

# 2015 **North Atlantic Hurricane** Season Review



## **Executive Summary**

The 2015 North Atlantic hurricane season was a quiet one, closing with eleven named storms, four hurricanes, and two major hurricanes (Category 3 or stronger). This year stands as the third successive quiet hurricane season in the Atlantic Basin marked by predominantly short-lived, low-intensity storms.

Forecast groups predicted that below-average sea surface temperatures (SSTs) and above-average sea-level pressure in the Atlantic Main Development Region (MDR)<sup>1</sup> would continue through the 2015 season. These conditions, combined with the anticipated development of a strong of El Niño event, were expected to inhibit cyclogenesis in 2015, leading to a below-average season. Although predicted SST and sea-level pressure conditions did not materialize, 2015 was indeed a quiet season, as a result of the anticipated El Niño event, which is currently tied with 1997 as the strongest event on record.

In addition to the strong El Niño event, the scientific community identified a number of other oceanic and atmospheric conditions detrimental to hurricane formation in 2015: above-average wind shear across the Caribbean and the central tropical Atlantic, anomalously low Atlantic mid-level moisture, strong steering currents over the eastern United States, and anomalously high tropical Atlantic subsidence (sinking air) in the MDR. Many of these conditions were also present in the 2013 and 2014 hurricane seasons, inhibiting cyclogenesis and resulting in below-average activity in the Atlantic Basin.

The conclusion of the 2015 season extends the longest period on record to ten years with no major U.S. hurricane landfalls, according to records dating back to 1851. The last major U.S. landfalling hurricane was Hurricane Wilma in 2005, also the last hurricane to make landfall over the coastline of Florida.

The 2015 hurricane season had an early start, as Tropical Storm Ana formed on Friday, May 8, and made landfall over Myrtle Beach, South Carolina, on Sunday, May 10, making Ana the earliest tropical storm landfall over the U.S. since records began and the earliest subtropical storm to form in the Atlantic since 2003. Tropical Storm Bill formed on Tuesday, June 16, before making landfall over Matagorda Island, Texas, on the same day. The tropical wave that was the precursor to Bill brought heavy rainfall to Central America, causing flooding in Honduras, Guatemala, and southern Mexico. Ana and Bill were the only two storms to make landfall over the U.S. in 2015. The Caribbean was impacted by three storms this season: Tropical Storm Erika, Major Hurricane Joaquin, and Hurricane Kate. Erika caused significant damage in the Lesser Antilles and Greater Antilles, though Joaquin proved to be the strongest and most destructive named storm of the 2015 season. Hurricane force winds and storm surge from Joaquin devastated the islands of the central Bahamas and caused damage in Cuba and Haiti. Kate brought tropical storm force winds to the Central Bahamas, though did not cause significant damage.

Early 2016 hurricane season forecasts by Tropical Storm Risk (TSR) predict the 2016 season will be below the 1950-2014 average, continuing the recent succession of quiet hurricane seasons. Colorado State University (CSU) anticipates that the activity in 2016 will be determined by the strength of the thermohaline circulation (THC) and Atlantic Multidecadal Oscillation (AMO), as well as the phase of El Niño Southern Oscillation (ENSO).

The Main Development Region spans the tropical Atlantic Ocean and the Caribbean Sea between 10-20°N, 20-80°W.

## **Overview of the 2015 North Atlantic Hurricane Season**

The Atlantic hurricane season runs from June 1 to November 30, with activity characterized by the number of named storms, hurricanes, and major hurricanes<sup>2</sup> in the Atlantic throughout this period. The 2015 North Atlantic hurricane season was relatively quiet (see Figure 1), closing with eleven named storms, four hurricanes, and two major hurricanes (Category 3 or stronger).



Figure 1: Comparison of the 2015 North Atlantic hurricane season storms to the 1950-2014 and 1995-2014 averages (data from Hurricane Research Division, 2015)

The 2015 season saw the fourth-lowest number of named storms in the last 20 years, since 1995, with eleven named storms forming in 2015, just slightly below (1.8%) the 1950-2014 average<sup>3</sup> (11.2 storms), though substantially lower (26%) than the 1995-2014 average<sup>4</sup> (14.8 storms).

While the total number of storms in 2015 was similar to the 1950-2014 average, the number of hurricanes and major hurricanes in 2015 fell significantly below both the 1950-2014 and 1995-2014 averages. The total of four hurricanes in 2015 was 47% below the 1995-2014 average (7.6 storms) and 35% below the 1950-2014 average (6.2 storms). Of the 2015 hurricanes, two reached Category 1 strength while the other two reached major hurricane strength (Category 3 and above), as defined by the Saffir-Simpson Hurricane Wind Scale (SSHWS). The number of major hurricanes during the 2015 season was 44% below the 1995-2014 average (3.6 storms) and 26% below the 1950-2014 average (2.7 storms).

