Changing Trends in Wave Heights in the U.S. Mid-Atlantic Region

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CHANGING TRENDS IN WAVE HEIGHTS

IN THE U.S. MID- ATLANTIC REGION

by

Hillary Lane

B.S., May 1988, The University of Pennsylvania

A Thesis Submitted to the Faculty of Old Dominion University in Partial Fulfillment of the Requirements for the Degree of

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The pace and effects of climate change are an area of constant focus for coastal engineers as evolving patterns in the atmosphere worldwide affect the oceans and coasts on a regional and global scale. Surface waves respond to changing wind patterns both locally and from propagating swell, and the difficulty in predicting future wind patterns is well-established. Expectations that climate change will result in more frequent and intense coastal storms and consequently greater wave heights in the North Atlantic are still unrealized, and recent forecasts from a variety of atmosphere-ocean coupled global climate models instead predict decreasing wave heights through the end of the century in many areas of the world, including the U.S. Atlantic coast.

In this thesis, an analysis of trends in significant wave heights and extreme waves using hourly data recorded by the National Oceanic and Atmospheric Administration’s National Data Buoy Center buoys finds wave heights along the mid-Atlantic region of the U.S. east coast unchanged or beginning to trend downward from the later years of the 20th century into the 21st century. From the southernmost latitude in the study to the northernmost, a progressive change is evident with latitude. At the southernmost buoy, 44014, located off of Virginia Beach, VA, hourly significant wave heights are virtually unchanged during the time series (1.83e^-6 m/year from 1991-2002 and -5.57e^-6 m/year from 2003 - 2015). At buoy 44009, located off the southern tip of New Jersey, the trend reverses from slightly upward to slightly downward (+3.85e^-5 m/year in 1986 - June 2001 versus -2.42e^-5 m/year from Jul 2001 - Dec 2015). Farthest north, at buoy 44025 south of Islip, NY, the trend reversal again occurs (+ 2.39e^-5 m/year in April 1991 - Jan 2003 versus -2.41e^-5 m/year in Jan 2003 - Dec 2015). Seasonal trends follow the same path with the most evident change being a 0.05 m/year
decrease in extreme waves in the northern region of the study area. Hindcast data from the U.S. Geological Survey allow for an extension of the climatology and analysis to 40 years and shows a clear decrease in storm wave heights.
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CHAPTER 1
INTRODUCTION

1.1 PURPOSE

In a recent study, researchers concluded that changes to the coastline from storm-related waves can be compared to the effects of sea level rise.\(^1\) With the “unequivocal” warming of the Earth’s climate, the Intergovernmental Panel on Climate Change (IPCC) projects an increase in sea level rise, coastal flooding, and storm surge with “high” or “very high confidence”.\(^2\) Models predicting tropical cyclone activity show variations among ocean basins that are directly correlated to changes in sea surface temperature (SST).\(^3\) How the wave climate will respond and evolve is an uncertainty that coastal managers and engineers will strive to understand as they plan for shoreline defenses and offshore projects that can withstand routine storms and extreme events. While global warming studies predict a reduction in tropical cyclone formation on the U.S. east coast through the later part of the 21\(^{st}\) century, they forecast an increase in the number of “very intense” cyclones (winds \(\geq\) 60 m/s).\(^4\) Using three National Data Buoy Center (NDBC) stations with data records spanning 1986-2015 and modeled data from the United States Geological Survey (USGS), this thesis analyzes how climate change has affected wave heights off the U.S. mid-Atlantic coast over the past 30 - 40 years.

Nearly 60 million people live along the Atlantic coast of the United States\(^5\) with nearly 34 million, as of 2014, in mid-Atlantic coastal counties from Virginia to New York.\(^6\) Employment and population density both are growing, and gross domestic product of coastal counties in this region alone topped $2.4 trillion in 2015.\(^7\) Whether it is more frequent precipitation events or more common and/or stronger coastal storms, climate change and sea level rise pose serious danger to the lives and economies in these areas. Using a variety of forecasting models and direct monitoring of wave heights, the coastal engineering community can properly strategize to strengthen and protect these communities.
The NDBC buoys capture and record a range of hourly ocean and meteorological data including significant wave height, peak period, wind speed and direction, and air and water temperature. Buoys are located in both the Atlantic and Pacific basins, as well as in the Gulf of Mexico. This study uses, from south to north, station 44014 (64 nautical miles off of Virginia Beach, Virginia, (VA)), station 44009 (at the entrance to the Delaware Bay, 26 nautical miles southeast of Cape May, New Jersey (NJ)), and station 44025 (30 nautical miles south of Islip, New York (NY)). Each of these buoys is located in deep enough water, between 30.5 - 47.8 meters depth, so that the effects of shoaling, refraction and meaningful bottom friction can be disregarded. The continental shelf along most of the U.S. Atlantic coast (with a few exceptions that are not relevant in this study) is greater than 100 km wide, which results in some dissipation of wave energy.

In July 2016, the United States Geological Survey (USGS) released a report modeling current and future winds and waves along the U.S. mainland coasts. The report includes data from four atmosphere-ocean couple general circulation models (AOGCMs) which hindcast winds and waves from 1976 until 2005 and then projects for two future periods (2026 - 2045 and 2081 - 2100) under two climate change scenarios, RCP4.5 and RCP8.5. (Representative Concentration Pathway (RCP) is the measurement of extra energy absorbed by the Earth system in units of watts per square meter due to the greenhouse effect). After comparing the results of the models with the actual wave height record, the best-fit model became the source of hindcast data to extend and fill gaps in the buoy records.

1.2 OBJECTIVES

By analyzing actual data from the NDBC and filling gaps, where possible, with modeled data from the USGS, this thesis attempts to create the most accurate and complete record possible of waves in the mid-Atlantic region. Since satellite readings of the sea surface height anomaly (SSHA) for the coastal zone are negatively affected both by “noise” from human and natural sources as well as by coarse spatial and temporal resolution, buoy data provide the most trustworthy reading of trends in waves as they approach the nearshore region. Using the
modeled data also allows for the extension of the wave climatology to 40 years (from the 24 - 30 years actually recorded by the NDBC, depending on the buoy). In turn, the longer climatology allows for more meaningful comparisons of trends in wave heights.

The wave climate in this region within the continental shelf should provide a reflection of the storm climate, since the largest waves measured are generated in most cases by the winds associated with these storms. The comparison of the actual and modeled data also provides an additional confirmation of the accuracy of the models used.

1.3 CLIMATE CHANGE AND THE TIMING OF THIS STUDY

There is near consensus among scientists that Earth’s climate is warming and that even with the cyclical nature of climate change of the past, increases in the current cycle are largely human-induced. Globally-averaged surface temperatures on Earth were the highest on record in 2015. In the contiguous 48 United States, temperatures were the second warmest on record. The annual mean temperature in the U.S. Northeast has risen 0.2 degrees F/decade (0.11 degrees C) and 0.1 degrees F/decade (0.056 degrees C) in the Southeast between 1895 - 2015.

The IPCC says the rate of global warming is higher now than at any time in the past 1,300 years and that is “extremely likely” due to anthropogenic factors. Greenhouse gas emissions have led to levels of carbon dioxide, methane, and nitrous oxide in the atmosphere that have not been seen for hundreds of thousands of years. The IPCC predicts that even if emissions of greenhouse gases are curbed, many of the effects of climate change will continue for centuries to come.

