

# Hurricane Occurrence and Seasonal Activity: An Analysis of the 2017 Atlantic Hurricane Season

Henry Ngenyam Bang , Lee Stuart Miles, Richard Duncan Gordon

Disaster Management Centre, Bournemouth University, Dorset, Talbot Campus, Fern Barrow, Poole, UK  
Email: hbang@bournemouth.ac.uk

**How to cite this paper:** Bang, H.N., Miles, L.S. and Gordon, R.D. (2019) Hurricane Occurrence and Seasonal Activity: An Analysis of the 2017 Atlantic Hurricane Season. *American Journal of Climate Change*, 8, 454-481.

<https://doi.org/10.4236/ajcc.2019.84025>

**Received:** July 31, 2019

**Accepted:** October 21, 2019

**Published:** October 24, 2019

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## Abstract

This article provides a reckoning of the 2017 Atlantic Hurricane Season's place in history to ascertain how unique it was from other hurricane seasons. A research strategy involving qualitative, descriptive and analytical research approaches, including content analysis, sequential description of events and comparative analysis, were used to assess how and why the 2017 AHS season is distinct from others. Findings reveal that the 2017 AHS was extraordinary by all meteorological standards—in many ways, being hyperactive, and producing a frenetic stretch of huge, long-lived and dramatic, tropical storms including 10 hurricanes. The season was, arguably, the most expensive in history and will be remembered for the unprecedented devastation caused by the season's major hurricanes (Harvey, Irma and Maria). While the extremely active season can be attributed to anomalously high, climate change induced, hurricane friendly environmental conditions in the Atlantic basin, early forecasts did not also predict the hyperactivity of the season. This article, therefore, advances for a more strategic anticipatory and proactive approach in dealing with these severe storms, underpinned by effective mitigation of their effects. Furthermore, the article adds value to the literature examining extreme natural forces, particularly in understanding variations in the ferocity of the meteorological events associated with hurricane seasons.

## Keywords

Hurricanes, Disaster, Hurricane Season, Tropical Cyclones, Seasonal Activity

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## 1. Introduction

Considering that hurricanes are amongst nature's most powerful and violent storms with the potential to wreak havoc in stupendously dramatic ways, the

fascination and curiosity to better understand these extra-ordinary forces of nature is extremely high. These storms are a common phenomenon in the Atlantic Ocean [1] and their frequency, intensity and destructive potential have been increasing in recent years [2] [3]. At the same time, the exposure of the global population to tropical cyclone (TC) hazards has been increasing as more people settle in coastal areas [4]. Indeed, an increase in the vulnerable population is reflected in a 6% rise in TC damage between 1970 and 2015, costing about US\$700 billion. Moreover, about 470,000 people (roughly 10,000 lives per year) were killed by hurricanes between 1970 and 2010 [5].

Hurricane occurrence is not random. Particular environmental conditions are required for their formation (see Section 2.2) and countries within the vicinity of where hurricanes form is at their mercy. Historically, storms that form in the Caribbean have been a threat to all Caribbean countries while such storms, including those that form in the tropical North Atlantic and Gulf of Mexico, account for most of the hurricanes that eventually reach the South East (SE) coasts of the USA and the Greater Antilles [6] [7] [8]. Therefore, the Caribbean and the USA are amongst the most vulnerable regions in the world to severe storms. In fact, since hurricane records began in 1851, a total of 577 hurricanes have made landfall in the US up to 2016; 97 of these reaching Category 3 or above on the Saffir-Simpson scale [9]. When the 2017 Atlantic Hurricane Season (AHS) is added, the number increases to 587 hurricanes.

Of immense concern, however, is not just the number of TCs that develop in a season, but the number of major hurricanes (>category 3). The EM-DAT<sup>1</sup> reports that 581 TCs have occurred throughout the Caribbean between 1950 and 2014, with 238 developing to hurricanes that proved disastrous to the communities affected [5]. Indeed, this number might actually be higher because only 62% of the natural hazard-induced disasters caused by TC over the last 65 years have data on the damage they caused. Systematic recording of disasters only started in 1988 [10].

Worryingly, the effects of hurricanes (destruction of physical infrastructure, capital stock and agricultural products etc.) can have a heavy toll on the economy of the affected regions. In fact, hurricanes are the costliest natural disasters in the US. For instance, since 1980, weather and climate disasters have costed the USA more than \$1.2 trillion [2] [11]. Owing to the strength of the US economy, such hazards have had less of an economic effect compared to the much smaller economies of the Caribbean countries [12] [13] [14].

These storms pose a grave threat to the development of the Caribbean region, often causing huge social, economic and environmental costs that can set back development in the affected Caribbean countries for decades [13]. Hurricanes are a major source of macroeconomic risk in the Caribbean countries with the

<sup>1</sup>The EM-DAT database records disasters throughout the world. For a disaster to be included in the database at least one of the following criteria must be met: 2) ten or more people reported killed, 2) hundred or more people reported affected, or 3) there was a declaration of a state of emergency, or a call for international assistance was made.

potential to cause losses that wipe out an entire year of GDP. Indeed, over the past 65 years, 148 disasters occurred in the Caribbean, costing US\$52 billion, which amounts to an average of 82% GDP of the Caribbean economy. The largest disasters, particularly for the smaller islands, caused damages above 100% of GDP. For example, the damages caused by Hurricane Hugo in 1989, hitting Montserrat, costed 434% of that island's GDP [10] (Table 1).

In recent years, the Caribbean has seen a trend of mostly weaker hurricanes; most of which stayed in the Atlantic, or if they did make landfall, did not affect densely populated areas [15]. However, this trend seems to have changed during the 2017 AHS<sup>2</sup>.

**Table 1.** Damage per Caribbean Island from 1950 to 2014.

Caribbean Islands	Disasters	Total Damages	Storm	Year	Max Wind (kts/h)	H Cat <sup>a</sup>	Landfall?	% of GDP
Anguilla	3	209	Donna	1960	120	H4	Yes	NA <sup>b</sup>
Antigua & Barbuda	6	809	Luis	1995	120	H4	Yes	60.1
Bahamas	10	3185	Frances	2004	120	H4	Yes	14.1
Bermuda	3	449	Fabian	2003	105	H3	NO	7.2
Barbados	4	178	Emily	1987	40	TS	NO	5.8
British Virgin Islands	2	16	Marilyn	1995	95	H2	NO	2.5
Cuba	19	15,054	Flora	1963	104	H3	Yes	NA
Cayman Islands	5	3976	Ivan	2004	135	H4	NO	128.9
Dominica	8	715	Lenry	1999	120	H4	NO	67.8
Dominican Republic	14	6084	Georges	1998	105	H4	Yes	9.7
Grenada	3	1141	Ivan	2004	115	H3	NO	148.4
Haiti	14	2898	Flora	1963	125	H4	Yes	74.1
Jamaica	20	5556	Gilbert	1988	110	H3	Yes	49.7
Montserrat	2	404	Hugo	1989	125	H4	NO	434.1
Puerto Rico	11	8637	Georges	1998	95	H2	Yes	6
St. Kitts & Nevis	4	1416	Georges	1998	100	H3	Yes	220.5
St Lucia	8	626	Allen	1980	115	H4	NO	155.2
St Vincent & the Grenadines	6	113	Allen	1980	115	H4	NO	23.3
Trinidad and Tobago	4	188	Flora	1963	97	H3	Yes	4.5
Turks & Caicos	2	513	Ike	2008	115	H4	NO	58
Total	148	104,336			2176			1469.9
Average	7.4	4968.4			108.8			81.7

a. Cat = Hurricane Category b. GDP data not available. Related references: Adapted from the Emergency Events Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters (CRED), website of the US government's National Oceanic and Atmospheric Administration (NOAA) agency, [10].

<sup>2</sup>The Atlantic Hurricane Season is the period in a year (01 June - 30 November) when hurricanes usually form in the North Atlantic Ocean, including the Caribbean Sea and regions along the Gulf of Mexico and the Gulf Coast.

In this article we set out to review the 2017 AHS. The primary objective is to understand how and why the 2017 AHS is different from other seasons. Therefore, the main question this research seeks to answer is: How was the 2017 AHS unique from other seasons? To this end, this article has explored the characteristics that distinguish the 2017 AHS from other seasons. In so doing, we note that despite unprecedented scientific innovations in the detection and monitoring of TCs in the 21st century, these severe storms continue to threaten human civilization.

The article adds value to the literature of extreme natural events that cause disasters. And is particularly useful for students and teachers—to provide further knowledge about the meteorological events associated with hurricane seasons (subsequently called seasons); for academics and researchers—to ensure there is justification for further research; for policy makers and disaster managers—to take concerns about natural hazard/disaster policy and resourcing more seriously.

The structure of the paper is as follows: Section 2 provides the theoretical framework that highlights key aspects of hurricanes; Section 3 describes the methods used in the study; Section 4 presents the results and discussion while Section 5 is the conclusion and recommendation.

## 2. Theoretical Framework

This section considers key aspects of hurricanes. It is underpinned by an overview of hurricane formation, distribution, measurement, seasonal activity and forecast. This sets the framework for understanding severe storms and to realize the objective of this article.