The U.S. saw two landfalling tropical storms in 2015 — Ana and Bill — though no hurricanes, and therefore no major hurricanes made landfall over the U.S. in 2015. The last major hurricane to make landfall in the U.S. was Hurricane Wilma (2005), which means the U.S. has gone ten years without a major hurricane landfall — the longest period since records began in 1851. The previous record was eight years without a major hurricane landfall, which occurred between 1861 and 1868 (Masters & Henson, 2015).

<sup>&</sup>lt;sup>2</sup>Named storms are defined as systems that reach tropical storm strength or above on the Saffir-Simpson Hurricane Wind Scale (SSHWS) (NHC, 2014). The term hurricane is given to a system that reaches Category 1 on the SSHWS, while a major hurricane is classified as a Category 3 or higher on the SSHWS (NHC, 2014).

<sup>&</sup>lt;sup>3</sup>The historical database for landfalling hurricanes 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 increases in aircraft reconnaissance and the onset of satellite technology.

<sup>&</sup>lt;sup>4</sup>It is widely recognized that the Atlantic Basin entered a period of elevated activity in 1995 compared to the long-term historical average, driven by a positive phase in the Atlantic Multidecadal Oscillation (AMO).

Major Hurricane Joaquin was the strongest named storm of the 2015 season, reaching peak intensity as a Category 4 hurricane over the North Atlantic on Saturday, October 2. Prior to reaching peak intensity, Joaquin tracked slowly over the central Bahamas as a Category 4 hurricane, becoming the first Category 4 hurricane to impact the Bahamas during the month of October since 1866.

In 2015, the Accumulated Cyclone Energy (ACE)<sup>5</sup> index, which provides an alternative assessment of hurricane activity and defines the intensity and duration of tropical cyclones, was 62, 36% lower than the 1950-2014 average of 100.9, as seen in Figure 2, and the fourth lowest that has been observed during the 1995-2014 average. Just under half of the ACE index in 2015, 46.3%, is attributed to Major Hurricane Joaquin, which generated an ACE value of 28.7 (see Figure 3). The ACE value in September 2015 was just 11, bringing the September three-year (2013-2015) ACE average to 44, the lowest on record since 1912-1914 when a three-year September ACE of 29 was recorded.



Figure 2: Atlantic hurricane season ACE totals and averages 1950-2015 (data from WeatherBell, 2015)

<sup>&</sup>lt;sup>5</sup>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<sup>4</sup> kt<sup>2</sup>.



Figure 3: ACE values for named storms in the 2015 season (data from WeatherBell, 2015; TS = Tropical Storm, H = Hurricane, and MH = Major Hurricane)

The decade-long absence of a major hurricane landfall over the U.S. has attracted attention from the scientific community, with recent research declaring this gap a "hurricane drought" (Hall & Hereid, 2015). However, additional research suggests that this "drought" is shortened or even eliminated in the context of other measures of hurricane intensity, such as maximum wind or minimum central pressure (Hart, Chavas, & Guishard, 2015). While the 2013-2015 seasons have exhibited a below-average frequency of hurricane landfalls, occurrences of cyclogenesis remain at or above the historical average (Figure 2). This stands in contrast to previous periods of low landfall frequency occurring between the late 1960s and early 1990s, in which overall cyclogenesis rates remained low. These two periods therefore may be driven by different physical mechanisms; an understanding of the true nature of the last ten years' "drought" may require many more years of observation, particularly given the ongoing uncertainty around governing Atlantic hurricane activity.

## The 2015 North Atlantic Storms and Their Impacts

As outlined previously, two storms, Tropical Storm Ana and Tropical Storm Bill, made landfall over the U.S. in 2015. Since 1900, on average, 3.5 named storms, 1.8 hurricanes, and 0.7 major hurricanes made U.S. landfall annually. The Atlantic coastline of Mexico and Central America saw a particularly quiet year with no landfalls, although they were impacted by Tropical Storm Bill. The Caribbean was impacted by three storms this season: Tropical Storm Erika, Major Hurricane Joaquin, and Hurricane Kate. Bermuda was also impacted by Major Hurricane Joaquin. The 2015 season's hurricane activity is illustrated in Figure 4 and Figure 5.



Figure 4: The 2015 Atlantic storm tracks and intensities (data from NHC, 2015)

Named Storm	Мау	June	July	August	September	October	November
TS Ana	2.6						
TS Bill		1.6					
TS Claudette			1.1				
MH Danny				9.	.2		
TS Erika					3.2		
H Fred					5.7		
TS Grace					1.5		
TS Henri					0.9		
TS Ida					3.	4	
MH Joaquin						28.7	
H Kate							4.4

Figure 5: Timeline of the 2015 Atlantic hurricane season (data from the NHC as of December 1, 2015; TS = Tropical Storm, H = Hurricane, and MH = Major Hurricane) with ACE values in red for each storm

#### **Tropical Storm Ana**

The first named storm of the 2015 season, Tropical Storm Ana, formed as a subtropical storm on Friday, May 8, approximately 170 mi (275 km) south-southeast of Myrtle Beach, South Carolina. Ana was the earliest subtropical or tropical storm to form in the Atlantic since 2003, when a tropical storm of the same name formed on Sunday, April 20. Due to the warm waters of the Gulf Stream and abnormally cold upper-level temperatures, Ana reached its peak intensity on Friday, May 8, with wind speeds of 60 mph (95 km/hr), before completing its transition to a tropical storm on Saturday, May 21, approximately 130 mi (210 km) southeast of Myrtle Beach.