Despite agreement about the nature of climate change, many questions exist about the rate and local effects of global warming. Some of the biggest uncertainties are the pace of change, the rate of sea level rise, and the effect that climate change will have on precipitation, flooding, drought, and the frequency and intensity of coastal storms.

When looking at wave records and tropical storms in the North Atlantic, an area that faces both tropical and extra-tropical storms during the summer and winter months, respectively, it is clear that the most extreme waves have been generated by these storms. Latitude appears to play a significant role. As results of the data analysis will show in a
subsequent section (Chapter 4, Results) and perhaps not surprisingly, the most southern buoy faces the most severe tropical storms while the most northern buoy sees a larger number of extreme waves from “nor’easters” during the winter months. Studying trends in the wave climate and comparing numbers of extreme waves during periods in the climatology also reflect important trends in the timing and tracks of coastal storms.

### 1.4 EFFECTS OF SEA LEVEL RISE

#### 1.4.1 Sea Level Rise Estimates and Causes

The ocean absorbs a large amount of heat and carbon dioxide. Figure 1 shows how heat absorption has increased decadally. Feedback loops between the atmosphere and ocean make it difficult to predict future absorption of gas. But it is clear that as greenhouse gases trap more energy from the sun, as much as 90% of this excess heat is being absorbed by the ocean.⁹

![Ocean Heat Content, 1955–2015](image)

**Figure 1: Ocean Heat Content 1955:2015.** Source: Environmental Protection Agency (CSIRO: Commonwealth Scientific and Industrial Research Organisation, MRI/JMA: Meteorological Research Institute/Japan Meteorological Association, NOAA).
Mean global sea surface temperature has increased 0.06 degrees Celsius/decade between 1880 and 2015. Much of this heat remains in the top 700 meters of the ocean, but the increasing temperature gradient, shown in Figure 2 between ocean layers is predicted to influence currents and affect ocean circulation.

![Figure 2: Global Annual Ocean Temp Anomaly 1880 - 2015. Source: NOAA National Centers for Environmental Information.](image)

The expanding of molecules as water temperature increases is responsible for steric sea level rise. Steric sea level rise between 1972 and 2008 generated approximately 38% of overall sea level rise, and as shown in Figure 3, averages 0.8mm/year globally.
Melting of glaciers, ice caps, and ice sheets during that same 1972 - 2008 time period led to an estimated 52% of sea level rise, but that percentage is estimated to be have risen to as much as 75 - 80% of the overall rise in sea level. As shown in Figure 4, mean global sea level rise now averages 3.5 mm/year. Other factors such as groundwater withdrawal make up the difference.
1.4.2 Future Sea Level Rise Projections

Since the beginning of the 20th century, sea level globally has risen at least 20 centimeters, with a greater change in some regions. Current research points to a continued increase, with the most aggressive estimate of nearly one meter more by the end of this century.\(^{14}\)

The Atlantic coast is particularly vulnerable to sea level rise, as is evident in Figure 5, and the area near Virginia Beach and within the region of study of this thesis, has been called a “hot spot of accelerated SLR”.\(^{15}\) Much of the land is flat and sits at a low elevation. Much is tidal wetland and marshland. Land is still recovering from isostatic rebound after the last glacial retreat close to 18,000 years ago. In addition, a shift and weakening in the Gulfstream current has been highly correlated with an acceleration of SLR in this area.\(^{16}\) Near Virginia Beach, sea level rise has been measured at 4.5 mm/year, nearly 30 percent above the global mean.
Figure 5: Land Loss on the U.S. Atlantic Coast. Source: NOAA/EPA 2013: Land Loss on the U.S. Atlantic Coast. Net land converted to open water. Negative readings occur when the creation of new dry land outpaces land loss.
CHAPTER 2
LITERATURE REVIEW

2.1 TRENDS IN WAVE HEIGHTS

It is of key importance to stress that ocean waves are influenced both by local winds and remotely-generated swell. Historical trends are difficult to measure because buoy and satellite data are limited to the past few decades. Some studies have relied on the measurements from voluntary observing ships at sea. But these data are limited in scope and subject to the ships’ positions and routes.

Waves off of the U.S. Atlantic coast show definite seasonal variability and correlation with tropical and extra-tropical storms. In a reconstruction of wave height trends during the last century (1870-2010), Xiolan Wang and colleagues found small increases in the seasonal maximum significant wave height on both sides of the Atlantic during the months of January – March, with larger increases at higher latitudes. The largest increase in wave height was during the summer months of July – September. However, in the southwest North Atlantic which is the region most applicable to this study, wave heights trended downward.\(^\text{17}\) Shimura and colleagues also reported their models projecting future decreases (2075 - 2099) in annual mean wave height in the southwestern North Atlantic as well as in extreme waves throughout the North Atlantic basin.\(^\text{18}\) Other studies found increases in the annual mean across both sides of the North Atlantic, though the change in higher latitudes (50 - 70 degrees) was far more substantial than in more southern areas.\(^\text{19}\) Changes in the annual mean appear to be more dependent on differences in SST whereas variations in extreme waves are believed to be more of a result of changes in storm track.\(^\text{20}\)

In 2008, Paul Komar and Jonathan Allan published a paper reporting an upward trend in summer wave heights from three NDBC buoys in the U.S. Southeast and one in the Gulf of Mexico, especially in waves greater than 3 meters (0.059 m/year off of Charleston, SC; 0.024 m/year off of Cape Hatteras, NC and 0.017 m/year off of Cape May, NJ). The study, which covered an area just south of the area of interest of this thesis, was based on data from 1976 - 2005 and showed a systematic latitudinal variation.\(^\text{21}\) The authors analyzed wave-height
histograms that divided the climatology into two periods to attempt to determine whether there was an increase in the number of higher waves in the later period than in the earlier. They found that there was. Komar and Allan noted that measuring waves on the U.S. Atlantic coast is complicated by the fact that the summer wave climate is strongly affected by tropical storms, and they concluded, “The measured increases in wave heights during the summer hurricane seasons ... must reflect a parallel change in Earth’s climate that has affected the capacity of the hurricanes to generate those higher waves.”

While the evidence that hurricanes generate higher wave heights is clear, and empirical formulas are available to correlate the waves generated by such storms with the storms’ central pressure, subsequent reports from NOAA and other government agencies appear to find that the conclusion that climate change is responsible for the measured increase in wave heights to be premature or as yet unfounded.

More recently, a 2013 study by a team of researchers from four continents projected significant wave heights to decrease across 1/4 to 1/3 of the global ocean, depending on the season. The only region of increase was in the Southern Ocean, generated by predicted strengthening of the Westerly winds. The study projects that swell from this region will propagate northward globally, but the authors note variability in the wave climate due to changes in the marine and wind fields.

### 2.2 Predictions of the Effect of Climate Change on Tropical Storms

Because extreme events such as hurricanes are rare, putting together a long enough timeline over a wide enough geographical area to discern trends is an ongoing challenge. The Geophysical Fluid Dynamics Laboratory (GFDL) set out to analyze a record of more than 100 years for Atlantic hurricanes, more specifically Atlantic basin hurricanes, and even more specifically landfalling Atlantic basin hurricanes. Going back as far as 1860 - 1880, GFDL found “no significant positive trend” for Atlantic basin hurricanes and even weaker evidence for an upward trend in those making landfall. GFDL concludes, “…the historical Atlantic hurricane record does not provide compelling evidence for a substantial greenhouse warming induced long-term increase.”
On its website, NOAA scientists write, “...neither our model projections for the 21st century nor our analyses of trends in Atlantic hurricane and tropical storm counts over the past 120+ years support the notion that greenhouse gas-induced warming leads to large increases in either tropical storm or overall hurricane numbers in the Atlantic. A new modeling study projects a large (~100%) increase in Atlantic category 4 - 5 hurricanes (measured by the Saffir Simpson scale to have sustained winds greater than 58 meters/second) over the 21st century, but we estimate that this increase may not be detectable until the latter half of the century.” (See Section 2.6).

