Vero Beach, Florida, and became a category 2 hurricane by 0000 UTC 8 October when the cyclone was located about 50 n mi east-northeast of Jacksonville Beach, Florida.

Hurricane Matthew moved northward around the western periphery of a subtropical ridge early on 8 October, remaining about 50 n mi offshore of the Georgia coast. The approaching mid-latitude trough eroded the subtropical ridge further, causing hurricane to make a sharp turn toward the northeast and weaken more. This led the now category 1 hurricane to make landfall around 1500 UTC 8 that day just south of McClellanville, South Carolina, in the Cape Romain Wildlife Sanctuary. The center moved back offshore the coast of South Carolina by 1800 UTC, and remained just offshore of the coast of North Carolina through 9 October. Matthew moved east-northeastward and lost its tropical characteristics late by 1200 UTC 9 October, with the system subsequently merging with a frontal system 12 h later about 200 n mi east of Cape Hatteras, North Carolina. Still possessing hurricane-force winds, the elongated cyclone turned northeastward along the frontal boundary, brushing the coast of eastern Nova Scotia late on 10 October. The remnants of Matthew eventually merged with a larger extratropical low pressure system near Atlantic Canada on 11 October.

Matthew affected a large area from the eastern and central Caribbean Sea northward across Hispaniola, Cuba and the Bahamas to the southeastern United States. Hurricane conditions occurred over portions of Haiti, eastern Cuba, the Bahamas, and the coastal regions of the southeastern United States from Florida to North Carolina, while tropical storm conditions occurred over portions of the Lesser Antilles, the Dominican Republic, elsewhere in central/eastern Cuba and the Bahamas, and the southeastern U. S. coast. Punta de Maisí, Cuba, measured a 1-min mean wind of 108 kt with a gust to 132 kt before the instrument stopped functioning, while a sustained wind of 103 kt and a gust of 151 kt were reported along the northeast coast of Cuba in Jamal. Storm surges of 10-13 ft occurred in eastern Cuba, with significant surges also reported in the Bahamas and the southeastern United States. Widespread heavy rain occurred along the track of Mathew, with 26.04 in measured at Punta de Maisí, Cuba, 23.80 inches measured at Anse-à-Veau, Haiti, and numerous other reports in excess of 15 inches.

Matthew was responsible for 585 direct deaths: 546 in Haiti, 34 in the United States, 4 in the Dominican Republic, and 1 in St. Vincent and the Grenadines. An additional 18 indirect deaths occurred in the United States, and 128 persons are missing and 439 persons were injured in Haiti.

Reported property damage includes $1.9 billion in Haiti, $2.58 billion on Cuba, $600 million in the Bahamas, and $10 billion in the United States.

Hurricane Nicole

The long and complex history of Nicole began when a tropical wave emerged from the west coast of Africa on 25 September. The system was showing some signs of organization on 30 September when it encountered strong southwesterly shear associated with a middle- to upper-tropospheric cyclone over the subtropical east-central Atlantic. This inhibited subsequent development until a portion of the wave fractured and moved northwestward, placing it in a lighter-shear and more-diffluent environment on the northern side of the upper-level low by 2 October. Deep convection associated with the disturbance became organized into a smaller, quasi-circular mass, and a mid-level cyclonic circulation became evident in satellite imagery late that same day. An elongated surface circulation formed on 3 October, and ASCAT data at 0144 UTC ASCAT 4 October showed that the system had tropical-storm-force winds. The circulation then became sufficiently well-defined to mark the formation of a tropical storm around 0600 UTC that day about 460 n mi northeast of San Juan, Puerto Rico.

Nicole moved northwestward along the southwestern edge of a low- to mid-level subtropical ridge on 4-5 October under northwesterly shear caused by the outflow from Hurricane Matthew. However, this shear was confined to a narrow layer at the top of the troposphere, and Nicole managed to strengthen slightly while producing occasional bursts of deep convection. Nicole entered a col region in the steering currents on 6 October, and became nearly stationary later that day. As the shear diminished, Nicole's cloud pattern became better organized and a period of rapid intensification began; the small tropical cyclone is estimated to have reached an intensity of 90 kt around 0000 UTC 7 October while centered about 285 n mi south of Bermuda. This intensification was interrupted when a shortwave trough diving southeastward from the northeastern United States into the central Atlantic produced a deeper layer of northerly shear. Nicole weakened as rapidly as it had strengthened, and the cyclone became a tropical storm by 1200 UTC 7 October.