Ana weakened slightly prior to making landfall just north of Myrtle Beach, South Carolina, as a tropical storm around 10:00 UTC on Sunday, May 10, becoming the earliest tropical storm to make landfall over the U.S. since records began. After making landfall, the system quickly weakened to a tropical depression and curved to the northeast, passing over North Carolina and southeastern Virginia prior to degenerating to a remnant low and emerging off the coast of the Delmarva Peninsula on Tuesday, May 12. Tropical Storm Ana produced rainfall accumulations of up to 170 mm (6.7 in) in South Carolina and North Carolina, which caused minor street flooding, while tropical storm force winds downed trees and power lines in North Carolina, resulting in one fatality.

#### **Tropical Storm Bill**

Tropical Storm Bill formed as the result of an upper-level trough identified over the western Caribbean Sea on Friday, June 12. After tracking northeast over the following days and encountering favorable conditions in the Gulf of Mexico, Bill became the second named storm of the 2015 season early UTC on Tuesday, June 16, off the coast of Mexico. The system reached its peak intensity of 60 mph (95 km/hr) prior to making landfall over Matagorda Island, Texas, around 16:45 UTC on Tuesday, June 16 (see Figure 6). While over Texas, Bill rapidly weakened to a tropical depression and curved to the northeast, tracking over the Central Plains during the following two days before dissipating on Thursday, June 18.

Prior to formation, the tropical wave that was the precursor to Bill brought heavy rainfall to Central America, causing flooding in Honduras, Guatemala, and southern Mexico. More than 516,000 people were affected in Guatemala, while 100 homes were damaged and two fatalities were reported as the result of a landslide. Two people died in Honduras, while two others were officially classified as missing. In the Yucatan Peninsula, Mexico, rainfall accumulations of 330 mm (13 in) were recorded in Cancun over a period of 24 hours — the highest daily total in the city in almost two years. Damage to trees and cars was reported in Cancun, while one fatality was recorded in the city.

In the U.S., Bill brought heavy rainfall and flooding to Texas and Oklahoma, which closed highways, caused over 20,000





Destuctive Fotenula Ratingto-6) Wind: 0.0. Surgenwaves: 0.5 Observed Max. Surface Wind: 46 kts, 33 nm NE of center based on 1432 z AFRC Analyzed Max. Wind: 46 kts, 35 nm E of center Uncertainty -> mean wind speed error: -0.66 kt, mean direction error: 0.00 deg mrs wind speed error: -0.13 kt, rms direction error: 10.58 deg (c) 2015 Hwind Scientific

Figure 6: Real-time snapshot of Tropical Storm Bill's wind field conditions at landfall over the Texas coastline on June 16, 2015 (source: Hwind Scientific)

power outages, and disrupted ferry services and more than 250 flights. Rainfall and severe thunderstorms also impacted Indiana, Ohio, Kentucky, West Virginia, Virginia, and North Carolina, where floodwaters inundated roads and several basements. Three fatalities attributed to Tropical Storm Bill were recorded across the United States.

#### **Tropical Storm Claudette**

On Monday, July 13, a surface low off the coast of the Outer Banks, North Carolina, rapidly strengthened into a tropical storm, Claudette. The sudden formation of Claudette was not well forecast at the time and was attributed to increased atmospheric convection while the system was crossing the Gulf Stream. Tropical Storm Claudette gradually tracked northeast over the North Atlantic, reaching peak intensity with winds of 50 mph (85 km/hr) around 18:00 UTC on Monday, July 13, far off the eastern U.S. coastline. On Tuesday, July 14, Claudette entered an area of increased wind shear, prompting the system to weaken, transitioning to a remnant low by 00:00 UTC on Wednesday, July 15, approximately 250 mi (410 km) east of Nova Scotia, Canada.

The remnants of the system, which passed over Newfoundland, Canada, on Wednesday, July 15, caused transport disruption and forced a number of flight cancellations.

#### Major Hurricane Danny

Danny formed from a tropical wave south-southwest of the Cape Verde Islands. Favorable atmospheric conditions over the Main Development Region (MDR) allowed Danny to strengthen to a tropical storm on Tuesday, August 18. Danny continued to strengthen while tracking towards the west, becoming the first hurricane of the 2015 season by Thursday, August 20. Danny reached peak intensity the following day as a Category 3 hurricane approximately 810 mi (1,300 km) east of the Lesser Antilles with winds of 115 mph (185 km/hr), becoming the first major hurricane of the 2015 Atlantic hurricane season. At this time, the system had an unusually high central pressure for a Category 3 hurricane, 974 mb, which is usually associated with a Category 2 hurricane. While tracking west towards the Lesser Antilles, Danny entered an area of high wind shear and drier air, causing the system to weaken rapidly. On Monday, August 24, Danny dissipated approximately 45 mi (72 km) west-southwest of Guadeloupe before reaching land.