2005 was a record year for high-category hurricanes in the U.S., and since then, no Category 3 or greater hurricane has made landfall on the U.S. east coast. A re-analysis of waves at these buoys that extends for another decade therefore is in order to see if the same or any conclusion can be drawn about the effect of climate change on hurricanes and subsequently on wave height. That is one of the main goals of this thesis.

Recent studies have begun to analyze negative feedbacks such as ocean coupling and the “cold wake” generated by certain hurricanes that can temper the intensity of storms following in its path. Other researchers have found “startlingly different impacts” on the tropical cyclone environment generated by differential warming in other remote basins, and are exploring the combination and accumulation of regional and local effects.

2.3 INFLUENCE OF CLIMATE MODES SUCH AS MADDEN-JULIAN OSCILLATION, ATLANTIC MULTIDECADAL OSCILLATION AND NORTH ATLANTIC OSCILLATION ON TROPICAL STORM ACTIVITY AND WAVE HEIGHTS

Wind waves are at the center of the interaction between the atmosphere, the ocean, and the land. However, as the studies mentioned above show, it is still unclear whether increasing and decreasing trends in ocean waves are due to natural variations in climate or to ongoing climate change. Mikhail Dobrynin and colleagues simulated climate change under high emissions scenario RCP8.5. They found a positive trend in wave heights in major parts of the global ocean that was not discernible under preindustrial climate conditions. They also found areas where ongoing climate change results in lower wind speeds and decreasing wave heights,
including the North Atlantic and South Pacific. The researchers noted that, “in the regions of high variability, such as the North Pacific and Atlantic, the climate change signal is hardly detectable over the analyzed period” (2010 - 2060).28

Despite the difficulty in measuring long-term trends in wave heights, there is clear inter-decadal variability in the tropical storm activity and in the waves generated by these storms. Over the past decade, numerous studies have tied the genesis of hurricanes, major hurricanes, and an increase in the number of hurricanes making landfall to oscillatory phenomena and longer-term cycles such as the North Atlantic Oscillation (NAO), the Atlantic Meridional Mode, and the Atlantic Multidecadal Oscillation (AMO), and the Madden-Julian Oscillation (MJO).

The North Atlantic Oscillation has the most influence on climate variability in the region. Its strength is measured by the difference in sea level pressure (SLP) between Iceland and Portugal during the months of December through March. During the positive phase of the NAO, the pressure gradient is high and the eastern half of the U.S. tends toward wet but mild winters. Following a positive phase, there is a dramatic drop in SSTs in much of the Atlantic basin, which may weaken tropical storms much like a “cold wake” or force them to turn toward the northeast. In a negative or low phase, there is little difference in SLP between Iceland and Portugal, and U.S. east coast winters tend to be colder with more snow. After a negative NAO during the prior winter, Atlantic tropical storms tend to track closer to the U.S. east coast, presumably due to the breakdown in subtropical high pressure. Whether the NAO was positive or negative has not been shown to affect the number of storms that formed but rather their tracks in relation to the U.S. east coast.29 Figure 6 shows the standardized 3-month running mean NAO index through October 2016.
The AMO is a cycle in large-scale atmospheric flow and ocean currents that has a period of approximately 60-80 years. The atmosphere and ocean interact and the result is warm and cool periods of sea surface temperature in the area of the North Atlantic south of 60 degrees North and between 7.5 and 75 degrees West. Positive phases in the AMO have warmer-than-normal waters in the tropical and sub-polar North Atlantic. As shown in Figure 7, in the past century, these phases occurred 1926 - 1969 and 1995 - 2011. In 2001, Goldenberg and team documented multidecadal variations in observed major hurricane activity in the period 1944 to
2000 which they associated with the AMO. The late 1940s – mid-1960s and 1995 - 1999, most recently, were active years with a strong mean intensity of storms, which they attribute to changes in atmospheric circulation in the tropics (Main Development Region, MDR) which in turn reduces vertical shear in the troposphere allowing for tropical storm formation. \(^{31}\)

The peaks in strong hurricane seasons in 1955, 1961, 1995, 2004 and 2005 have corresponded to positive peaks in the AMO.\(^{32}\)

![Observed AMO Index](image)

Figure 7: Observed Atlantic Multidecadal Oscillation Index. Source: Trenberth, Kevin, Zhang, Rong & National Center for Atmospheric Research Staff (Eds). 19 Apr 2016. "The Climate Data Guide: Atlantic Multi-decadal Oscillation (AMO)."

On a much shorter scale, the Madden-Julian Oscillation, which affects atmospheric humidity, winds, and temperature, propagates around the equator in a 30 - 70 day period. Past studies have tied MJO-related convection during certain phases of the cycle to strong periods of hurricane formation in the Atlantic MDR. Klotzbach and Oliver find that the MJO enhances tropical storm activity in conjunction with other oscillations such as the AMO or La Niña (Figure
8) but on its own does not generate measurable increases in tropical storm activity to counter the dampening effects of El Niño or a cool phase of the AMO.

Climate modes can modulate each other’s effects as well. Upper-level winds, changes in circulation and vertical shear, and changes in the temperature in the upper layers of the atmosphere are the factors that drive these oscillations.

Figure 8: Relationship of Accumulated Cyclone Energy with Atlantic Multidecadal Oscillation. Source: Klotzbach and Oliver, Journal of Climate, 2014. Normalized Accumulated Cyclone Energy (ACE) relationship with Atlantic Multidecadal Oscillation and Madden-Julian Oscillation Phase (Phases 1 - 3 tend to result in strong tropical storm formation in the Atlantic while phases 5 - 7 are likely to be unfavorable to hurricane formation).

In their analysis of Atlantic hurricane activity between 1851 - 2007, Petr Chylek and Glen Lesins noted that the probability of two consecutive intense hurricane seasons, such as 2004 and 2005, occurring is less than 1 percent. In comparing the climatologies of 1953 – 1980
with that of 1980-2007 they reported a “modest” increase in the number of Category 1 and 2 hurricanes, but no increase in hurricanes of Category 3 and greater.

While they identified a strong correlation between the Atlantic Multidecadal Oscillation and hurricane activity in the North Atlantic basin, they were reluctant to connect any increase in hurricane activity through 2007 to global warming. But rather than ruling it out entirely, they wrote that the warm phase of the AMO known to have begun in 1995 would have made that connection difficult to detect. Even though its cycles usually last closer to 70 years, some question whether the AMO could be entering a cooling phase, which would result in lower SSTs and a likely decrease in tropical storm formation, as has been predicted in some recent reports.\(^{36}\)

The El Niño Southern Oscillation does not tend to have a major effect on the U.S. Atlantic coast and because it increases upper-level winds and vertical shear in the atmosphere, it dampens tropical storm formation in the Atlantic. It is believed that the La Niña cycle, which often follows an ENSO, can result in a more active tropical storm season for the US east coast.