Over the next couple of days, the shortwave trough caused northerly shear and dry air entrainment, which inhibited intensification while a blocking high to the north of Nicole nudged the tropical cyclone slowly southward. The slow motion induced a broad region of oceanic upwelling and decreased sea surface temperatures near Nicole, which also helped to inhibit development until Nicole moved away from the affected region early on 11 October. Nicole regained hurricane intensity between 1200 and 1800 UTC 11 October that day while centered a few hundred n mi south-southwest of Bermuda. The shear decreased further while the cyclone was moving over sea surface temperatures of 29ºC - 30ºC (record high temperatures for that time of the year over the west-central Atlantic) and a microwave pass from around 1200 UTC that day showed a closed low-level ring of convection, typically a harbinger of rapid intensification. Nicole subsequently did just that, strengthening into a major hurricane about 24 h later while centered about 260 n mi south-southwest of Bermuda, and it reached a peak intensity of 120 kt around 0600 UTC 13 October, when it was about 120 n mi southwest of the island.

Nicole then accelerated north-northeastward to northeastward toward Bermuda on 13 October, ahead of a mid-latitude trough moving through the northeastern United States. Increasing shear started a weakening trend, but Nicole was still a major hurricane when the eye passed over the island between 1400 and 1500 UTC. The hurricane then rapidly weakened, with all of its central convection dissipating by around 0600 UTC 14 October. A negatively tilted shortwave trough, the second in a series, approached the cyclone from the northwest later that day, and a portion of the trough merged with the tropical cyclone the following day. Baroclinic forcing associated with this feature during the next 24-48 h resulted in Nicole acquiring some of the characteristics of a subtropical cyclone while it was centered several hundred n mi south of Newfoundland. A comma-shaped area of shallow-to-moderate convection developed on 15 October as the trough interaction caused Nicole to re-intensify, with a 1252 UTC 15 October ASCAT pass suggesting peak winds of about 75 kt. As this occurred, the cyclone's radii of tropical-storm-force winds nearly doubled in size from 14-16 October.

The influence of the trough diminished on 15 October, and a ragged eye surrounded by disorganized shallow convection appeared the next day. Nicole turned east-northeastward to eastward at a decreased forward speed when the trough moved away and left it in a region of weak steering in the mid-latitude westerly flow. By 17 October, a large and well-defined eye had formed within a circular and relatively symmetric central dense overcast while centered about 500 n mi southeast of Cape Race, Newfoundland, indicating that Nicole had regained some of the tropical cyclone characteristics it had previously lost. Another trough moving through Atlantic Canada that day caused Nicole to accelerate northeastward, which brought it over progressively colder waters and into a cooler air mass, causing extratropical transition to begin. Nicole weakened to a tropical storm at 0000 UTC 18 October and became extratropical 6 h later while moving north-northeastward with increasing forward speed. The cyclone was absorbed by a larger extratropical storm forming over the far North Atlantic the next day several hundred n mi southeast of Greenland.

Nicole produced hurricane conditions on Bermuda. Comissioner's Point (elevation 46 m) reported a 1-min mean wind of 87 kt with a peak gust of 111 kt, while Pearl Island reported a 10-min mean wind of 76 kt. A storm surge of 3.72 ft above normal tide levels occurred at St. George, with about 1 ft of inundation occurring. The hurricane produced storm-total rainfalls of 6-9 inches on the island.

There were no reports of casualties from Nicole. The hurricane caused widespread damage on Bermuda with estimated total insured losses of $15 million.