The remnants of the system brought wind gusts and rain to the Leeward Islands on Monday, August 24, while Puerto Rico and the Virgin Islands experienced rain on Tuesday, August 25, though impacts were minimal.

#### **Tropical Storm Erika**

The fifth storm of the year, Tropical Storm Erika, formed from an African easterly wave in the open waters of the eastern Atlantic in late August. Erika was located south of a region of high atmospheric pressure, which caused the system to track rapidly to the west over the MDR, passing between Guadeloupe and Antigua on Thursday, August 27. Certain forecast models predicted that Erika would intensify and curve north towards Florida, which triggered a state of emergency on Friday, August 28. However, Erika remained disorganized amid the unfavorable environment surrounding the Caribbean Islands, only reaching a peak intensity with maximum sustained winds of 50 mph (85 km/hr) and a central pressure of 1001 mb.

By the time Erika reached the Dominican Republic on Friday, August 28, it no longer had a closed circulation, and over the following two days the storm degenerated into an open tropical wave before dissipating near Cuba.

Erika brought tropical storm force winds and heavy rainfall across the Caribbean. The island of Dominica was the worst impacted by the storm, with rainfall accumulations of 321 mm (12.64 in) recorded at Canefield Airport over a period of 12 hours. The heavy rainfall triggered flooding, which damaged buildings and airports, cut power to 80% of the island, and caused 31 fatalities. Approximately 890 homes on Dominica were destroyed or rendered uninhabitable, displacing more than 14,200 people. In the Greater Antilles, the Dominican Republic experienced significant damage due to flooding, as 200,000 power outages were reported, more than 400 roads were blocked by debris, and 823 homes were damaged, displacing 7,345 people. Haiti was also impacted by heavy rainfall, which damaged some homes, triggered landslides, and resulted in one fatality and two injuries. Rainfall generated by the system was welcomed in Cuba, which was suffering from its worst drought since 1901.

#### Hurricane Fred

On Thursday, August 27, a well-defined tropical wave was observed over western Africa. As the tropical wave tracked west, it strengthened early UTC on Sunday, August 30, to become the sixth named storm of the 2015 Atlantic hurricane season. Fred is one of a small number of recorded tropical storms that have formed east of 20°W over the eastern Atlantic. The system strengthened further, becoming a hurricane on Monday, August 31, topping out with maximum sustained winds of 85 mph (140 km/hr) and a central pressure of 986 mb. Fred skirted the island of Boa Vista of the Cape Verde Islands soon after reaching hurricane intensity, becoming the first hurricane to impact the islands since 1892. After impacting the islands, Fred continued to track northwest over the eastern Atlantic and entered an area of drier air, causing the system to gradually weaken and dissipate over the cooler waters of the central Atlantic by Saturday, September 5.

Fred brought high surf and strong winds to the Cape Verde Islands, which flooded and damaged buildings, uprooted trees, and caused widespread power outages. The island of Boa Vista was the worst impacted, with 70% of buildings in the village of Povoacao Velha experiencing varying degrees of damage. Stormy weather from Fred is believed to have caused the sinking of dozens of boats around the Cape Verde Islands, as well as two fatalities.

Swells generated by Hurricane Fred produced high surf, which impacted western Africa, particularly Senegal. In the district of Hann, approximately 200 houses were destroyed as high surf collapsed walls. Further south, in Guinea-Bissau, storm surge damaged low-lying buildings, offices, and military barracks. Seven fatalities reported in western Africa have been attributed to Hurricane Fred.

#### **Tropical Storm Grace**

Grace formed as the result of a tropical wave in the eastern Atlantic, first observed on Friday, September 4, off the western coast of Africa. The system was declared a tropical storm the following day, Saturday, September 5, approximately 670 mi (1,080 km) west of Africa. The system reached its peak intensity over the Atlantic late UTC on Sunday, September 6, with maximum sustained winds of 50 mph (85 km/hr) and central pressure of 1002 mb. Over the following days, Tropical Storm Grace tracked rapidly to the west into an area of high wind shear and drier air, which caused the system to weaken to a tropical depression by Tuesday, September 8, over the central Atlantic, remaining far from land throughout its lifespan.

#### **Tropical Storm Henri**

On Tuesday, September 8, a low pressure system 240 mi (385 km) southeast of Bermuda developed a well-defined circulation and was classified as a tropical depression. While tracking north, the system intensified to a tropical storm the following day to become the eighth named storm of the 2015 Atlantic hurricane season, Tropical Storm Henri. Over the following days, Henri continued to track north as a tropical storm while interacting with an upper-level trough, which eventually caused Henri to become disorganized on Friday, September 11.