### 2.1. Tropical Cyclone Nomenclature

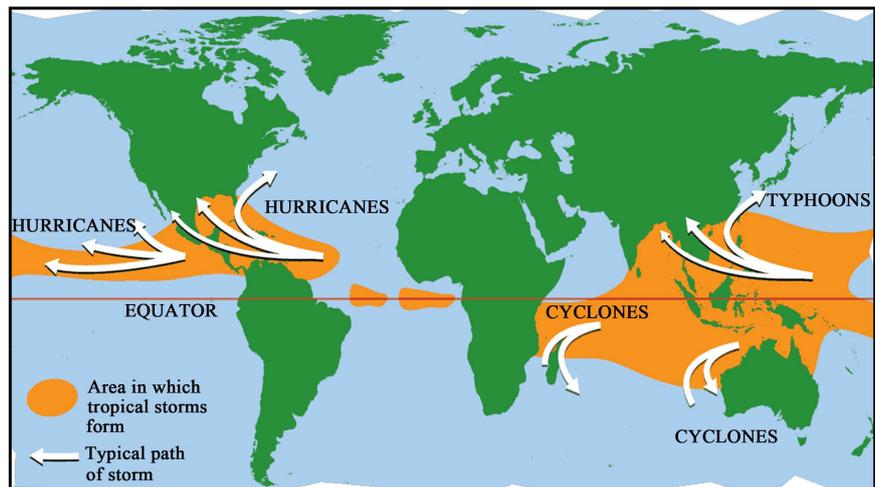
The term Hurricane originated from the name *Hurakan*<sup>3</sup>, an ancient Mayan storm god that was considered evil by the Arawakan Indians of the Caribbean islands and South America. Hurricanes are TCs that occur in the North Atlantic Ocean, North East Pacific Ocean and South Pacific Ocean. These storms are warm-core, *rapid-onset* and low-pressure intense tropical weather systems with sustained winds of 74 mph (64 knots) or higher<sup>4</sup>. When the same storms occur in the North West Pacific Ocean, they are called Typhoons. When they occur in the South West Pacific and Indian Oceans, the word “Cyclone” is used [16] [17] [18] [19] [20] (Figure 1).

### 2.2. Necessary Conditions for the Formation of Hurricanes

Hurricanes are also called *severe tropical storms*. The phrase tropical indicates the region and environmental condition in the world where they form—warm

<sup>3</sup>Hurakan personified the tempest, rain, thunder, lightning bolt and the illumination produced by sheet lightning.

<sup>4</sup>Most definitions of TCs tend to focus on the area where they form, their mode of occurrence, their appearance and damage/loss potential.



**Figure 1.** Areas where tropical cyclones form and typical tropical cyclone paths. Related references: Adapted from [17] [25] [26].

oceans and seas between the Tropics of Cancer and Capricorn, between longitudes 100 - 300 North and South of the equator. It should be noted, however, that not all tropical waves, disturbances, or storms develop into hurricanes. Particular environmental conditions are required for the formation of hurricanes, including: 1) Warm Tropical Ocean waters of at least  $27^{\circ}\text{C}/80^{\circ}\text{F}$  with a depth of about 46 - 50 m—the heat in these warm waters is necessary to fuel the storm; 2) An atmosphere that cools fast enough with height such that it is potentially unstable for moist convection—the thunderstorm activity allows the heat stored in the ocean waters to be released and used for tropical cyclone development; 3) The mid-troposphere (5 km or 3 miles altitude), must contain enough moisture to sustain the thunderstorms—dry mid-levels are not conducive to the continuing development of thunderstorms; 4) There must be an initial disturbance of air near the surface of the ocean (within the tropics at a minimum distance of at least 500 km from the equator)—which causes the air to begin to spin and has low-level inflow of moist air; 5) The Coriolis force must be present<sup>5</sup>—without the Coriolis force, the low pressure of the disturbance cannot be maintained and 6) There should be a vertical wind shear<sup>6</sup> of less than  $10\text{ m/s}^7$  (between 20 - 23 mph) between the surface of the ocean and the upper troposphere [17] [19]-[24].

### 2.3. Worldwide Distribution of Tropical Cyclones

TC activity varies in the different oceans. Around 12% of all TCs develop in the Atlantic Ocean, 12% develop in the southern Pacific Ocean, 15% develop in the eastern Pacific Ocean, 30% develop in the western Pacific Ocean and 31% in the

<sup>5</sup>Except in rare circumstances, hurricanes do not form within  $5^{\circ}$  latitude of the equator because of the lack of Coriolis Force. The Coriolis effect is zero near the equator and increases to the north and south of the equator.

<sup>6</sup>Vertical wind shear is the rate of change of wind velocity with altitude.

<sup>7</sup>Large values of vertical wind shear disrupt the development of the tropical cyclone by removing the rising moist air too quickly.

Indian Ocean both N and S of the equator (including 7% NE of Australia) (**Figure 1**). Their movement is affected by the prevailing wind system—from East to West under the influence of trade winds [17] [25] [26] [27].

## 2.4. Tropical Cyclone Seasons

Each ocean has its own particular seasonal patterns of tropical storm activity that constitutes the seven tropical cyclone seasons as shown in **Table 2**. TC activity tends to peak worldwide in September, while the storms are least active in May.

## 2.5. Stages in the Formation of a Tropical Cyclone/Hurricane

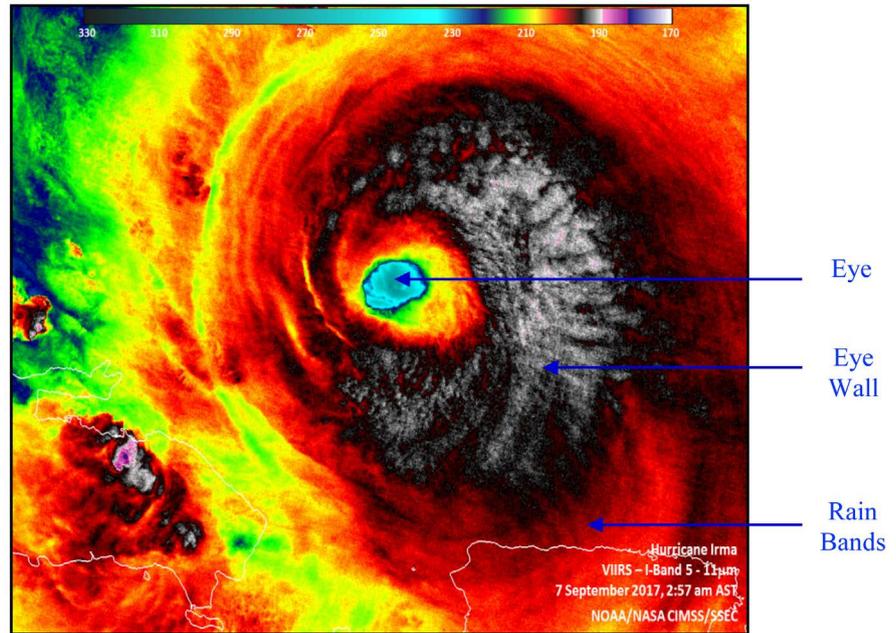
There are different stages in the formation of TCs. It begins as a *tropical disturbance* with thunderstorm activity that might stretch about 100 miles and remain active for about 24 hours. In the Atlantic Ocean, these disturbances start as *tropical waves* from two dominant source regions North and South of latitude 150 over the coast of Africa and move westward often with wind speeds of less than 25 mph [28] [29]. If the right environmental conditions exist (see Section 2.2), a tropical disturbance can develop further and begin to spin around a low-pressure center. When this happens, it is known as a *tropical depression* if it has wind speeds between 25 - 38 mph. Under suitable conditions, the pressure in the center of the tropical depression can drop, causing air to rush inwards. If the wind speed is strong enough to go beyond 39 mph but less than 73 mph, the system is called a *tropical storm*. If favorable conditions persist, the pressure in the center of the tropical depression drops further and the winds pick up more speed. When the wind speed in this growing, swirling, vortex of air and clouds exceeds 74 mph, the system is dubbed a *TC* or *hurricane* depending on where the storm developed.

A full-grown hurricane has a distinct easily identifiable structure with a *spiral shape* as shown on **Figure 2**. At the center of the spiral is a visible “*eye*” (empty space) where air sinks (downdraft), in an attempt to fill the empty space. The eye is a clear, calm region (light winds of no more than 15 mph with no clouds) that

**Table 2.** The seven tropical cyclone seasons in the world.

Season name	Starts	Ends
Atlantic Hurricane Season	June 1	November 30
Eastern Pacific Hurricane Season	May 15	November 30
Northwest Pacific Typhoon Season	all year	all year
North Indian Cyclone Season	April 1	December 31
Southwest Indian Cyclone Season	October 15	May 31
Australian/Southeast Indian Cyclone Season	October 15	May 31
Australian/Southwest Pacific Cyclone Season	November 1	April 30

Related references: Authors, adapted from various sources including the websites of the NOAA’s Hurricane Research Centre (HRC) and National Weather Service (NWS), the UK Met Office.