Hurricane Otto

Otto, the first hurricane on record in Costa Rica, formed from a broad cyclonic gyre that developed over the southwestern Caribbean Sea, which likely resulted from the combination of an eastward-moving convectively coupled Kelvin wave and a couple of tropical waves that passed through the area in mid-November. A broad surface low pressure area formed a few hundred n mi northwest of Colombia on 15 November. The low produced disorganized cloudiness, thunderstorms, and generally light winds for the next several days as it meandered across the southwestern Caribbean. Early on 20 November, a surge of northerly low-level winds associated with a cold front and high pressure ridge over the Gulf of Mexico moved across the northwestern Caribbean Sea and pushed southward along the east coast of Nicaragua. This northerly surge appears to have helped to concentrate the low-level vorticity within the pre-existing low pressure area, which led to the low becoming better defined. The associated thunderstorm activity increased in organization later that day, resulting in the formation of a tropical depression at 1800 UTC 20 November about 105 n mi north of Colón, Panama.

The tropical cyclone drifted eastward, and then southward on 21-22 November while it was located within a col between two mid-level ridges. Steady strengthening occurred within an environment of moderate south-southeasterly shear and over warm 29°C waters. The tropical depression strengthened into a tropical storm by 0600 UTC 21 November, and Otto reached an intensity of 60 kt at 1200 UTC 22 November, while it was centered about 75 n mi north-northeast of Colon. Around that time, Otto began moving slowly west-northwestward to the south of a building mid-level ridge. Later that day, Otto's development ceased when a slight increase in southeasterly shear and the entrainment of dry-mid level air caused the inner-core structure of the tropical cyclone to become less organized.

Around 1800 UTC 23 November, a burst of deep convection developed over the center of the tropical cyclone and it is estimated that Otto became a hurricane at that time, while located about 150 n mi east of the Nicaragua/Costa Rica border. Shortly after that, decreasing shear allowed a period of rapid intensification while Otto began moving more quickly westward toward the coast of Central America. Microwave and geostationary satellite data showed the formation of a well-defined eye shortly before 1200 UTC 24 November. Subsequent United States Air Force Reserve Hurricane Hunter aircraft data and satellite imagery indicate that Otto reached its estimated peak intensity of 100 kt (category 3) at 1200 UTC while located about 40 n mi east of the Nicaragua/Costa Rica border. Little change in strength occurred before Otto made landfall in the Indio Maíz Biological Reserve in extreme southern Nicaragua about 10 n mi northwest of the Nicaragua/Costa Rica border around 1730 UTC 24 November.

The hurricane rapidly weakened while moving inland over southern Nicaragua, and by 0000 UTC Otto had become a category 1 hurricane when it turned west-southwestward and passed over extreme northwestern Costa Rica. Radar data from Las Nubes, Nicaragua, and microwave satellite imagery showed that the eye of Otto remained intact while the storm traversed Central America. Otto weakened to a tropical storm just before it exited the Pacific coast of northwestern Costa Rica near the Gulf of Papagayo around 0330 UTC 25 November. The tropical cyclone encountered less favorable atmospheric conditions over the far eastern Pacific Ocean that included stronger southeasterly shear and dry mid-level air, which caused the tropical storm to gradually weaken while it moved west-southwestward at an increasingly faster forward speed. Deep convection associated with Otto quickly decreased in organization on 26 November, and the system weakened to a tropical depression by 1200 UTC that day. Shortly after that time, Otto degenerated into a trough of low pressure about 425 n mi south of Salina Cruz, Mexico. The remnants of Otto continued to produce disorganized showers during the next few days while remaining well south of the southern coast of Mexico.

Otto brought hurricane conditions to portions of southeastern Nicaragua and northern Costa Rica. However, no observations of winds, pressures, or storm surge are available near the path of the center. The cyclone brought storm total rainfalls of up to 12 inches in Costa Rica, as well as locally heavy rains in Nicaragua and Panama.

Hurricane Otto is responsible for 18 direct deaths in Central America, of which 10 occurred in Costa Rica and 8 in Panama. Extensive damage to homes, roads, bridges, and crops were reported from portions of Panama, Costa Rica, and Nicaragua.