#### **Tropical Storm Ida**

The ninth named storm of the 2015 season, Tropical Storm Ida, formed on Saturday, September 19, from a tropical wave off the western coast of Africa. Ida tracked west-northwest over the following days, strengthening slowly as the result of westerly wind shear. On Monday, September 21, the westerly wind shear decreased, allowing Ida to reach maximum sustained winds of 50 mph (85 km/hr) approximately 1,030 mi (1,655 km) east of the Leeward Islands. Over the following hours, Ida was once again impacted by high wind shear, which caused the system to begin weakening to a tropical depression by Thursday, September 24, and becoming a remnant low on Sunday, September 27.

#### Major Hurricane Joaquin

On Friday, September 25, the NHC began monitoring an upper-level low, which was accompanied by a surface trough several hundred miles south-southwest of Bermuda. The disturbance was classified as a tropical depression on Monday, September 28, approximately 405 mi (650 km) south-southwest. At this time, computer models anticipated that the tropical depression would have a limited window for development into a weak tropical storm before wind shear increased.

Instead, Joaquin remained mostly stationary before moving to the southwest towards the Bahamas as high pressure built in the north. While approaching the Bahamas, Joaquin intensified rapidly, reaching Category 3 strength by 03:00 UTC on Thursday, October 1. Joaquin made its first landfall on the small and uninhabited Bahamian island of Samana Cay as a Category 3 storm at 12:00 UTC on Thursday, October 1 (see Figure 7). In the following six hours the system intensified to Category 4 strength approximately 10 mi (16 km) north of Crooked Island. Beginning Friday, October 2, the hurricane track began to curve northwards, as the ridge that was previously steering Joaquin southwest began retreating to the north. The center of the system tracked parallel to Long Island in the Central Bahamas, before passing over the central Bahamian islands of Rum Cay and San Salvador as a weak Category 4 and a strong Category 3 hurricane respectively.

#### Hurricane Joaquin 1200 UTC 01 OCT 2015 Max 1-min sustained surface winds (kt)

Valid for marine exposure over water, open terrain exposure over land Analysis based on MOORED\_BUOY from 0900 - 1520z; SFMR\_AFRC from 0915 - 1523z; GOES from 1307 - 1307z; ASCAT from 1357 - 1403z; GPSSONDE\_WL150 from 0909 - 1520z; METAR from 0900 - 1512z; CMAN from 0900 - 1518z; SFMR\_AFRC\_FLAG from 0946 - 1520z; SFIIP from 0900 - 1520z; 1200 z position interpolated from 1151 User; mslp =





On Saturday, October 3, Joaquin began to track north-northeast away from the central Bahamas, re-intensifying to a Category 4 hurricane one final time. Afterwards, the storm steadily weakened as it passed approximately 55 mi (90 km) west of Bermuda as a Category 1 hurricane, bringing tropical storm force winds to the island. Joaquin transitioned to an extratropical storm over the cold waters of the North Atlantic on Thursday, October 8, approximately 770 mi (1,240 km) east of Newfoundland, Canada, before tracking across the Atlantic and impacting Portugal on Saturday, October 10.

Joaquin caused severe damage across the central Bahamas as heavy rainfall and storm surge caused widespread flooding and power outages across the islands. Long Island was subject to storm surge of 18 ft (5.5 m), which inundated two thirds of the island with flood waters of 4 to 6 ft (1.2 to 1.8 m). The southern region of the island was the worst impacted, with coastal roads washed away and fishing vessels washed onshore. It is estimated that 75% of the island's fishing vessels were destroyed. Over Crooked Island, floodwaters of up to 5 ft (1.5 m) submerged approximately 70% of the island, resulting in widespread damage and causing power outages across the entire island. Major Hurricane Joaquin directly affected nearly 7,000 people across the Bahamas and destroyed 836 buildings. The system also caused the sinking of a 790 ft cargo ship, El Faro, in the central Bahamas on Thursday, October 1, killing all 28 crew members on board.

The system also brought heavy rainfall to the Greater Antilles, where flooding blocked roads and damaged more than 200 homes in Cuba and Haiti. Property damage was also reported in Bermuda, as well as 15,000 power outages and transport disruptions. However, the total damage in Bermuda was minor when compared to the resulting damage from hurricanes Fay and Gonzalo of October 2014.

#### Hurricane Kate

A tropical wave interacted with an upper-level trough east of the Lesser Antilles and was declared a tropical depression on Monday, November 9, after entering a favorable environment for cyclogenesis. The system strengthened to a tropical storm hours later, becoming the eleventh and last named storm of the 2015 Atlantic hurricane season. Kate tracked northwest, passing just north of the central and northeastern Bahamas on August 9 and 10, though no damage was reported on the islands. The system curved to the northeast and strengthened to a Category 1 hurricane approximately 450 mi (725 km) east of North Carolina on Wednesday, August 11, becoming the fourth and last hurricane of the season. Kate maintained hurricane strength for less than 24 hours, weakening to a tropical storm and then transitioning to an extratropical system on Thursday, August 12, approximately 620 mi (995 km) east of Nova Scotia, Canada.