2.4 SEA SURFACE TEMPERATURE

While sea surface temperature is by no means the only determinant of tropical storm generation and intensity, it is well-established that Atlantic tropical storms form only when the “warm pool “ in the main development region maintains a minimum SST of 26.6 degrees Celsius (82 degrees Fahrenheit). Changes in the Power Dissipation Index (PDI), a measure of the wind stress and surface friction of a storm, are highly correlated with SSTs in the regions where storms develop.\(^{37}\) One highly intense storm can have more far-reaching and damaging effects than several small storms. Thus storms’ tracks, size, and duration are as important of the number of tropical storms during any season.

Air temperature matters as well, since warm air can hold more water vapor than cold air by approximately 4 percent per 1 degree Fahrenheit rise in air temperature.
2.5 ANTHROPOGENIC FORCING

The IPCC again uses the word “unequivocal” when describing whether human activity has increased the level of greenhouse gases in the atmosphere. Increased cultivation of land and deforestation, industrialization, and the release of aerosols and gases, which in some cases have lifetimes of thousands of years, have affected the surface and cloud albedo. These effects are both positive (warming) and negative (cooling), at times depending on latitude. Drawing any conclusions is complicated and uncertain, given that different reactions occur regionally and that climate modes can affect outcomes. Enfield and colleagues found the most recent multidecadal warming (measured 1975 - 2000) to be three times the increase in SST over the main development region for Atlantic hurricanes. Projecting forward to 2025, the researchers say whether the warm pool of water in the Atlantic continues to grow will depend on whether the Atlantic Multidecadal Oscillation (AMO) warm cycle continues or cools. They question the effect that human-induced global warming is having on this phenomenon.\textsuperscript{38}

2.6 FUTURE PREDICTIONS OF TROPICAL STORM ACTIVITY AND THE EFFECT ON WAVE HEIGHTS

The first Intergovernmental Panel on Climate Change (IPCC) in 1990 warned of sea levels rising by as much as 50 cm by 2050 and of the potential for increased flooding and other socioeconomic consequences if storms were to become more severe. Despite predictions in its earlier reports of an increase in both the number and intensity of tropical storms, the IPCC said in its latest major report in 2013, “Projections for the 21\textsuperscript{st} century indicate that it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rain rates. The influence of future climate change on tropical cyclones is likely to vary by region, but there is low confidence in region-specific projections. The frequency of the most intense storms will more likely than not increase substantially in some basins”.\textsuperscript{39}

More recently, Knutson and team used a two-stage dynamical downscaling procedure to conduct a historical analysis of hurricanes globally, a present-day control, and a 21\textsuperscript{st} century projection. While there are global variations, the majority of ocean basins are predicted to see
a decrease in the overall number of hurricanes as the century progresses. However, both the number of “intense” storms (Saffir-Simpson Category 4 - 5) and the number of days of occurrence of these storms are projected to increase in the Northern Hemisphere. The researchers note that the relative change in SST (the global mean SST or SST in the tropics compared to localized SST) in each basin “appears to be a reasonable statistical predictor for the interbasin variation of response in storm frequency for various category storms,” the specific number of intense storm days, and of precipitation rates.40 This observation reiterates the fact that tropical storm formation and the waves that these storms generate have both local and global influences.

The many recent studies that predict and project tropical storms in the coming decades pose a variety of hypotheses about the cause of variations among ocean basins in tropical storms and wave heights. Among them are levels of carbon dioxide in the atmosphere, a slowing of large-scale tropical circulation, pattern changes in atmospheric pressure and wind fields, gradients in relative SST change, and enhanced latent heat release. 41

2.7 LIMITATIONS OF EXISTING STUDIES

Challenges exist to working with wind, wave, and storm data. Buoys gathering wind speed, direction, and wave height data are subject to the harsh effects of those physical factors and often have large gaps in their data records. The tracks of tropical and extra-tropical storms dictate which storms are recorded and whether the buoy captures peak wave heights. The distance of the buoys from the shore as well as the shape of the shoreline can also affect the magnitude of wave height, therefore making comparisons between or among buoys difficult or inaccurate. Perhaps most importantly, despite the strong correlation between winds and waves, it is difficult to determine whether localized winds or remotely-generated swell caused the waves of interest.

For reasons listed above, it is as yet impossible to determine whether wave trends are a result of natural variability or climate change. The cyclical nature of atmospheric flows, their timing, and their effect on and interaction with ocean currents and circulation add uncertainty to any connection.
Since the past wave climate in any region may not be indicative of future trends, it is difficult to make comparisons between climatologies. Because satellite imagery only became available in the 1970s, some researchers question the reliability of storm counts from earlier decades (based on aircraft surveillance and on visual observation reports from ships) and therefore the accuracy of perceived trends.42

Global versus regional climate patterns and their effect on each other and on tracks of storms is another area of current study, especially given ongoing climate change. So is the question of whether climate change is altering the traditional boundaries of the summer hurricane season and resulting in later-season storms, which brings into question the very definition of the seasons used in past and current research.

Data gathered remotely also are subject to spatial and temporal limitations. Similar to the most recent USGS study of waves on the U.S. mainland coasts, the resolution of the grids for the models used may be too coarse to capture shorter storms and their winds. Various forms of downscaling can help better localize results. However, any model that relies on forcing input such as projected wind speed or atmospheric concentration of carbon dioxide or other gases is inherently subject to a range of uncertainties.
3.1 STUDY AREA

The mid-Atlantic region already experiences the highest number of flooding days and has registered the largest increases in coastal flooding in the U.S.\textsuperscript{43} The focus of this study is the section of the U.S. mid-Atlantic coast between $36.61$ and $40.25$ degrees North and $73.16$ and $74.82$ degrees West, an area of approximately $6,088$ square kilometers. The study area comprises a large part of what is known as the mid-Atlantic bight. The area of interest begins just north of North Carolina’s Outer Banks, purposefully eliminated from the study because it juts out further east into the Atlantic Ocean than other points of land and because the continental shelf is far narrower at Cape Hatteras than elsewhere in the area. To the west in the middle of the study area lies Cape May, the southernmost point in New Jersey at the intersection of the Delaware Bay and the Atlantic Ocean. More than half of the homes in Cape May, NJ are situated less than 5 feet above the high tide line.\textsuperscript{44} The northern boundary of the study area is the buoy at Islip, New York, just south of Long Island, the narrow peninsula running eastward into the ocean.
Figure 9 above shows the three NDBC buoys used in this thesis. Station 44014, the southernmost buoy, off the coast of Virginia Beach, VA at 36.61N and 74.82W is situated in water 47.6 meters deep and close to the edge of the continental shelf. Station 44009 (38.46 N, 74.70 W), near the mouth of the Delaware Bay and south of Cape May, NJ, is closest to shore, with water depth of 30.5 meters, and Station 44025, south of Long Island, NY (40.25 N, 73.16 W), sits in water 40.8 meters deep. The water at all three stations is deep enough to avoid having to adjust results for the effects of shoaling, refraction, and extensive bottom friction.
Local bathymetry plays a large role in the wave climate and in how storms affect the coastline, so nearshore wave conditions can be different from those recorded by buoys out at sea.