**Figure 2.** Satellite image of Hurricane Irma showing the eye of the storm. Related references: NOAA/NASA.

can extend to diameters of a hundred miles or more. Bordering the eye is the *eye wall* that consists of bands of clouds, very strong winds and heavy rainfall. Beyond the eye wall are *feeder or rain bands*, with intense thunderstorms, gusty winds, and often heavy rain showers that spiral inward toward the eye wall. Feeder bands can be very extensive, going outwards for many miles and they often cause tornadoes. The spiral shape or *rotating vortex* can have an average diameter of about 500 km and can extend to a height of about 15 km. A fully formed TC may only cease after making landfall when the heat source is terminated or when the moisture content is cut off on land [16] [19] [20] [25] [30] [31] [32] [33].

## 2.6. Categories of Tropical Storms

Hurricanes are ranked into five different intensities based on their wind speed; strength and damage potential according to the Saffir-Simpson hurricane wind scale (**Table 3**). The ranks increase from one to five as the wind speed increases. Category 1 is the weakest, with wind speeds of 74 - 95 mph while category five is the strongest and most dangerous with wind speeds exceeding 157 mph.

## 2.7. Total Overall Hurricane Seasonal Activity

Concise metrics have been developed to summarize a hurricane “*seasonal activity*”<sup>8</sup> indicating how busy or intense a hurricane season or regional storm activity has been. This is determined by calculating the season’s *accumulated cyclone*

<sup>8</sup>The phrase total seasonal activity refers to the collective intensity and duration of Atlantic named storms and hurricanes occurring during a given season.

**Table 3.** The five categories of severe storms.

Category	Sustained wind speed			Storm surge (ft)	Damage potential
	mph	km/h	knots		
Tropical Depression	<39	<63	<34	-	-
Tropical Storm	40 - 73	64 - 117	34 - 63	-	Very Minimal
1	74 - 95	119 - 153	64 - 82	4 - 5	Minimal
2	96 - 110	154 - 177	83 - 95	6 - 8	Moderate
3	111 - 129	178 - 208	96 - 112	9 - 12	Major
4	130 - 156	209 - 251	113 - 136	13 - 18	Extensive
5	≥157	≥252	≥137	>18	Catastrophic

Related references: Authors, adapted from various sources including the websites of the NOAA's Hurricane Research Centre (HRC) and National Weather Service (NWS), the UK Met Office.

*energy (ACE) index*<sup>9</sup> or *Track Integrated Kinetic Energy (TIKE) metric*<sup>10</sup> [34] [35]. The ACE index of a season considers the number, frequency, strength or intensity and duration of all the tropical storms and hurricanes in the season. It is computed taking into account the lifetime of the storms and the maximum sustained wind speed [36]. The TIKE, however, is influenced by the size and strength of each storm, rather than solely focusing on maximum intensity without consideration for storm structure, as is the case with ACE [35].

The Climate Prediction Centre of the US government's *National Atmospheric and Oceanic Administration* (NOAA) classifies, or ranks, seasons based on the ACE index and the number of storms that have formed within a particular season as *above normal*, *near normal*, or *below normal*. An above-normal season is one that has an ACE index above  $111 \times 10^4 \text{ kt}^2$  and at least two of the following conditions: 1) thirteen or more tropical storms, 2) seven or more hurricanes and 3) three or more major hurricanes. A near-normal season has an ACE index below  $66 \times 10^4 \text{ kt}^2$  and the following three conditions: 1) nine or less tropical storms, 2) four or less hurricanes and 2) one or less major hurricanes. A season is called below normal when it has an ACE range of  $66 - 111 \times 10^4 \text{ kt}^2$  and 1) four or less tropical storms and 2) two or less hurricanes. In particular, *long-lived*, intense hurricanes have a high ACE index, while *short-lived*, weak tropical storms have a low value [37]. **Table 4** shows the ten extreme seasons from 1960-2017 based on their ACE index.

## 2.8. Tropical Cyclone Season Forecasts

Before the season starts, meteorologists forecast how active the upcoming season may be. Forecast agencies including governments, universities and private companies issue publicly available AHS predictions. The lead agencies in this field

<sup>9</sup>The ACE index is a wind energy index measured by convolving the AHS's intensity, duration and frequency every six hours for all named systems while they are at least tropical storm strength.

<sup>10</sup>TIKE is calculated by accumulating the integrated kinetic energy of each tropical cyclone wind field in six-hour intervals throughout a hurricane season.

**Table 4.** 10 extreme hurricane seasons based on the ACE from 1960 to 2016.

Year	Named storm	Named storm days	Hurricanes	Hurricane days	Major hurricanes	Major hurricane days	Accumulated cyclone energy (ACE)
2005	28	131.5	15	49.75	7	17.5	250
2004	15	93	9	45.5	6	22.25	227
1995	19	121.25	11	61.5	5	11.5	227
1998	14	88	10	48.5	3	9.5	182
1999	12	78.5	8	41	5	14.25	177
2003	16	81.5	7	32.75	3	16.75	176
1969	18	92.25	12	40.25	5	6.5	166
1996	13	79	9	45	6	13	166
2010	19	89.5	11	38.5	12	5	165
1980	11	62.25	9	38.25	2	7.25	149

Related references: Authors, Adapted from [38].

are the NOAA agency, UK government's *National Weather Service* (Met Office), the *Tropical Meteorology Project* (TMP) at Colorado State University (CSU), North Carolina State University, University College London's (UCL) *Tropical Storm Risk (TSR) Consortium* and the Commercial forecaster AccuWeather.com (see **Table 8**). The pre-season outlooks and/or forecasts<sup>11</sup> include guesstimates of the number of named storms, hurricanes, and major hurricanes. These are usually issued twice each year—April or May prior to the start of the season in June, and then an update in August [39].

Forecasting hurricanes have several limitations. It is based, for instance, on statistical schemes, which, owing to their intrinsically probabilistic nature, can fail in some years and forecasts do not predict with precision where the storms will strike within the Atlantic basin [40]. Moreover, forecasters caution that, within a single year, there is no solid relationship between the number of storms in a season and the number of landfalls because local weather conditions determine whether hurricanes will make landfall. For example, Hurricane Andrew (1992) occurred in one of the quietest AHS; yet at the time, it was the most expensive hurricane ever to hit the US. These shortcomings highlight the fact that despite huge efforts in prediction/forecasts, there has been little improvement in hurricane intensity forecasts since 1990 [41].

Regardless of the shortcomings in forecasting, an undisputable fact is that seasonal forecasts are good for hurricane risk reduction and management. Indeed, TC mortality and injury have been reduced by improved forecasts and preparedness, especially in developed countries [4]. People may sometimes base key decisions, such as to buy insurance on forecasts of an inactive season. How-

<sup>11</sup>Forecasts are based on the premise that past global oceanic and atmospheric conditions that preceded comparatively active or inactive hurricane seasons in the past provide meaningful information about similar trends in future seasons.

ever, the danger is that seasonal forecast can be grossly misinterpreted making it counterproductive. This is because seasons with few hurricanes do not necessarily imply the hurricanes will not be very powerful. For example, as mentioned earlier, the relatively quiet 1992 season produced devastating hurricanes like Hurricane Andrew [41].

### 3. Method

This article adopts a qualitative, analytic approach. The objective is to explore the 2017 AHS to understand how it was different from other seasons. Qualitative research is appropriate for investigating the “who, what, and where” of events or experiences and for gaining insights regarding a poorly understood phenomenon [42]. The techniques used are based mainly upon secondary and primary information sources. Secondary sources of information include peer review articles, reports from government, private and local weather/climate monitoring and prediction/forecasting agencies. In particular, key primary information sources (various types of analytical, cause/effect, interpretive, argumentative and forecast papers and reports) about the 2017 AHS were obtained from the websites of the US NOAA’s National Weather Service (NWS) and National Hurricane Centre (NHC) and the UK’s Meteorological Office (UK Met Office). Other reports and statements made by prominent meteorologists, weather forecasters and climatologists about the 2017 AHS from varied sources also constitute primary source of information. In addition, grey literature from media/newspaper sources about the 2017 AHS and other reports from internet searches also informed the research. Indeed, due to unprecedented innovations in scientific monitoring and measurements of hurricane activity, meteorological data, substantiated by the analysis of meteorologists/climatologists and the effects of the storms was available even as the season unfolded. Multiple techniques were used to analyze data, including content analysis, descriptive statistics and constant comparison and sequential description of events [42] [43] [44] [45].

### 4. Result and Discussion

This section analyzes how the 2017 AHS is distinct from other seasons in terms of the characteristics of the storms that formed, their impact, effects or losses caused, why the season was very active and its forecast.

#### 4.1. The Storms of the 2017 Atlantic Hurricane Season

The NOAA, UK Met Office and forecast agencies track, monitor and document all the storms that develop every year. In 2017, the Atlantic region was hit by a *frenetic stretch of long-lived tropical monster storms*, many of them major and dramatic. The 2017 AHS produced 17 storms. Ten were hurricanes (six category 3 or stronger) and the other seven were tropical storms. The season started on April 19 with tropical storm Arlene and extended to November 9, lasting 7 months (**Figure 3**). The maximum wind speed recorded was 185 mph (295 km/h) by Hurricane Irma.