The extratropical system tracked northeast across the North Atlantic and passed over Ireland and the U.K. on November 15-16, bringing strong winds and heavy rainfall and causing isolated occurrences of flooding in Wales.

## **Review of the 2015 Season Forecasts**

Many forecasting groups predicted that 2015 would be a quiet season with below-average activity rates in the Atlantic, with fewer than the 1950-2014 average and 1995-2014 average of tropical storms, hurricanes, and major hurricanes. Predicted ACE values, which were significantly below the 1950-2014 and 1995-2014 averages, suggested short-lived storms would occur, which was also reflected by the low number of major hurricanes forecasted. The 2015 season, indeed, closed with below the 1950-2014 average activity in terms of named storms, hurricanes, and major hurricanes, though it was close to the 1955-2014 average of named storms. However, many of the oceanic and atmospheric conditions that drove the below-average season were not those predicted by the main forecasting groups. Instead, other conditions influenced the low basin activity of 2015, which is discussed in the following section, "Role of the Ocean and Atmosphere in the 2015 Season Activity."

Table 1 shows the 2015 seasonal forecasts from the three main forecasting groups: Colorado State University (CSU), Tropical Storm Risk (TSR), and National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA CPC). Activity averages for 1950-2014 and 1995-2014 are also presented.

Forecast Group	Named Storms	Hurricanes	Major Hurricanes	ACE Index (10 <sup>4</sup> kt <sup>2</sup> )
CSU (August 4)	7	3	1	40
TSR (August 5)	11	4	1	44
NOAA CPC (August 7)	6 to 10	1 to 4	0 to 1	-
1950-2014 Average	11.2	6.2	2.7	100.9
1995-2014 Average	14.8	7.6	3.6	130.6
2015 Season	11	4	2	62

Table 1: Summary of the 2015 Atlantic Basin seasonal forecasts, average activity, and 2015 season storm totals

The 2015 forecasts anticipated a below-average season in the Atlantic Basin due to a combination of interrelated atmospheric and oceanic conditions, including:

- Below-average sea surface temperatures (SSTs) observed in the Atlantic Main Development Region (MDR) during the first half of 2015, which were expected to continue throughout the 2015 season
- Above-average sea-level pressure in the MDR in early 2015, which was expected to continue throughout the season
- The expected strengthening of an early-stage El Niño phase in the tropical Pacific, with a low likelihood of neutral or La Niña conditions

Although the strengthening of the El Niño phase in the tropical Pacific was well predicted, the remaining two predictions made by the main forecasting groups proved somewhat inaccurate. Increasing SSTs from July to the end of the season were recorded across the North Atlantic Basin, while below-average sea-level pressure was observed in the MDR and across the Caribbean from August to October. Increasing SSTs were also observed in the 2014 season, though the increase across the entire MDR was greater in 2015. In the MDR, below-average sea-level pressure was recorded in the peak of the 2015 hurricane season; however, the 2014 season was characterized by above-average sea-level pressure, as discussed in the following section.

## Role of the Ocean and Atmosphere in the 2015 Season Activity

The 2015 season closed as expected with a strong El Niño phase. Oceanic and atmospheric conditions, difficult to predict more than a few weeks in advance, aided the strong El Niño event in suppressing tropical cyclone activity in 2015. The following unforeseen conditions also contributed to the below-average 2015 North Atlantic hurricane season:

- Above-average levels of wind shear across the Caribbean and the central tropical Atlantic
- Anomalously low Atlantic mid-level moisture in the Main Development Region (MDR) from August to October
- Strong steering currents and anomalous troughing in the eastern and western North Atlantic Basin
- Anomalously high tropical Atlantic subsidence over the MDR during the peak months of hurricane season, August to October

These conditions, which created an unfavorable environment for tropical cyclone development, also contributed to the low tropical cyclone activity of the 2013 and 2014 seasons.

The following section discusses the conditions generally used for seasonal forecasts, as well as the factors that contributed to suppressed activity in 2015.

#### Atlantic Sea Surface Temperatures

The North Atlantic Basin was characterized by significant changes in sea surface temperatures (SSTs) during the course of the 2015 season, which was also observed in the hurricane seasons of 2013 and 2014. The anomalous warming of SSTs across the North Atlantic has been highlighted as the most surprising atmospheric and oceanic feature of the 2015 season by Klotzbach and Gray (2015a).

In June, low SST anomalies were observed in the tropics and the North Atlantic, while warm SST anomalies were recorded off the U.S. East Coast (see Figure 8a). Klotzbach and Gray (2015a) established that these anomalies were associated with a weak thermohaline circulation (THC) across the North Atlantic.