At 4.5mm/year, relative sea level rise near Station 44014 is nearly 30 percent above the global mean. It is the highest on the east coast and second highest in the U.S., after New Orleans, Louisiana. The reasons for this are detailed in Sections 1.3 and 1.4 above. But even at its extreme, SLR does not yet affect the damage potential of waves this far offshore; it still is just a tiny fraction of the water depth. However, recent studies have begun to analyze whether SLR has begun to change the profile of minor and moderate flooding events on shore in this region and others.45

3.2 CLIMATE OF THE STUDY AREA

3.2.1 Sea Surface Temperature

Satellite imagery composites such as the one in Figure 10 below only became available at the turn of the 21st century. The figure below is the composite SST of the study area and during the summer months from 2002 - 2015. It comes from Aqua MODIS 11μ at nighttime with a spatial resolution of 4 km.
The annual mean water temperature off of Virginia Beach, VA, measured at 0.5 meters below the surface, by NDBC buoy 44014 (at the buoy hull’s waterline) rose from an annual mean of 17.81 degrees C in 1991 to 18.62 degrees C in 2015. Over the period of the study, the mean water temperature was 16.84 degrees C (Figure 11). Several years in the middle of the range (1992, 1994, 1995, 2000, and 2013) were omitted from the mean calculation because missing data skewed the average. Off of Cape May, NJ, station 44009 registered an annual mean of 16.54 degrees C in 1986 and 14.70 degrees C in 2015. But over the period of the study, the buoy shows an uptrend in water temperature and a mean of 14.43 degrees C during 27 years (omitting 1991, 1993, and 2000 for missing data). Northernmost station 44025 off of Islip, New York showed the largest uptrend in water temperature, an upward slope of 0.09 during the study period. SST registered an annual mean of just 11.95 degrees C in 1992, an unusually cool year for the region, and 14.03 degrees in 2015 with a mean of 13.28 degrees C during the period of analysis (1991, 2000, 2011, and 2013 were omitted for missing data).
3.2.2 Air Temperature

The annual mean air temperature measured by buoy 44014 at 4 meters above the surface was 16.52 degrees C in 1991 and 17.17 degrees C in 2015. During the period of this study, the mean air temperature 64 nautical miles off the coast of Virginia Beach was 16.16 degrees C and showed an upward trend (1998, 2006, and 2012 were omitted due to missing data which skewed the results) (Figure 12). At buoy 44009, 26 NM off of the coast of Cape May, NJ, air temperature shows a very slight downtrend (-0.0005) between 1987 and 2015 (omitting 1986, 1993, 1997, 1998, 2000 and 2006). 1987’s annual mean air temperature was 12.67 degrees C and 2015’s was 13.93 degrees C. Off the southern coast of Islip, NY, the annual mean air temperature (omitting 1991, 2000, and 2015 for missing data) was 12.1 degrees C during the study period, with the air temperature at the buoy registering an annual mean of 11.38 degrees C in 1992 and 12.19 degrees C in 2014. The temperature sloped upward at an incline of 0.04 degrees C/year.
Figure 12: Air Temperature Annual Means at Stations 44014, 44009, and 44025 from Historical Data Provided by NDBC Buoys.

3.3 SELECTION OF BUOYS AND DATA USED

All three buoys in this study are 3-meter discus buoys owned and maintained by the NDBC. They sit at sea level and take water temperature readings 0.6 m below the water line and air temperature readings 4 meters above. Their watch circle radius is between 63-75 meters.

The buoys for this analysis of trends in wave heights in the mid-Atlantic were chosen for their location and the length of their data records. The initial goal was to construct a wave climatology as close as possible to 30-years. Two of the buoys, stations 44014 and 44025, have historical data records from 1991–2015 and wave height data from station 44009 extend from 1986–2015. Other buoys in the region were considered, but were unsuitable due to too short a data collection period. All of the buoys have gaps in their records, some longer than a year, due to the harsh effects of wind and waves on the equipment or to other mechanical or technological difficulties. NDBC hourly significant wave height (hourly readings) and wind speed data (every 3 hours) data were downloaded from the NDBC website at www.ndbc.noaa.gov.
In a variation of the methodology of Ruggiero 2010 via Mendez et al. (2006, 2008), if more than 40 percent of the hourly readings in a given year were missing, that year was deemed unusable in the analysis of annual means. In their earlier paper, Komar and Allan used a more restrictive cutoff of 20 percent missing data for the elimination of months from their analysis. However, in more specific analyses of summer and winter means, they excluded only months in which more than 40 percent of the readings were unavailable.

3.4 RECONSTRUCTING THE DATA RECORD WITH MODELED DATA

In July 2016, the USGS released extensive projections of winds and waves for the mainland U.S. coasts using winds from four atmosphere-ocean general coupled circulation models (AOGCMs) or Global Climate Models (GCMs) and the WaveWatch III numerical wave model (with bathymetry and shoreline positions populated from the Naval Research Laboratory Digital Bathymetry Database and the National Geophysical Data Center Global Self-Consistent Hierarchical High Resolution Shoreline). The USGS hindcast the 30 years from 1976 - 2005 and then projected future wind and wave heights under both RCP4.5 and RCP8.5 from 2026 - 2045 and from 2080 - 2100. The hindcasting did not cover 2006-2015 despite the availability of actual data because the researchers believed that, “As a rule-of-thumb, 30 years provides a decent climatology.” The USGS results and conclusions will be detailed in Section 4.7.

This new collection of data makes it possible to extend the length of the climatology from 30 years to 40 years, allowing the time frame to be divided into two longer periods which are the basis of a comparison of trends. The hindcast data also provide an appropriate substitute to fill the many gaps in the actual wave record that occurred due to buoys’ downtime or failure to capture data. Modeled data from the USGS are available for 17 output points, seven of which are collocated with NDBC buoys. Only one of the NDBC buoys in this thesis is collocated, station 44014 in Virginia Beach, VA with output n44014. Of the four AOGCMs used, NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL) model aligned best with the actual data. Figure 13 shows a comparison of hindcast data from the above-mentioned collocated USGS output point n44014 with actual data from NDBC buoy 44014 for the year 2004, which had the fewest missing wave height records in the buoy’s history.
A similar wave hindcast (of data from 1979-2009) also generated using WAVEWATCH III found “excellent” agreement between the model and data to the 99.9th percentile.\textsuperscript{51} Buoy 44025 was one of the buoys included in that comparison, which was conducted in 2013.

NDBC station 44025, south of Islip, NY (40.25 N, 73.16 W) aligns best with USGS output point NAEC6 (North America East Coast 6, at 39.03 N, 71.68 W). Although no USGS output point matches as well with NDBC buoy 44009 south of Cape May, NJ (38.46 N, 74.70 W), hindcast data from USGS output NAEC7, located (at 37.07 N, 74.09 W) is substituted for missing data where necessary. Fortunately, of the three NDBC buoys used in this analysis, station 44009 has the longest and most complete data record, missing large amounts of data only in 1993 and 1994.
3.5 MISSING DATA

Given the nature of the buoy readings and dependence on technology, there are both large and small areas of missing data. The large blocks are obvious. At times, however, the buoys fail to record an hour or a few hours of data, or skip them entirely. These small gaps in the readings can be difficult to detect. Therefore, at times the recorded rows and dates of actual data do not align perfectly with the modeled readings. A careful matching of actual, combined actual/hindcast (which replaces missing actual readings with modeled data of the same date and hour wherever possible), and purely hindcast data allow the data to line up as well as possible. There appears to be at the most, is a discrepancy of less than half a year (or approximately 1 - 2 percent of the readings).