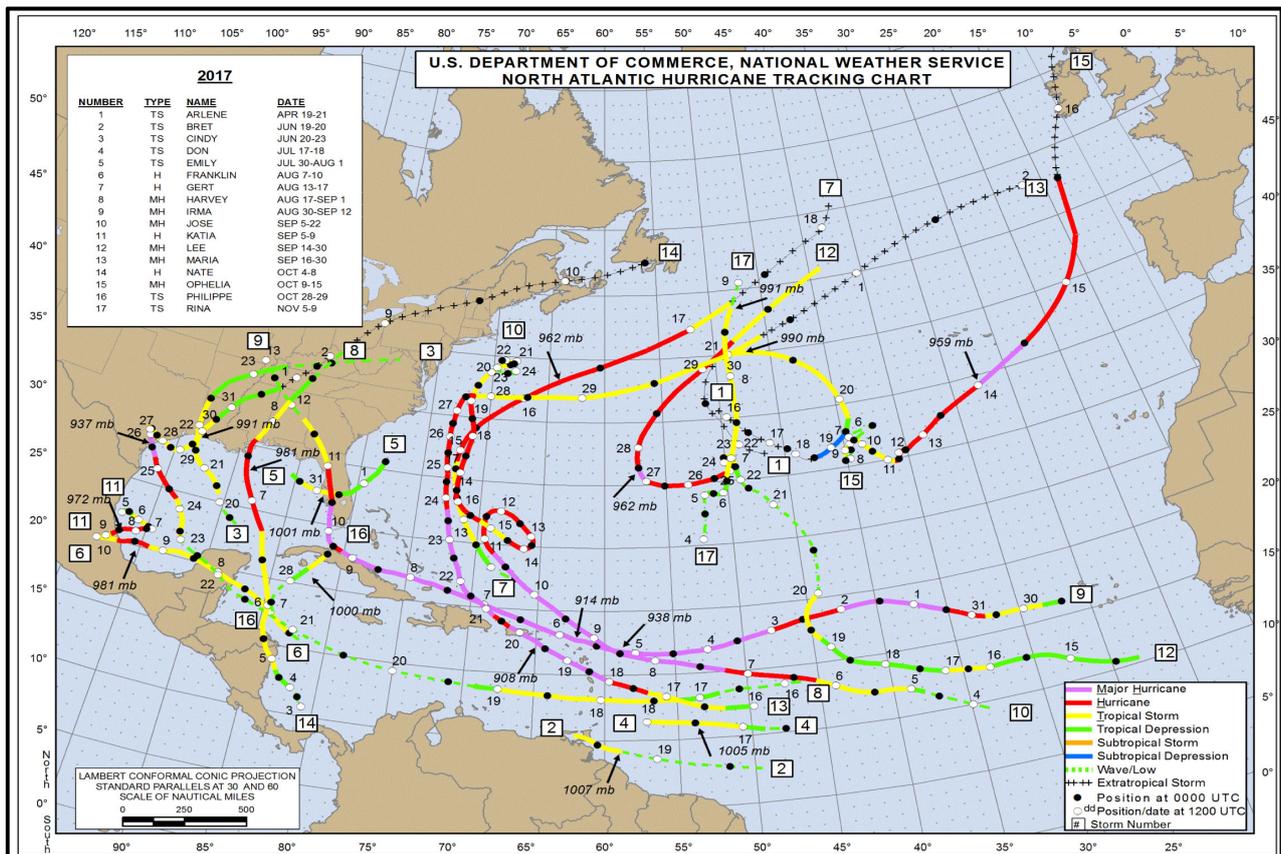


Figure 3. 2017 Atlantic Tropical Cyclone tracks. Related references: NOAA’s NHC website.

A prominent caveat of the 2017 AHS is the occurrence of several storms and *back-to-back* hurricanes (Table 5) in a season classified as above average (see Section 2.7).

The first hurricane of the season was “Franklin” that developed into a hurricane on August 8 and made landfall in Lechuguillas (Mexico). It quickly dissipated into a tropical storm two days later. On August 13, storm “Gert” intensified to a Category 1 hurricane but just 12 hours after achieving peak intensity, the storm weakened below hurricane status. While Gert was dissipating, Hurricane Harvey was brewing in the Caribbean and attained hurricane status on August 24. After leaving a trail of destruction in the Caribbean and South East USA, Harvey spun down into a tropical storm on the August 26. Barely 7 days after Harvey’s onslaught, Hurricane Irma came into line and developed into Category 5 intensity. Irma ravaged several Caribbean islands and barreled directly into Florida before losing its hurricane character. Irma was downgraded into a tropical storm on September 11.

While Irma was still battering the US, storm Jose attained hurricane intensity on September 6 in the Atlantic Ocean and peaked to Category 4 hurricane on September 9. After leaving a lasting impact in the Caribbean islands, Jose stalled offshore into the North East USA on September 22 as a post-tropical cyclone [46]. On September 6, in the Gulf of Mexico, storm Katia also became a hurricane

**Table 5.** Storms that formed in the 2017 North Atlantic hurricane season.

Name of storm	Active storm dates	Max wind speed Mph (km/h)	Category at peak intensity
Arlene	19-21 April	50 (80)	TS
Bret	19-20 Jun	45 (72)	TS
Cindy	20-23 Jun	60 (97)	TS
Don	17-1 Jul	50 (85)	TS
Emily	31 July-2 Aug	45 (80)	TS
Franklin	8-10 Aug	85 (138)	H Cat 1
Gert	13-17 Aug	105 (170)	H Cat 2
Harvey	17 Aug-1 Sep	130 (209)	H Cat 4
Irma	30 Aug-12 Sep	185 (298)	H Cat 5
Jose	5-22 Sep	155 (249)	H Cat 4
Katia	5-9 Sep	105 (169)	H Cat 2
Lee	15-30 Sept	115 (185)	H Cat 3
Maria	16-30 Sep	175 (282)	H Cat 5
Nate	4-9 Oct	90 (149)	H Cat 1
Ophelia	9-15 Oct	115(185)	H Cat 3
Philippe	28-29 Oct	60 (95)	TS
Rina	5-9 Nov.	60 (95)	TS
Total for Season			
17	April 19-Nov. 9	1540 (2496)	

Related references: Authors, compiled from various sources including the websites of the NOAA's NHC/NWS, UK Met Office; Caribbean Weather/Weather.org.

but peaked only at Category 2. After making landfall in Tecolutla (Mexico) as a Category 2 hurricane, the system quickly dissipated on September 9. While Irma was still active, storm Maria developed into a hurricane on September 16 and quickly attained Category 5 status on September 18. After devastating the Eastern Caribbean Islands and some areas of South East USA, Maria transitioned into a tropical cyclone on September 30. "Nate" developed into TS from the SW Caribbean Sea on October 5. After making landfall in the US on October 8 as Category 1 hurricane, it quickly dissipated into a tropical depression the next day. Storm Ophelia attained hurricane status on October 11. It dissipated into a tropical storm on October 16 shortly before making landfall in the British Isles—although still alive even at this stage with gusts in excess of 90 mph that devastated parts of Northern Ireland (causing three fatalities).

#### 4.2. How the 2017 Atlantic Hurricane Season Is Unique

**Table 6** is a summary of the unique characteristics of the 2017 AHS, including new meteorological records set when compared to other seasons.