Over the following months, a negative North Atlantic Oscillation (NAO) developed. Typical of a negative NAO, weakened trade winds and reduced mixing and upwelling of cooler sub-surface waters resulted in warming SSTs in the MDR. SSTs across the North Atlantic continued to warm since July (see Figure 8b), while SSTs off the U.S. East Coast cooled slightly, though remaining at about average.

SSTs in the North Atlantic continued to warm throughout the remainder of the hurricane season due to the negative NAO, resulting in warm SSTs observed in October 2015 (see Figure 8c), particularly in the tropical Atlantic. SST anomalies in the tropical Atlantic (10-20°N, 60-20°W) for October 2015 were the warmest on record since 1982, when NOAA Optimal Interpolation SST records became available. These warm SST anomalies have likely driven the formation of several systems in the far eastern tropical Atlantic in 2015, including Hurricane Fred and Tropical Storm Grace, for example.



Figure 8: Anomalous SST (°C) changes across the North Atlantic Basin (images from NOAA/ESRL); (a) June 2015, (b) July to September 2015, (c) October 2015. The MDR is outlined in red.

#### **Tropical Atlantic Sea-Level Pressure**

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

The 2015 hurricane season experienced below-average sea-level pressure from August to October 2015, as seen in Figure 9. This low sea-level pressure was observed across much of the MDR, the Caribbean, and off the southeastern U.S. coastline, where it peaked. Although the below-average sea-level pressure had the potential to increase tropical cyclone activity in the basin, stronger oceanic and atmospheric conditions suppressed cyclogenesis, contributing to the below-average hurricane season in 2015.



Figure 9: August to October 2015 anomalous changes in sea-level pressure (mb) across the North Atlantic Basin (image from NOAA/ESRL). The MDR is outlined in red.

#### El Niño Southern Oscillation

There is a strong relationship between the El Niño Southern Oscillation (ENSO) and hurricane activity (Gray, 1984). El Niño events (ENSO warm phase) in the Pacific Basin inhibit Atlantic hurricane activity due to teleconnections that increase vertical wind shear over the MDR, with the reverse true for La Niña events.

The development of a strong El Niño event during the 2015 season was correctly predicted by dynamic and statistical models, as well as many of the main forecasting groups. In the spring of 2015, warm neutral ENSO conditions quickly transitioned to an El Niño phase across the eastern and central tropical Pacific, as seen in Figure 10.

The current El Niño phase is now tied for the strongest on record, equivalent to the El Niño event of 1997. NOAA's Climate Prediction Center (CPC) reported that SSTs over the equatorial central and eastern Pacific Ocean were 2.3°C above average from October to December (see Figure 10), tying the peak anomaly measured during the 1997 El Niño. Data from NOAA CPC suggests that this year's El Niño reached its peak in December 2015 or may have peaked in November. This El Niño event is expect to remain strong throughout the winter before beginning to weaken and transition to neutral conditions by late spring.



Figure 10: The 2015 Oceanic Niño Index (ONI) (°C) [three-month running mean of ERSST.v3b SST anomalies in the Niño 3.4 region (5°N-5°S, 120°-170°W)], based on the 1971-2010 base period. Months of the year are abbreviated with first letter (e.g., A = April or August). Data from NOAA CPC, 2015. El Niño/ La Niña conditions are defined by six or more consecutive months above/below the (-)0.5°C threshold.

#### **Tropical Atlantic Vertical Wind Shear**

Strong vertical wind shear dominated the Caribbean and the central tropical Atlantic throughout the 2015 season. Vertical wind shear from June to October was the strongest on record across the Caribbean (10-20°N, 90-60°W), 28.5 knots, since records began in 1979.

In Figure 11, strong vertical wind shear can be seen across the southern U.S. coastline, the Caribbean, and the central tropical Atlantic from September to October, though weak wind shear is observed in regions of the eastern tropical Atlantic. During a typical El Niño phase, strong wind shear usually propagates further into the eastern tropical Atlantic; therefore, the wind shear in the region was somewhat below average. The formation of several tropical storms in the eastern tropical Atlantic in 2015 was assisted by this weak wind shear. However, many of these systems were diminished while tracking west by the strong vertical wind shear in the central tropical Atlantic and the Caribbean.



Figure 11: Anomalous vertical wind shear (ms-1) observed across the Atlantic from September 1 to October 30, 2015 (image from NOAA/NCEP). The MDR is outlined in red.

#### **Tropical Atlantic Moisture**

One of the main contributing factors to the 2015 season's inactivity was the anomalous dryness that persisted across the tropical Atlantic throughout the season, which was also observed in 2013 and 2014. Large amounts of Saharan dust blown across the Atlantic Basin at the beginning of the hurricane season have contributed to the anomalous dryness in 2015.