Wherever missing data were noted, hindcast data were substituted. But even in areas with large gaps in the data record, actual data were used wherever available with as few
substitutions of modeled data as possible, in order to monitor ongoing trends. There were a notable number of instances, often on the last day of a month, where the hours of midnight (00:00) through 22:00 hours were missing. NDBC says this is not due to routine maintenance and believes it to be a systemic issue with “older data”. The year 2000 proved to be difficult to analyze due to a formatting change in the way NDBC reports historical data. Modeled data are substituted during that year. The USGS historical data are only available from 1976 - 2005, so gaps in the actual data record between 2006 - 2015 of all the NDBC stations in this study were filled with NaNs and omitted from the calculations of means.

As mentioned in Section 2.7, it is important to note that the USGS study most likely does not account for hurricane-related winds because the resolution of the grids of the models used in their study is too coarse. While the models may underestimate waves during major storms, it is clear from the process of examining the modeled data that the individual models and averaged results also overestimate wave heights at other times.

3.6 WIND AND WAVE INTERACTION

Understanding how and when parts of the wave spectrum are exposed to and react to change is key to determining any effects of global warming on the wind-wave interaction. While it would be expected that wind and waves are highly correlated, separating the effects of local winds, remotely-generated swell, and limited but extreme wind events is quite complicated. Swell is found to dominate the global field resulting in what are considered to be rare occurrences of wind-wave equilibrium. One of the major questions that the findings of this thesis raise is whether trends in wind direction and strength have changed over the period of analysis. If there is evidence of changes, perhaps the result of variations in atmospheric circulation patterns or gradients in sea surface temperature, these potentially could explain, at least in part, the variations in wave height trends and extreme waves in different parts of the study area. As noted in Section 2.1, current research points to strengthening westerlies in the southern hemisphere and swell that propagates northward affecting wave heights in the global ocean. Uncertainty results from the wind forcing and atmospheric gas inputs used in the
various atmosphere-ocean models and how global and marine wind fields will change in a warming climate.

According to a study of extreme wind events in the mid-Atlantic region, from 1990 – 2011, the predominant wind direction in the area including buoys 44014, 44009, and 44025 was along the coast toward the S-SSE in spring and summer and opposite, toward the NNW, during winter. At all three buoys, the hourly average wind speed is above the annual mean during winter and fall and below the annual mean during spring and summer, with the lowest wind speed averages recorded during summer.
CHAPTER 4
RESULTS AND ANALYSIS

There are many ways to parse the large amount of hourly significant wave height data recorded by these buoys during the years of this study. Clearly, the decisions of which years to analyze, which months to include in the winter or summer season, and how to compare different ranges of years significantly can affect the trends that appear.

Looking broadly across the region from Virginia Beach north to Islip, New York (Figures 15 - 17), trends in wave heights seasonally and annually are flat or slightly downward with few exceptions. Histograms of the distribution of waves of different heights show a stable wave climate with a small decrease in larger waves over time. The extreme end of the wave height spectrum can be influenced by just a few seasonal storms and merits discussion with respect to individual locations.


4.1 LEAST SQUARES REGRESSION ANALYSIS

The data records at all three NDBC buoys have gaps in the wave data at different times and of different lengths. Supplementing these records with hindcast data help to build a more clear picture of trends in wave heights on an annual and seasonal basis. Extreme waves are not as conducive to regression analysis because a normal distribution cannot be assumed. However, while the hindcast data provide a solid match and allow for a better analysis of trends in means of the data due to the extended time frame, looking at the full record of actual waves is useful and important.
4.1.1 Actual Hourly Significant Wave Height Record

The data record of buoy 44014 is the weakest of the three with large gaps in data during the year 2000 and 2013 into 2014. There exist multi-week-long and month-long gaps at other times. When examining annual means, years with large gaps must be excluded. However in looking at the trend from the beginning to the end of the actual wave record, all recorded data can be included, as in Figures 18 and 19 below. Examining all available actual hourly SWH data, the slopes of the trendlines from 1991 – 2002 and 2003 – 2015 at the buoy off of Virginia Beach are nearly flat.

Figure 18: Buoy 44014 Actual Hourly SWH Plotted with Trendlines 1991 - 2002 and 2003 - 2015. On the x-axis, hours are in MATLAB datenum form.

A t-test of the two groups of data confirm that the data come from normal distributions with unequal means and unknown variance. An analysis of covariance (ANOCOVA) which fits a
separate line to each group and compares the two lines for statistical difference, results in an F-stat of 3.36 and a p-value of 0.067 and thereby no significant difference in their slopes.

Figure 19: ANOCOVA Prediction from Buoy 44014. Hourly SWH data are grouped 1991 - 2002 and 2003 - 2015. The trendlines fit to each group are visible, but barely distinguishable from each other, between the 1m and 2m mark. They cannot be deemed significantly different at a confidence level of 95%. (Hours scaled by 1/100).

At buoy 44009, there is a longer range of available data plus fewer gaps in the data record. The trends in actual data are more evident and are shown to be statistically significant. While the slopes still are near flat, there is a change in direction from uptrend (+3.85e⁻⁵ m/year) to downtrend (- 2.42e⁻⁵ m/year). The ANOCOVA-fitted lines in Figure 7 below confirm this difference in the slopes of the groups with an F-stat of 1020.45 and p-value of nearly zero. At this buoy, located just 16.9 nautical miles off of the Delaware coast and 26 nautical miles southeast of Cape May, NJ, wave heights consistently are lower than at the other two buoys, presumably due to the buoy’s position closer to land, near the Cape May tip and the opening to
the estuary of the Delaware Bay, where the topography, bathymetry, and currents could affect winds and locally-generated waves.

Despite a wave climate that generally is milder than that of the other two buoys further offshore, buoy 44009 (Figures 20 - 21) sees waves over 7 meters high, on rare occasions topping 8 meters. Waves of this height have occurred in eight of the 29 years of available data from this buoy. The extreme end of the wave climate will be further explored in Sections 4.3 and 4.4.

Figure 20: Buoy 44009 Actual SWH Plotted with Trendlines March 1986 - June 2001 and July 2002 - December 2015. On the x-axis, hours are in MATLAB datenum form.
The trends in wave heights at buoy 44025 (Figures 22 and 23) are quite similar. During the earlier period, there is a slight increase (+ 2.39e^{-5} m/year) which reverses itself (- 2.41e^{-5} m/year) with nearly the same slope in the opposite direction. A t-test confirms that the two groups are normally distributed and have unequal means with confidence at the 95% level. The ANOCOVA test confirms that the slopes of the trendlines, although both very slight in magnitude, are significantly different with 95 % confidence. The F-stat is 339.5 and the p-value is nearly 0.

Waves at this more northern buoy also top 7 meters during storms, most often nor’easters during the late fall and winter and have reached as high as 9.2 meters, notably during the 1992 nor’easter and during Superstorm Sandy in late October 2012. Hurricanes often track toward the east as they move up the U.S. Atlantic coast and therefore do not generate larger summer waves near the buoy. But on occasion (see Appendix A), the tracks of summer storms take them right up to and over the buoy, when these largest extreme waves are measured.
Figure 22: Buoy 44025 Actual SWH Plotted with Trendlines April 1991 - Jan 2003 and Feb 2003 - December 2015. On the x-axis, hours are in MATLAB datenum form.