The 2017 AHS is compelling and stands out as one of the most notorious

**Table 6.** Unique characteristics of the 2017 AHS.

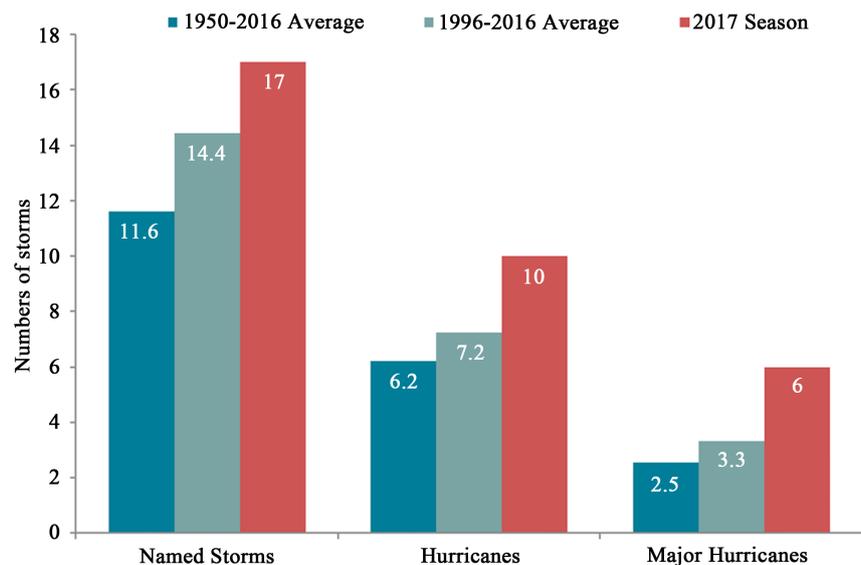
Criteria	Characteristic of the 2017 Atlantic Hurricane Season	
All-Time Record	<ul style="list-style-type: none"> <li>The ACE units produced by the Atlantic basin storms in September (155.4, surpassed that of September 2004 to become the most active calendar month in the Atlantic on record.</li> <li>More ACE was generated on September 8, 2017 than any other calendar day in the Atlantic basin on record, jointly contributed by Hurricanes Jose, Irma and Katia.</li> <li>First time on record since that to Category 4 major Hurricanes (Irma and Harvey) made landfall in the continental USA in a single year.</li> <li>Ophelia was the easternmost major hurricane in the Atlantic basin on record that underwent extratropical transition as it impacted the United Kingdom and Ireland in mid-October.</li> <li>Tropical Storm Bret was the earliest named storm to form in the main development region<sup>12</sup> on record, surpassing the record of Tropical Storm Ana in 1979.</li> <li>Harvey was the most enduring tropical storm on record after making landfall as a hurricane in Texas staying at tropical storm strength or greater for 117 hrs.</li> <li>Harvey was the wettest tropical cyclone in the US history, dropping 34 trillion gallons of water across East Texas and Western Louisiana and almost 52 inches of rain in six days</li> <li>Harvey produced 51.8 inches of rain at Cedar Bayou, Texas—the most ever recorded in US mainland from a tropical cyclone.</li> <li>Hurricane Harvey was the first storm to make two landfalls in the Gulf of Mexico more than 60 hours apart.</li> <li>Irma was the strongest Atlantic storm in Caribbean Sea on record.</li> <li>Irma was the strongest hurricane to hit the Leeward Islands on record.</li> <li>Irma stayed as a Category 5 hurricane in the Atlantic for the longest time (78 hours)</li> <li>Irma is the only tropical storm to have sustained very intensive wind speeds at 185 mph (298 km/h) for about 37 hours.</li> <li>Hurricane Nate’s forward speed of 28 mph (45 km/hr) was the fastest recorded motion of a hurricane in the Gulf of Mexico.</li> <li>Hurricane Irma was the closest approach of a Category 5 hurricane to the Turks and Caicos Islands</li> </ul>	
	Compared to Other Seasons	<ul style="list-style-type: none"> <li>The most active since the record-breaking season of 2005, with 17 named storms, 10 hurricanes, and six major hurricanes above Category 3.</li> <li>Seventeen named storms formed, above the 1950-2016 average<sup>1</sup> (11.6 named storms) and above the 1996-2016 average (14.4).</li> <li>Ten hurricanes formed, above both the 1950-2016 average (6.2 hurricanes) and 1996-2016 average (7.2).</li> <li>There were six major hurricanes (Category 3 or greater), which lies above the average of 1950-2016 (2.5 major hurricanes and 1996-2016 (3.3).</li> <li>The seventh season since 1950 to have at least six major hurricanes.</li> <li>Hurricanes developed in the Atlantic for more than 52 days, being the sixth highest number of days since 1851, the most since 2004, and are more than double the seasonal average.</li> <li>The stretch of hurricanes was the longest since the early twentieth century.</li> <li>The ACE index total of 226 was well above both the 1950-2016 (101 ACE) and 1996-2016 (124 ACE) averages.</li> <li>The season’s ACE total ranks as the fourth largest since 1950 and the largest since 2005.</li> <li>Hurricane Irma (the season’s largest ACE contributor), generated 67.5 ACE units, the second largest ACE total for a single storm in the Atlantic since 1966 when the satellite era began.</li> <li>The TIKE total was approximately 25% higher than the annual mean calculated from 1990 onward.</li> <li>Tropical Storm Arlene was the second tropical storm on record to form in the month of April (20th), before the official start of the hurricane season since Ana in 2003.</li> <li>Tropical Storm Bret was the lowest latitude named storm in the month of June, since 1933.</li> <li>The joined presence, on June 20, of Tropical Storms Cindy and Bret in the Atlantic, marked the first time in 49 years, and only the third time on record, that two named storms co-existed in the Atlantic before July 1.</li> <li>Hurricane Harvey was the first Category 4 hurricane to make landfall in the US since Hurricane Charley in 2004.</li> <li>Hurricane Irma was the first Category 5 hurricane to make landfall on the Camaguey Archipelago of Cuba since 1924.</li> <li>It was the first time since 2010 that three hurricanes (Irma, Jose, and Katia) were active in the Atlantic basin at the same time (September 8)</li> <li>Hurricane Nate was the first hurricane to make landfall in Louisiana since Hurricane Katrina in 2005 and the fourth hurricane to make landfall in mainland USA in 45 days.</li> <li>The fourth on record and the first year since 1893 to have 10 consecutive storms gain hurricane status in the Atlantic basin.</li> <li>Hurricane Irma was the first Category 5 hurricane to make landfall in the Bahamas since Andrew in 1992.</li> </ul>

Related references: Authors, compiled from various sources including NOAA’s NWS, UK Met Office [19] [47] [48] [49].

<sup>12</sup>The main development region spans the tropical Atlantic Ocean and the Caribbean Sea between 10°N - 20°N, 20°W - 80°W.

when compared to other hurricane seasons. Many new hurricane records were set. Since the development of the satellite for observing hurricane formation in the early 1960s, 2017 is the only year where there have been ten consecutive hurricanes in the Atlantic basin. The 2017 AHS is the most active since the record-breaking season of 2005 and is now ranked amongst the top ten most active seasons since records began. Compared to historical database for land falling hurricanes (Figure 4), the 17 storms that formed in 2017 is above the 1950-2016 average<sup>13</sup> (11.6) and the 1996-2016 average (14.4). The number of hurricanes (10) is above both the 1950-2016 average (6.2 hurricanes) and 1996-2016 average (7.2). The major hurricanes of the season (6) surpass the average of 1950-2016 (2.5) and 1996-2016 (3.3).

Philippe Klotzbach<sup>14</sup> tweeted that there were “*only eight other years, dating to the mid-19<sup>th</sup> century that had generated seven or more hurricanes by September 17*”. Indeed, it was the first time two Category 4 hurricanes (or stronger) had made landfall in the USA from the Atlantic Ocean since weather records began in 1851. It is rare for a Category 4 (or stronger) Atlantic hurricane to reach the US. Only 29 hurricanes (including Harvey, Irma, Jose and Maria that formed in 2017) have been documented since 1851; of which four were Category 5 hurricanes. Since Hurricane Charley devastated South West Florida in 2004, Harvey’s strike on Texas was the first to occur in the US and landfalls of that strength have not happened since Hurricane Andrew (Category 5) devastated South Florida in 1992. In the Caribbean, the situation is similar. Harvey was the first Category



**Figure 4.** Comparison of the 2017 AHS storms to that between 1950-2016 and 1996-2016 averages. Related references [47].

<sup>13</sup>Although the historical database for hurricanes that make landfall worldwide is complete from 1900, the record of hurricane activity in the Atlantic Basin is complete only from 1950 onward due to the start of satellite technology and aircraft reconnaissance.

<sup>14</sup>Philippe Klotzbach is a Meteorologist with Colorado State University and expert in both hurricane seasonal forecasting and hurricane climatology.

5 hurricane to hit Dominica and Puerto Rico since at least 1851 and 1928 respectively.

During 2017, hurricanes developed in the Atlantic for more than 52 days. That is the sixth highest number of days since 1851, the most since 2004, and is more than double the seasonal average. Eminent meteorologists Bob Hansen<sup>15</sup> described the season: “*This season has been an overachiever by almost every index...we are running at about twice the pace of a typical season*”. Eric Blake<sup>16</sup>, a scientist at the NOAA similarly remarked: “*Never seen anything like this in the modern record*”.

In addition, it is notable that during the 2017 AHS *six major hurricanes* (>Category 3) passed through the Atlantic hurricane basin. It is rare for two hurricanes to pass through the same region in the same year. The last time this happened was in 1829 when the northern Leeward Islands were hit by two major hurricanes in the same season. Maria (Category 4) was *the strongest storm to have hit Puerto Rico in 85 years*. The 30-year average number of hurricanes for an entire AHS is six. Yet by mid-October 2017, 10 hurricanes had been recorded in the Atlantic.

The first major hurricane of the season, Harvey (Category 4) was *the 18th strongest hurricane to make landfall in the US since 1851 and ninth strongest to hit Texas*. Harvey has gone down on record as *the wettest tropical cyclone in the US history*, dropping 34 trillion gallons of water across East Texas and western Louisiana and almost 52 inches of rain in six days [49]. The storm produced 51.8 inches of rain at Cedar Bayou, Texas—*the most ever recorded in US mainland from a tropical cyclone*, breaking the previous record of 48 inches set in Texas by Tropical Storm Claudette in 1979. Philippe Klotzbach tweeted that, “*Harvey broke the longest-running US land falling major hurricane drought at 4,323 days*”.

Irma was the 11th most intense hurricane on record in the Atlantic basin, *the strongest Atlantic storm in Caribbean Sea on record* and the only Category 5 storm to have made direct impact in the northern Leeward Islands [46] [50]. Hurricane Irma’s peak wind speed of 185 mph *is the second highest<sup>17</sup> on record*, only surpassed by Hurricane Allen (1980) which reached wind speeds of 190 mph. Moreover, Irma is on record as *the only tropical storm worldwide to have sustained very intensive wind speeds at 185 mph (298 km/h) for about 37 hours*, beating the previous record for a storm of that intensity held by Typhoon Haiyan, which was at maximum intensity for 24 hours. Furthermore, Irma remained a Category 5 Hurricane for *the longest time since satellite storm tracking began (at 3.25 days)*, tied only with the 1932 Cuba Hurricane and the *first Category 5 Hurricane to have hit Cuba since 1924* [50].