Moist air in the low and mid-levels of the atmosphere is critical for tropical cyclone development. Dry air hinders development by increasing the energy barrier that must be overcome to allow air to rise up from the water's surface. Figure 12 shows the anomalous 600 mb relative humidity during the three-month period from August to October 2015, when relative humidity was low across the MDR and the Caribbean. During this period, the tropical Atlantic and Caribbean observed the lowest 600 mb relative humidity anomalies since the recording of reliable moisture data began in 1980. This low relative humidity, which is generally associated with an El Niño phase, was most noticeable over the Caribbean.



Figure 12: August to October 2015 600 mb relative humidity (%) moisture anomalies (image from NOAA/ESRL). The MDR is outlined in red.

#### **Steering Currents**

Steering currents in the troposphere, resulting from atmospheric pressure patterns across the northern hemisphere, determine the movement of storm systems. As has been the case for several years, an elongated region of relatively low atmospheric pressure, known as anomalous troughing, dominated the southeastern U.S. coast in 2015. In the peak of the season, August to October, this anomalous troughing was a dominant feature in the eastern and western North Atlantic Basin, as seen in Figure 13. This resulted in a predominant steering flow that prevented storms from progressing towards the U.S. East Coast, reducing tropical cyclone activity in the region. Although steering currents in the central tropical Atlantic and the Caribbean acted in favor of cyclogenesis, strong vertical wind shear in these regions diminished tropical cyclones as they approached the Lesser Antilles.



Figure 13: 700 mb geopotential height (m) anomalies in the eastern and western North Atlantic Basin from August to October 2015 (image from NOAA/ESRL). The MDR is outlined in red.

#### **Tropical Atlantic Subsidence**

Another potential reason for the relative inactivity in 2015 in the North Atlantic is anomalous atmospheric subsidence (sinking air) across the MDR. August to October was characterized by an anomalous sinking motion, which suppressed the deep convective development necessary for tropical cyclone formation and maintenance. This is measured by upper-level velocity potential anomalies, as shown in Figure 14, for the tropical Atlantic, where positive velocity potential indicates an upper-level convergence and sinking motion. It appears that from August to September a high proportion of the MDR and the eastern Caribbean was experiencing anomalous subsidence, which would have inhibited tropical cyclone development.



Figure 14: Upper-level velocity (m\*m/s) potential anomalies August to October 2015 (image from NOAA/ESRL). The MDR is outlined in red.

#### Madden-Julian Oscillation

The Madden-Julian Oscillation (MJO) is an intra-seasonal oscillation of tropical rainfall that often cycles every 30-60 days. It is characterized by an eastward progression of large regions of both enhanced and suppressed tropical rainfall.

There is evidence to show that the MJO modulates tropical cyclone activity by providing a large-scale environment that is both favorable and unfavorable for development. When the MJO is producing enhanced precipitation and divergent upper-level winds, Gulf of Mexico and Caribbean Sea hurricanes are four times more likely to occur (Klotzbach, 2010). Contrarily, when upper-level winds are convergent and precipitation is suppressed, tropical cyclone activity is decreased.

The MJO variability was relatively weak during the peak months of the 2015 North Atlantic hurricane season, having no significant impact on tropical storm development. Weak or absent MJO activity is typically associated with strong El Niño events.

## **Outlook for the 2016 North Atlantic Hurricane Season**

Early forecasts for the 2016 North Atlantic hurricane season were issued in December 2015 by TSR and CSU.

TSR issued its first forecast for the 2016 hurricane season on December 16, predicting 13 ( $\pm$ 5) tropical storms, 5 ( $\pm$ 3) hurricanes, and 2 ( $\pm$ 2) major hurricanes, approximately 20% below the 1950-2014 average. TSR forecast that the 2016 season ACE index will reach 79 ( $\pm$ 57) with a 25% probability that the index will be above the 1950-2014 average, a 34% probability it will be near average, and a 41% probability that the index will be below average. TSR's main predictor of this extended forecast is the July-September trade wind speed over the Caribbean Sea and the tropical Atlantic, which influences cyclonic vorticity and wind shear over the MDR. TSR noted a large degree of uncertainty associated with its December forecast, which the group attributed to the low forecasting skill this far in advance of the 2016 hurricane season (Saunders & Lea, 2015).

On December 10, CSU issued a qualitative discussion of features likely to affect the 2016 Atlantic hurricane season, rather than a specific quantitative forecast. According to Klotzbach and Gray (2015b), the 2016 Atlantic hurricane season will be determined by the strength of the thermohaline circulation (THC) and Atlantic Multidecadal Oscillation (AMO), as well as the phase of ENSO. CSU anticipates that the strong El Niño will have dissipated by the peak of the 2016 season, though it could potentially still impact some atmospheric conditions. Following three years of below-average activity in the Atlantic Basin (2013-2015), Klotzbach and Gray believe that considerable uncertainty surrounds whether it remains in an active AMO/THC phase.

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 or over the Caribbean in 2016 will be determined by the weather patterns and steering currents throughout the season, which cannot not 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 2016 hurricane season in June 2016, along with a detailed overview of its Event Response offerings for the 2016 season.

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