Figure 23: ANOCOVA Prediction Plot from Buoy 44025. Hourly SWH data are grouped Apr 1991 – Jan 2003 and Feb 2003 - Dec 2015. The trendlines are visible just above the 1m mark, with Group 1 wave heights increasing slightly over time and Group 2 wave heights decreasing by approximately the same amount. Statistically significant at a 95 % confidence level. (Hours scaled by 1/100).
4.1.2 Annual Means

Substituting hindcast data for gaps in the wave records and extending the climatology back to 1976 using consistent modeled data allows a comparison of longer trends in mean wave heights. Simple linear regression analysis shows the trends in annual mean wave heights progressively decreasing with latitude between 1976 - 2015. At buoy 44014, the rate of increase of the annual mean SWH between 1976 and 2015 is just 0.0009 m/year or about 4 cm over the 40-year period. For buoy 44009, the trend in annual means decreases by -0.007 m/year, a loss in height of approximately 28 cm over 40 years. Farthest north, buoy 44025 displays a steeper downtrend of -0.014 m/year in annual means which results in an average wave that is 56 cm lower over the study period. As will be more clear from the analysis of extreme waves, this northernmost buoy in the area of study only sees waves in excess of 7 meters on rare occasion. Four of the five years when the buoy measured a wave of that height or greater came between 1992 - 1996.

Figure 24: Trends in the Annual Mean SWH for all Stations over the Full Study Period 1976 - 2015 Using a Combination of Actual and Modeled Data.
There is more to learn from comparing how trends in wave heights have changed over time, as evidence can be matched with broader changes in atmospheric levels of carbon dioxide, SSTs, and other measurable effects of global warming. When the timeline is divided into two 20-year periods, as in Figure 25 below, the trend in annual means at the southernmost buoy, 44014, shows reverses. Annual mean wave heights trend slightly higher between 1976 - 1995, but then between 1996 - 2015, the trend shifts downward.

![Station 44014 and n44014 Annual Means 1976-1995 and 1996-2015](image)

Figure 25: Buoy 44014 Comparison of Trends in Annual Means 1976 - 1995 with 1996 - 2015 Using a Combination of Annual and Modeled Data. The difference in slopes is not statistically significant with 95% confidence.

At buoy 44009 (Figure 26) which displayed a downtrend during the full 40-year period, the rate of decrease in annual means between the two time periods is steady, and the difference in the slopes of the two periods of comparison is not statistically significant.
Figure 26: Buoy 44009 Comparison of Trends in Annual Means 1976 - 1995 with 1996 - 2015 using a combination of Annual and Modeled Data. The difference in slopes is not statistically significant with 95% confidence.

Finally, as is evident in Figure 27, there is a statistical difference in slopes when the two groups of annual means are compared for buoy 44025, both for actual data only (Fstat = 6.98, p-value = 0.016) and also for the combination of actual and modeled data (Fstat = 5.19; p-value = 0.03). With increasing latitude, the steepening of the decrease in the overall annual mean wave height has become evident. However, the rate of decline here may be decreasing.
Figure 27: Buoy 44025 Comparison of Trends in Annual Means 1976 - 1995 with 1996 - 2015 using a combination of Annual and Modeled Data. The difference in slopes is statistically significant with 95% confidence.

Importantly, this trend toward a flattening of the downtrend evident in the annual and seasonal means at this buoy and the others may be due in part to the combination of modeled and actual data in the analysis. The USGS hindcast data exist only through the end of 2005. As explained in Chapter 3, the USGS notes that the models used in its projections often fail to account for larger storm waves, so the means reflected may skewed lower. Therefore, there is an inherent upward bias any time modeled data or a combination of actual MODEELED data are compared with the purely actual waves from 2006 - 2015, which comprise half of the second time period of the study. Table 1 below summarizes the changes at each buoy during these two twenty-year periods.
### Annual Wave Height Means

<table>
<thead>
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<th>Buoy and Years</th>
<th>Annual Wave Height Means</th>
<th>Trendline Slopes Significantly Different?</th>
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<tr>
<td>44014 1976-1995</td>
<td>+0.003 m/year*</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>+0.002 m/year</td>
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</tr>
<tr>
<td>44009 1976-1995</td>
<td>-0.019 m/year*</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>-0.012 m/year</td>
<td>(Yes for actual data only F-stat=18.9,p-val=0.0002)</td>
</tr>
<tr>
<td>44025 1976-1995</td>
<td>-0.02 m/year*</td>
<td>Yes (actual and extended)</td>
</tr>
<tr>
<td></td>
<td>-0.005 m/year</td>
<td>F-stat=5.19; p-val=0.03</td>
</tr>
</tbody>
</table>

Table 1: Annual Wave Height Mean Trends for Buoys 44014, 44009, and 44025 for the Two Periods 1976 - 1995 and 1996 - 2015. The asterisk (*) reflects statistical significance at a confidence level of 95% or more.

#### 4.1.3 Wave Height Histograms

Dividing the 40-year climatology into two periods and analyzing the number distribution of wave heights using a log scale illustrates the frequency of occurrence of waves of different heights. The number of waves in each of the two periods is comparable within two percent, and the distribution seen in the histograms below (Figure 28) is consistent with only slight declines in and flattening of trendlines in the later years. It is important to note that just a few major storms can be responsible for the extreme waves seen on the upper end of the wave height scale. Overall, changes are minor. (See Appendix A for a chart of tropical storms occurring from 1976 - 2015 in the North Atlantic basin). A discussion of extreme waves follows in Sections 4.3 and 4.4.
4.2 SEASONAL TRENDS IN SIGNIFICANT WAVE HEIGHTS

It is clear both from the histograms and from matching the dates of major storms to the wave data recorded by the NDBC buoys that both tropical and extra-tropical storms tracking close to the recording buoys are responsible for the extreme waves visible in the data. In order to account for what appears to be a trend toward later season tropical storms, this study considers July through November to be “summer” months, the tropical storm season on the U.S. east coast. Waves from January, February, March, and December are designated as “winter”.

An overall flattening in the slope of the trendline is evident for each buoy, both in winter and in summer, between the 20-year periods, though the direction of the trendline may be different. Figure 29 below shows that at buoy 44014, Virginia Beach, both the summer and winter means trend higher during each of the 20-year periods. The 0.0018 m/year increase
during the 1996-2015 summers results in an average just 4 cm higher over the 20 year period. During the 23 years of actual wave height data available at buoy 44014, waves higher than 7 meters have been recorded during eight of those years. Six of the eight times, the waves in excess of 7 meters occurred during the summer months, including November. Only in 1992 and 1993 did a winter storm generate waves of those extreme heights.

![Graph showing wave height data](image)

Figure 29: Buoy 44014 and n44014 Seasonal Means. Summer (green) and winter (blue) means of actual and hindcast data from 1976 - 1995 and 1996 - 2015. Slopes are noted in Table 2.