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<sup>15</sup>Bob Hansen is Weather Underground’s senior meteorologist, co-editor of Category 6, and author of “Meteorology Today” and “The Thinking Person’s Guide to Climate Change.”

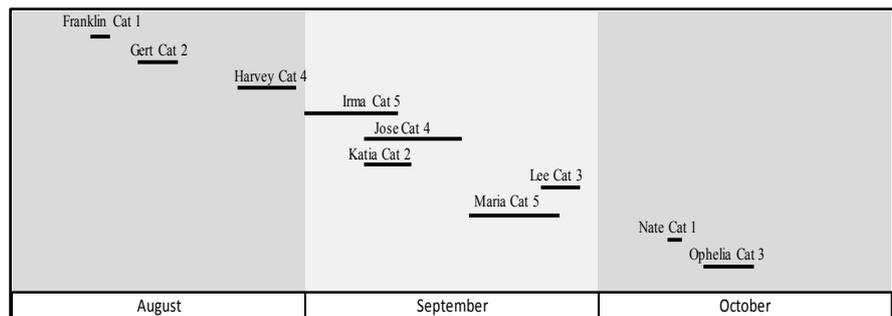
<sup>16</sup>Eric Blake is a hurricane specialist at NOAA’s National Hurricane Center in Miami, Florida.

<sup>17</sup>Irma’s speed is tied with hurricanes Gilbert (1988), Wilma (2005) and the Florida Keys hurricane of 1935.

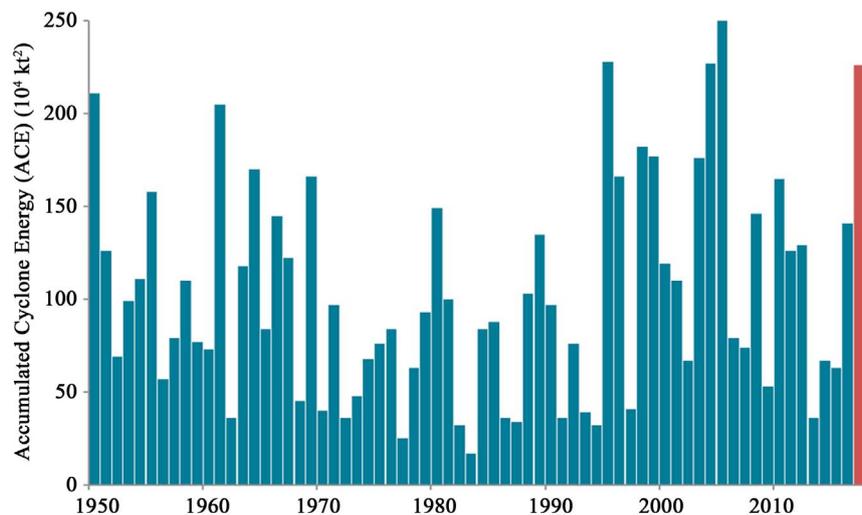
Moving north-westward at 28 mph (44 km/h), Hurricane Nate was *the fastest-moving storm ever recorded in the Gulf of Mexico*, according to the National Weather Service. In addition, Nate was the first tropical cyclone to move ashore in the state of Mississippi since Hurricane Katrina (Washington Post, edition of October 8, 2017). Hurricane Ophelia was the *easternmost Atlantic major hurricane on record* and the *worst storm on record to hit N Ireland* with gusts of 90 mph that caused three fatalities [45] [51].

Also remarkable during the 2017 AHS is the stretch of hurricanes. This was the *longest since the early twentieth century* (Figure 5). The timeline for each hurricane to form—one after the other, was very short, averaging only about 6 days between Hurricanes Franklin, Gert and Harvey. Indeed, for three weeks in September 2017, five hurricanes occurred concurrently in the NE Atlantic. These hurricanes were also, notably, long-lived. Included in this series was Harvey (15 days), followed by Irma (14 days) then by longest lived Jose (18 days) and the next longest-lived Maria (15 days) and then Nate (6 days).

The 2017 AHS had an ACE index of 226 that is above the 1950-2016 (101 ACE) average and ranked the fourth largest since 1950 (Figure 6). Only three other seasons (1995, 2004 and 2005) have had a higher ACE since 1960 (Table 4).



**Figure 5.** Timeline for hurricanes that formed in the 2017 Atlantic Season. Related references: Authors.



**Figure 6.** Atlantic Hurricane Season ACE totals from 1950-2017. Related references [47].

Irma, Jose and Maria, long-lived hurricanes with strong, wide wind fields, were the greatest contributors to the season's total ACE and TIKE. Irma generated more ACE than any Atlantic tropical cyclone on record and accrued the third-highest ACE index on record by mid-September although roughly 38% of an average AHS's ACE index occurs after September 18. The TIKE total for the 2017 AHS (10,500 TJs) was about 25% higher than the annual mean from 1990-2016 [46] [47] [50].

### 4.3. Losses Incurred during the 2017 Atlantic Hurricane Season

The 2017 AHS is the most expensive on record, culminating in more than \$202.6 billion in damage [52] [53]. The havoc caused was immense. **Table 7** shows the storms that caused considerable damage during the 2017 AHS, and their estimated financial and human costs.

Whilst the full economic impact of the 2017 hurricanes continues to be assessed, preliminary analysis indicates large gross losses from affected short-term investment flows and lost value of capital stock (damages to roads, infrastructure, housing, commercial property, agricultural). Arguably, 2017 is one of the most expensive seasons on record including in the USA especially when compared to Hurricane Katrina and other major hurricanes in 2005 that caused about \$143.5 billion in damage.

In the USA, Harvey caused damages of \$126 billion, mainly in Texas. Indeed, Harvey and Irma have joined the list of "*billion-dollar hurricanes*", the latter being the fifth most expensive hurricane to hit the US [11]. The secondary effects to the US economy could be dire. For instance, it was estimated that Harvey could have reduced Texas's GDP growth to 2.7% from 4.3% in 2017, while Irma also reduced Florida's real GDP growth from 3.6% down to 2.5% in 2017. According to the US Energy Information Administration, Hurricane Harvey caused the US refining capacity to drop from 97% on August 25 to 78% on September 8 and this caused retail gasoline prices to increase by 32 cents (13.2%) between August 21 and September 11 [49] [54].

Notwithstanding the relative size of the US economy, the much smaller economies of the Caribbean nations were seriously affected. Prior to 2017, the largest hurricane cost in the Caribbean was caused by Hurricane George (1998), which ravaged six islands causing almost US\$11 billion in damages [10]. In 2017, however, the cost was far higher. Irma and Maria caused losses worth \$51 billion and \$91 billion respectively in Puerto Rico [11]. Irma's damages amounted to \$1.5 billion for Saint Martin, \$500 million for the Turks and Caicos Islands, \$480 million for St. Bathelmy, \$150 - 300 million for Barbuda, \$190 million for Anguilla, and \$200 million (uninsured losses) for Cuba [50]. Indeed, such economic losses have the potential to set back development in the Caribbean for several decades. The Washington Post (edition of September 15, 2017) reported the Antigua and Barbuda's ambassador to the USA describing the damage: "*For the first time in 300 years there's not a single living person on the island of Barbuda—a civilization that has existed on that island for over 300 years has now been*

**Table 7.** Storms and associated hazards and their effects during the 2017 AHS.

Storm name	Locations affected	Associated hazards	Effect	Damage (USD)	Deaths
Bret	Trinidad, Tobago Venezuela, Guyana, Windward Islands	Strong winds, Heavy rainfall. Mudslides, Flooding.	Hundreds of houses damaged and flooded	≥\$3.3 million	1
Cindy	Mississippi, Louisiana, Honduras, Belize, Cayman Islands, Peninsula, Cuba, Southern Eastern USA Yucatán	Heavy rainfall Storm surge. Strong winds & Flash flooding.	Minor flooding in rivers, tidal flooding. Power outages, damage to property.	≈\$26 million	1
Don	Trinidad and Tobago, Port of Spain, Windward Island, Barbados	Heavy rainfall, Thunderstorms, Localized flash flooding.	Houses inundated & property damaged	NA	None
Emily	Florida (Collier & Miami-Dade Counties, Miami Beach, Bradenton)	Wind gusts, thunderstorms, high tides	Damages to homes, localized power outages & flooding.	≈\$11 million	None
Franklin	Veracruz, Guatemala, Honduras, Yucatan Peninsula, Central Mexico	Strong winds, heavy rains, flooding, landslides and mudslides	Dozens of homes damaged, power outages affected over 300,000 people, homes inundated by flood waters.	≈\$15 million	None
Harvey	NE and SE USA (Florida, Georgia, Texas) Leeward Hispaniola, Islands, Cape Verde, Puerto Rico, Turks and Caicos Islands, The Bahamas, Cuba,	Strong winds. Record breaking rainfall, Storm surge, tides, intense flash flooding.	More than 300,000 structures and 500,000 cars were damaged, over 110,000 structures flooded.	≈\$126 billion	68
Irma	Saint-Martin, Anguilla, Tortola, St. Thomas and St. John, Puerto Rico, Dominican Republic, Haiti, South Caicos, Hispaniola, Turks, The Bahamas, Cuba, SE United States (Florida and Georgia), NE United States	Strong hurricane category winds, heavy rains, storm surge, flood.	About 1100 buildings damaged or destroyed, water supply system damaged, Airport severely damaged, power & telecommunication affected	≈\$64.76 billion	52
Jose	Leeward Islands, Barbuda, East USA	Strong winds, heavy rainfall.	Hampered humanitarian and relief assistance	≈\$2.5 million	1
Katia	East Mexico	Heavy rainfall, mudslides, landslips	53 Municipalities reported damages to infrastructures.	NA	None
Maria	Lesser Antilles, Palmas Del Mar, Guayama, Rio Grande, Arecibo, Puerto Rico, San Juan. Hispaniola, Turks and Caicos Islands, Bahamas, SE USA.	Intense rainfall and winds, flash and river flooding.	≈90% of buildings in Dominica destroyed, Electricity & water supply affected, Communications systems downed, Plantations damaged in Guadeloupe. Disruption of normal operations, weather radar destroyed Roads and bridges damaged, Partial failure of Guajajara Dam.	≈\$92 billion	148
Nate	Honduras, Nicaragua, Panama, Costa Rica, Mexico, Cuba, Cayman Islands, SE & NE USA	Heavy rainfall, River & storm surge flooding, landslides	Extensive property/infrastructure damage, Downed trees and electricity poles	≈\$787 million	46
Ophelia	UK, Ireland	Strong winds	Affected power lines & caused minor damage to property and downed trees.	>\$14 million	3