FORECAST VERIFICATION

In 2016, the NHC issued 386 Atlantic basin tropical cyclone forecasts, which is above the long-term average of 316. The mean track errors ranged from 24 n mi at 12 h to 168 n mi at 120 h, which were smaller than the previous 5-yr means by up to 24%, However, the Climatology-Persistence (CLIPER) errors were also lower than average, indicating that the season's storms were a little easier to forecast than normal. Records for accuracy were set at all time periods except 120 h. The official track forecast vector biases were northwesterly (i.e., the official forecasts tended to fall to the northwest of the verifying position) at all forecast periods, and they increased with time. Track forecast skill compared to CLIPER ranged from 45% at 12 h to 72% at 72 h. While the official forecasts were highly skillful, they were slightly bested by the consensus models HCCA and TVCA from 12 to 96 h. The U. S. Global Forecast System and the United Kingdom Meteorological Office (UKMET) models were the best in the short range, while the European Center for Medium Range Weather Forecasting model was the most skillful individual model from 72 to 120 h. The UKMET ensemble mean (UEMI) was also very skillful and had similar or slightly lower errors than the above mentioned models.

Mean intensity forecast errors in 2016 ranged from 5 kt at 12 h to 16 kt at 120 h. These errors were below the 5-yr means from 12 to 72 h, but above the 5-yr means at 96 and 120 h. No records for accuracy were set in 2016. The official forecasts had a slight low bias at all forecast time periods. Decay-SHIFOR5 errors were above their 5-yr means at all times and were much larger than average at 96 and 120 h, implying that the season's storms were more challenging than normal to predict. In 2016, skill compared to Decay-SHIFOR5 was at an all-time high at 24 h. Skill values at the other forecast times, however, were lower than record levels set a couple of years ago. Among the guidance, the lowest forecast errors in 2016 were from the consensus aids IVCN and HCCA. The Florida State University Superensemble was competitive with IVCN and HCCA early, but its skill degraded at the longer lead times. Conversely, the Hurricane Weather Research and Forecast model (HWRF) and the U. S. Navy COAMPS-TC (CTC) models showed increased skill with forecast time and were the best models at 96 and 120 h. The Decay SHIPS and LGEM were fair performers, but were not as skillful as the consensus aids or regional models CTC and HWRF.

The NHC routinely issues Tropical Weather Outlooks (TWOs) for the Atlantic basin where forecasters subjectively assigned a probability of genesis (0 to 100%, in 10% increments) to each area of disturbed weather described in the TWO, where the assigned probabilities represented the forecaster's determination of the chance of tropical cyclone formation during the 48- and 120-h period following the nominal TWO issuance time. In 2016 in the Atlantic basin, a total of 586 genesis forecasts were made. These 48-h forecasts were quite reliable for the low probabilities (30% or less), but were not well calibrated at the medium probabilities (40-60%). An under-forecast (low) bias for a small sample existed at the high probabilities (70% or greater). The 120-

h forecasts were well calibrated at the medium probabilities, but a slight low bias existed at both the high and low categories.

References

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Table 1. 2016 Atlantic hurricane season statistics.

Storm Name	Class[a]	Dates[b]	Max. Winds (kt)	Min. Pressure (mb)	Deaths	U.S. Damage ($million)
Alex	H	12 – 15 Jan	75	981		
Bonnie	TS	27 May 27 – 4 Jun	40	1006	1	minor
Colin	TS	5 – 7 Jun	45	1001		minor
Danielle	TS	19 – 21 Jun	40	1007	1	
Earl	H	2 – 6 Aug	75	979	81	
Fiona	TS	16 – 23 Aug	45	1004		
Gaston	MH	22 Aug – 2 Sep	105	955		
Eight	TD	28 Aug – 1 Sep	30	1010		
Hermine	H	28 Aug – 3 Sep	70	981	1	550
Ian	TS	12 – 16 Sep	50	994		
Julia	TS	13 – 18 Sep	45	1007		minor
Karl	TS	14 – 25 Sep	60	988		
Lisa	TS	19 – 25 Sep	45	999		
Matthew	MH	28 Sep – 9 Oct	145	934	585	10000
Nicole	MH	4 – 18 Oct	120	950		
Otto[c]	MH	20 – 26 Nov	100	975	18	

[a] Tropical depression (TD), maximum sustained winds 33 kt or less; tropical storm (TS), winds 34-63 kt; hurricane (H), winds 64-95 kt; major hurricane (MH), winds 96 kt or higher.

[b] Dates begin at 0000 UTC and include all tropical and subtropical cyclone stages; non-tropical stages are excluded.

[c] Includes lifetime in the eastern North Pacific basin.

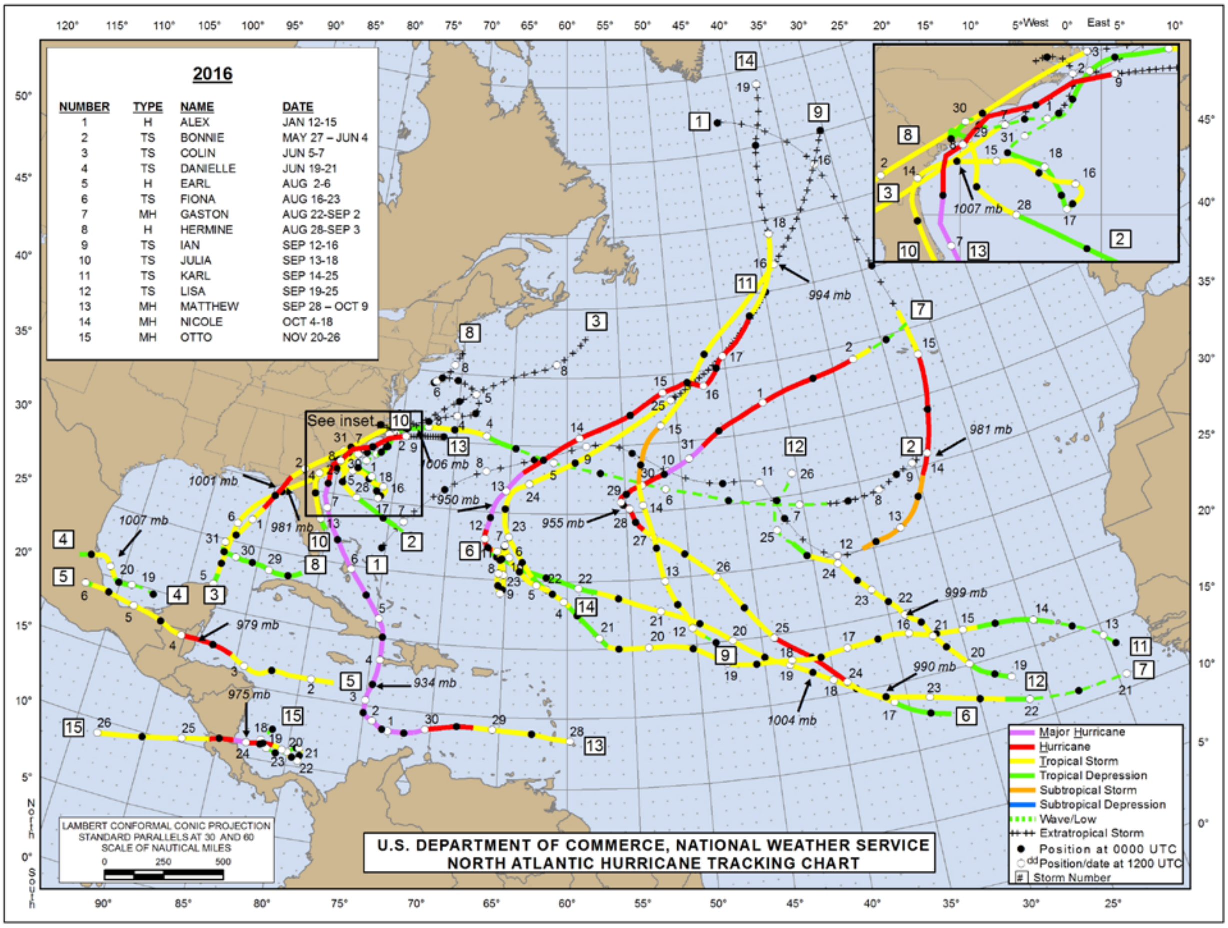

Figure 1: Tracks of the tropical storms and hurricanes of the 2016 Atlantic hurricane season.