**Continued**

Philippe	Florida, N. Carolina, Cuba, Cayman Islands, Yucatán Peninsula,	Gale-force winds, tornadoes, localized flooding.	Minimal damage to houses	NA	None
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Related references: Authors, compiled from various sources including [11], [46] [47] NOAA's NHC/NWS, UK Met Office.

*extinguished*'. He said reconstruction could cost up to USD \$300 million.

The impact on the population and to the environment was considerable. Irma caused untold sufferings in the Caribbean. Puerto Rico experienced island-wide power outages due to extensive damages on the energy grid. More than one million people were left without power and 6,000 others sort refuge in shelters. In Tortola, St. Thomas, St. John, Dominican Republic and Barbuda, Irma's severe wind and storm surge caused substantial structural damages to hundreds of buildings and the communication systems. Prime Minister Gaston Browne of Antigua and Barbuda claimed that the Islands were barely habitable afterwards, with 95% if the buildings destroyed. The international NGO, Oxfam, estimated that more than 24,000 people were displaced in the Dominican Republic and more than 5,000 people were evacuated. In Haiti, the storm caused flooding and mudslides that damaged hundreds of homes. In the USA, Irma's landfall was associated with riverine flooding that reached up to 1.8 meters in several locations in Florida, causing significant damage.

Maria caused substantial structural and roof damage to buildings in St. Croix and Palmas Del Mar, Guayama, Rio Grande, Fajardo, Caguas and Arecibo. Low lying areas at St. Thomas suffered flooding damage. Trees in the region were stripped of their leaves and Guadeloupe's banana plantations were severely damaged. In Puerto Rico, Maria exacerbated the power outages caused by Irma, causing significant damage to several large wind turbines and damaged weather radars on the Island. The storm also caused 70,000 people to be evacuated in northern Puerto Rico due to the danger of dam failure [47] [48] [49] [55].

The insurance industry also suffered huge losses from the major hurricanes. Estimates indicate insured losses from \$25 to \$40 billion for Harvey, \$35 to \$55 billion for Irma, \$15 to \$30 billion and \$15 to \$30 billion for Maria. These estimates represent insured loss associated with storm surge, coastal and inland flood and wind damage in the US and the Caribbean. Implications to the banking industry include higher delinquency rates and deterioration in the quality of collaterals in affected areas [47] [56].

The ramifications of the losses are even dire when the knock-on effects to the economies of the Caribbean countries are considered! These include a short-term curtailment of economic activity resulting from a reduction in trade and investment, income, consumption and value of services. These could seriously affect the national economies of the countries impacted in the long-term.

#### **4.4. Why Was the 2017 Atlantic Season So Active?**

The severity of the storms reignited discussions and arguments that seek to ex-

plain why the 2017 AHS season was so active. At the center of these discussions is whether global warming and/or Climate Change (CC) are playing a significant role. Many scientists argue, and we agree, that this seems to be the case, evidenced by the increasing number and intensity of the storms.

Scientists have established that ocean temperatures in the Atlantic have been increasing steadily over the last few decades due to CC, and this is fueling the frequency, intensity and tracks of TCs [3] [15]. For instance, they argue that global warming is contributing to an increase in water vapor in the atmosphere. Indeed since 1988, the amount of total water vapor column over the global oceans has increased by 1.3% per decade [57]. This is causing an increase in the rainfall potential with the prediction that this will lead to an increased ferocity of TCs in the second half of the 21st Century [3]. In fact, climate predictions based on global warming suggest that average-intensity TCs will likely get even more intense in the coming decades as the earth continues to warm<sup>18</sup> [15]. Actually, a 0.5 centigrade increase in sea surface temperature (SST) can lead to a 40% increase in hurricane activity [58].

The 2017 AHS was definitely characterized by highly favorable environmental oceanic and atmospheric conditions that favored cyclogenesis (see Section 2.5) and promoted the above-average hurricane activity (see Section 2.7). During the first half of 2017, the central equatorial Pacific Ocean warmed to borderline El Niño<sup>19</sup> conditions. At the start of the 2017 AHS, tropical Pacific Ocean SSTs and upper ocean heat content cooled rapidly, and El Niño-Southern Oscillation (ENSO)<sup>20</sup>, which significantly influence inter-annual hurricane activity, quickly transitioned toward La Niña conditions by mid-summer<sup>21</sup>. The lack of El Niño, therefore, leads to a reduction in mid-troposphere vertical wind shear in the Western Pacific Ocean in 2017 [15] [46]. This was highlighted by an atmospheric scientist at Massachusetts Institute of Technology, Kerry Emanuel, who remarked? “*El Niño is stuck in neutral this year...there’s currently little difference in wind speeds near the surface and those roughly 10 miles up, which ensures that miles-tall hurricanes can form and remain stable*”. Atlantic hurricanes are suppressed when an El Niño is underway in the Pacific because its shearing winds<sup>22</sup> can dissipate nascent storms [21] [29].

In August 2017, the NOAA explained that unseasonably warm ocean temper-

<sup>18</sup>Both higher standard surface temperatures and increased water vapor tend to increase the energy available for atmospheric convection, such as thunderstorms, and for the development of tropical cyclones.

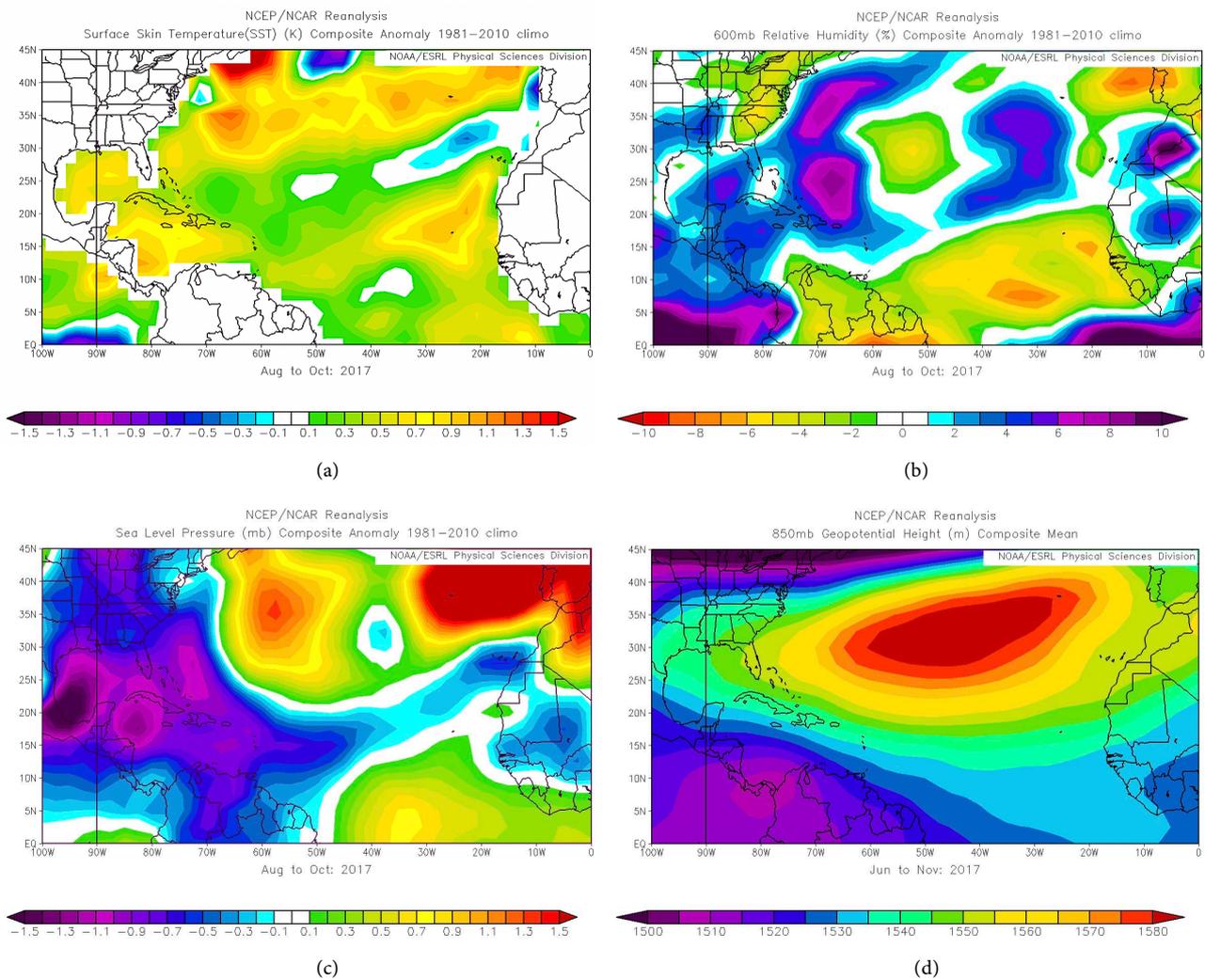
<sup>19</sup>El Niño is the warming of sea surface temperature that occurs every few years, typically concentrated in the central-east equatorial Pacific with a global impact including increasing wind shear across the tropical Atlantic.