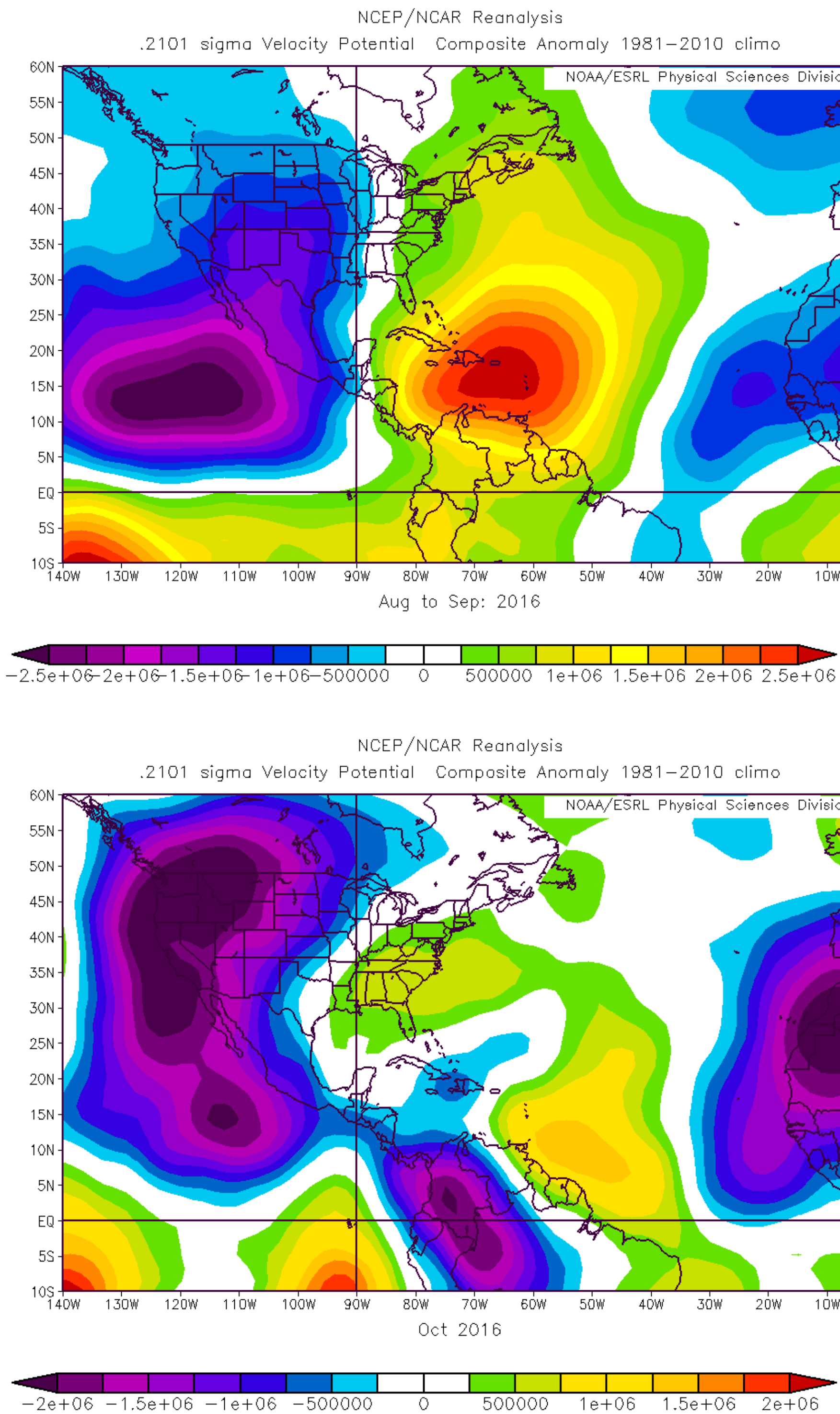

Figure 2. 200-mb velocity potential anomalies (m^2/s) for August/September 2016 (upper image) and October 2016 (lower image). Blue/purple areas experienced anomalous upper-level divergence or rising motion, while green/yellow areas experienced anomalous upper-level convergence or sinking air. Anomalies were computed relative to 1981-2010 climatology from NCEP/NCAR reanalysis. Images courtesy of the NOAA/Earth Systems Research Laboratory.