<sup>20</sup>ENSO is 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.

<sup>21</sup>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.

<sup>22</sup>This is the difference between the winds in the upper troposphere and those at the ocean surface, has been very weak over the tropical North Atlantic.

atures and the lack of El Niño would cause the busiest season in seven years. And this was the case in the main Atlantic basin where SSTs increased considerably<sup>23</sup> (Figure 7(a)), reaching their warmest since 2010. The high temperatures caused instability in the atmosphere, which led to the low-level convergence of moisture, winds, and latent heat creating very favorable conditions for systems to develop rapidly and sustain strong intensities for long periods of time. The warmer oceans arguably made Irma and Harvey far more destructive than they would have been in previous decades. Meteorologist Sean Sublette<sup>24</sup> stated that: “CC makes these bad storms worse... CC can make it totally disastrous or catastrophic”. If global temperatures continue to rise, it is estimated that the average annual hurricane damages in the Caribbean will increase between



**Figure 7.** (a) 2017 AHS Sea surface temperature anomalies ( $^{\circ}\text{K}$ ) from August to October; (b) 600 mb relative humidity (%) moisture anomalies for the period through August to October; (c) Sea surface pressure (mb) anomalies from August to October; (d) 850 mb Geopotential Height (m) composite mean for the period June to November 2017. Related references: NOAA/ESRL PSD.

<sup>23</sup>The sea surface temperatures in September were the third warmest temperature on record.

<sup>24</sup>Sean Sublette is a meteorologist with Climate Central, a non-profit group that studies climate change.

22% and 77% by the year 2100 [10].

The entire Atlantic basin (Gulf of Mexico, Caribbean Sea and Western Atlantic) experienced above-average moisture content (**Figure 7(b)**) especially in September (the peak months of the season) that produced the major hurricanes. As mentioned in Section 2.2, a higher concentration of water vapor in the atmosphere fuels storm development and intensification [59] [60] especially if there is no dust blowing across the Atlantic from Africa, which tends to have a drying effect on developing storms [28] [61]. In fact, the Climate Prediction Centre asset that in 2017, a strong West African monsoon aligned to make the Caribbean Sea and part of the tropical Atlantic particularly well suited to hurricanes. Furthermore, the sea level pressure across the Atlantic basin in 2017 was generally below average (**Figure 7(c)**); thereby enhancing cyclone activity. Furthermore, a proper steering pattern was in place—the Atlantic subtropical high extended much further west than in previous decades, creating a predominantly steering flow towards land (**Figure 7(d)**). This position, therefore, directed the major storms on a westward trajectory towards the Caribbean Sea and South East USA [45] [46]. These hurricane-friendly environmental and atmospheric conditions in 2017 arguably contributed not only to more, but stronger, hurricanes in 2017.

#### 4.5. 2017 Atlantic Hurricane Season Forecast

The pre-2017 season forecast did not reflect what actually transpired. Indeed, there was no indication of the hyperactivity of the season that involved the major hurricanes and associated ACE index observed. Rather, most pre-season forecasts issued between April and June indicated a slightly below-average to above-average activity.

The TMP's pre-season forecasts in April 2017 predicted a slightly below-average activity for the 2017 Atlantic basin hurricanes [48]. In fact, the CSU also made an early forecast that the season would be about 30% below both the 1950-2016 long-term norms and the recent 2006-2015 10-year norm [58]. Prior to the official start of the hurricane on June 1, the main forecast agencies (CSU and TSR) [38], predicted an average to slightly above-average activity (**Table 8**). In May 2017, the NOAA said the season had a 45% chance of an above average season<sup>25</sup>. In August, the NOAA upgraded their forecast that: “*the season has the potential to be extremely active and could be the most active since 2010*”. Accordingly, the TMP and TSR later updated their forecasts to indicate a busier season (above average). The agencies attributed the hyperactivity of the 2017 AHS to environmental anomalies in the central Atlantic. However, the disparities in the earlier forecasts show that it is impossible to precisely predict a season's hurricane activity in early April (see Section 2.7) [39].

<sup>25</sup>The NOAA predicted that there is a 70% chance of having 11 to 17 named storms, of which five to nine could develop into hurricanes, including two to four major hurricanes (categories 3-5).

**Table 8.** June 2017 Seasonal forecasts for North Atlantic Hurricane Season with the final numbers for the 2017 season.

Forecast group	Tropical storms	Hurricanes	Major hurricanes	ACE Index (104 kt <sup>2</sup> )
NOAA CPC15 (May 25)	11 - 17	5 - 9	2 - 4	-
CSU16 (June 1)	14 (10 - 18)	6 (4 - 8)	2 (1 - 3)	100 (52 - 148)
TSR (May 26)	14 ( $\pm 4$ )	6 ( $\pm 3$ )	3 ( $\pm 2$ )	98 ( $\pm 48$ )
U.K. Met Office17 (June 1)	13 (10 - 16)	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
Weather BELL 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

Related references: [46].

## 5. Conclusions and Recommendations

The 2017 AHS is arguably one of the worst seasons in years by various meteorological standards. The season will be remembered for its many storms, the number of these storms that became hurricanes, their intensity and ferocity, and the manner by which so many storms passed through the same path at the same time.

Key characteristics also make the 2017 AHS distinct from others. The season recorded 10 hurricanes cumulatively for 52 days, with six major ones (>Category 3); the September ACE index (155.4) makes it the most active Atlantic calendar month on record; it was the first time two Category 4 or stronger Atlantic hurricanes reach the US and the stretch of hurricanes that formed was the longest in the 20th and 21st century. The season recorded the most enduring wettest hurricane to hit the USA; Irma was the strongest Atlantic storm in the Caribbean Sea ever and was a Category 5 hurricane for the longest time since records began. In terms of cost, the season is the most expensive on record (>\$202.6 billion economic cost) with potentially dire ramifications to the small Caribbean economies in the long-term.

There is general consensus amongst scientists that the unusually high meteorological activities of the 2017 AHS were due to anomalous high hurricane friendly environmental conditions—such as, the lack of ENSO and reduction in mid-troposphere vertical wind shear, considerable increase in SSTs, above-average moisture content and below-average sea level pressures. They also advance scientific evidence to support the thesis that the magnitude of Harvey, Irma,

Maria and other recent storms highlights the effects of global warming and indicative of CC.

Interestingly, early forecasts predicted a rather calm season, contrary to what was experienced, which highlights limitations in forecasting these forces of nature. Yet, early predictions are important because they allow enough time to prepare for hurricane impact. With predictions that the incidence of storms will intensify and increase substantially by the end of this century and as rapid intensification is difficult to forecast [15], there is a risk of an increased frequency of poorly anticipated, high-intensity hurricanes making landfalls with potentially dire ramifications. These challenges call for the urgency to take action at every level of society to minimize the impact of an ever-increasing number and severity of severe storms as those experienced during the 2017 AHS.

Therefore, countries prone to TCs will be served well by focusing on ways to recognize and internalize the costs of these storms and to prepare for the predicted intensification of TCs due to CC. Consequently, appreciable decreases in vulnerability to these storms—for example, through land use policies, building codes or better preparedness, and evacuation procedures or better forecasting—could reduce TC-related casualties.

In this light, this paper advances for a more proactive approach in dealing with these severe storms. Effective mitigation of TC impacts and its effects on society will require a strategic move from a reactionary to an anticipatory policy. This will entail devising a well-designed and comprehensive emergency management system that focuses on effective disaster management evacuation plans, reducing the vulnerabilities of “*at-risk*” populations and enhancing capabilities. From a disaster management perspective, irrespective of how active a season might be, vulnerable communities should always heed to advice and directions from disaster/emergency management agencies. The 2017 AHS is a clear reminder for the world to always expect the unexpected in natural phenomenon, and for the emergency, disaster management and forecasting services to always strive for continual improvements in their anticipatory and preparatory strategies.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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