Wave heights are trending lower south of Cape May, at buoy 44009. But in this case the flattening of the slope means the decreases are less severe. Summer wave heights over the 1996 - 2015 period are little changed, reflecting the absence of major hurricanes from the east coast shoreline from 2005 until the present as well as the tendency for the largest storm waves to occur there during the late fall and winter months. The trends north at buoy 44025 reflect the same pattern and are very similar in magnitude.
Figure 30: Buoy 44009 and NAEC7 Seasonal Means. Summer (green) and winter (blue) means of actual and hindcast data from 1976 - 1995 and 1996 - 2015.
Figure 31: Buoy 44025 and NAEC6 Seasonal Means. NAEC6 summer and winter means of actual and hindcast data from 1976 - 1995 and 1996 - 2015.
### Summer and Winter Means

<table>
<thead>
<tr>
<th>Buoy and Years</th>
<th>Summer (July – Nov)</th>
<th>Winter (Jan, Feb, March, Dec)</th>
<th>Trend Differences Statistically Significant at 95 % confidence?</th>
</tr>
</thead>
<tbody>
<tr>
<td>44014 1976-1995 1996-2015</td>
<td>+0.006 m/year +0.01 m/year</td>
<td>+0.0008 m/year +0.009 m/year</td>
<td>Summer NO Winter NO</td>
</tr>
</tbody>
</table>

| 44009 1976-1995 1996-2015 | -0.016 m/year* -0.004 m/year | -0.034 m/year* -0.022 m/year* | Summer YES (actual data only) Fstat = 7.77, pval = 0.01 Winter YES (actual data only) Fstat = 4.96, pval = 0.04 |

| 44025 1976-1995 1996-2015 | -0.015 m/year* -0.002 m/year | -0.03 m/year* -0.01 m/year* | Summer YES (Fstat = 6.67, p = 0.02) actual (Fstat = 7.4; p = 0.01) extended Winter NO |

Table 2: Seasonal Mean Trends for Buoys 44014, 44009, and 44025 for the Two Periods 1976 - 1995 and 1996 - 2015. The asterisk (*) reflects statistical significance at a confidence level of 95 % or more.

### 4.3 STORM WAVES

Since extreme waves can be used as a proxy for the storms that generate them, filtering out smaller waves to focus on storm waves alone presents a more clear picture of whether and how climate change is affecting the formation and frequency of tropical and extra-tropical storms. Some researchers believe that the storm wave climate is best analyzed by separating waves into two groups: those generated by tropical storms and those generated by non-tropical storm events (which often are extra-tropical storms). The definition of a storm varies by location and wave climate. This thesis sets the threshold storm wave height at 1.5 meters and requires at least 12 consecutive hours of waves at or above this height for a storm to be considered. Storms are deemed independent when at least 48 hours passes without waves at or above the threshold height.
Using Peak Over Threshold analysis, the seasonal variability of the storm climate in the mid-Atlantic region is quite clear (Figure 32 below) and reflects the variations in summer and winter means evident in the graphs in Section 4.2. With the exception of extreme events such as hurricanes, the majority of storms in this region occur during the winter months of January through March and December, as well as in November. Section 4.4 on extreme value analysis compares the trends in storm wave heights over the full study period.

Figure 32: Number of Storms by Month at Stations 44014 (top left), 44009 (top right) and 44025 (bottom) from 1991 - 2015 (1986 - 2015 for Station 44009) Months are numbered 1-12 (January = 1, December = 12). Calculated using actual wave data only.
When outlier waves (above 6 meters) are removed and monthly data are smoothed with a one-year window, the trends in mean storm wave heights show a decrease from the first to second periods at all buoy locations. At buoy 44014/n44014 (Figure 33) the monthly mean storm wave height drops from 2.56 m to 2.24 m. Further north at buoy 44009/NAEC7 (Figure 34), the monthly mean storm wave height over the two time periods drops from 2.69 m to 2.33 m. And at buoy 44025/NAEC6 (Figure 35), the biggest drop is evident, with the monthly mean storm wave height dropping from 3.01 m to 2.23 m. These past decreases are consistent with model future projections from the USGS and other international researchers.57 (See Section 4.7).

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**Figure 33:** Buoy 44014 and n44014 Mean Storm Wave Heights. Buoy 44014 Collocated with n44014. Comparison over the two 20-year periods of the means of storm wave heights, designated as greater than 1.5 meters and occurring according to the parameters described in the body of the text.
Figure 34: Buoy 44009 and NAEC7 Mean Storm Wave Heights. Comparison over the two 20-year periods of the means of storm wave heights, designated as greater than 1.5 meters and occurring according to the parameters described in the body of the text.

Figure 35: Buoy 44025 and NAEC6 Mean Storm Wave Heights. Comparison over the two 20-year periods of the means of storm wave heights, designated as greater than 1.5 meters and occurring according to the parameters described in the body of the text.
Although the northernmost buoy takes the brunt of the most extreme waves during the winter (see seasonal breakdown of Top 5 waves in Table 3 below), it has seen its winter mean wave height trendline flatten over the past twenty years. The decline in the Storm Wave Height mean at this station, 44025, is even greater than the downtrend in the winter mean. Taken together, these results illustrate what appears to be a calming storm climate both during the traditional hurricane season as well as in the winter months.

| Percentage of Top 5 Waves Occurring Seasonally (Actual Waves 1991-2015) |
|-------------------------------------------------|-----------------|-----------------|-----------------|
| Station 44014 | Station 44009 | Station 44025 |
| July - September | July - September | July - September |
| 22% | 15% | 8% |
| December - February | December - February | December - February |
| 23% | 26% | 41% |
| March | March | March |
| 16% | 13% | 23% |
| October - November | October - November | October - November |
| 28% | 41% | 22% |

Table 3: Top 5 Waves Seasonally. Note: percentages reflect actual waves only. Modeled data are excluded because of tendency to miss storm-generated waves. Results are affected by missing months of data from buoy downtime (for example, but not limited to, Jan - Apr 1991 missing from 44025).

The percentage of Top 5 waves occurring in what are sometimes called the “transitional” months of October and November proves to be sizeable and increasing in all locations. In fact, the largest uptrend in the study of actual waves recorded at these buoys comes from the mean wave heights during these two months. At buoy 44009, as many Top 5 waves were recorded during October and November combined as during the entire winter (December - March), so SSTs also may be a factor. This is an area that merits further study, as increasing air and sea surface temperatures provide the latent heat needed for late season tropical storm development and the generation of extreme waves on the Atlantic seaboard.
October and November Mean Wave Heights for Stations 44014, 44009, and 44025 for Actual Waves Only. The trend in the full period from 1991 - 2015 or 1986 - 2015 is statistically significant at a confidence level of 95%.

### 4.4 TOP 5 EXTREME WAVES

Variations in the heights and timing of the most extreme waves appear dependent on latitude and how close to the recording buoy a storm tracks. From south to north, the change is progressive from an increase in both time periods at buoy 44014 (Figure 37), albeit less so in the later years, to a steepening decrease at buoy 44025 (Figure 39). With one exception, the
trend in the means of the annual Top 5 extreme waves is consistent with that of seasonal wave heights. Notably, at buoy, 44025, the annual mean of the most extreme waves declines quite markedly from 1996 - 2015 after little change during the prior twenty years. It is one of the largest changes during this time period. From 1996 - 2015, there are only two years when waves recorded at buoy 44025 topped 7 meters. One was in 1996 during a nor’easter in January. The other was during Superstorm Sandy, when a wave 9.65 meters high was recorded on October 29, 2012. Zhang et al. note in their 2004 study, however, that it is difficult to extract a trend of extreme wave heights using regression analysis because extremes are not normally distributed.  

Figure 37: Buoy 44014 and n44014 Top 5 Mean Wave Height. Actual and hindcast data. Note: the USGS warns, with the release of its July 2016 report that its models often fail to capture the most extreme waves. This potentially could affect the results from 1976 - 1990.
Figure 38: Buoy 44009 and NAEC7 Top 5 Mean Wave Height. Actual and hindcast data. Note: the USGS warns, with the release of its July 2016 report that its models often fail to capture the most extreme waves. This potentially could affect the results from 1976 - 1985.

Figure 39: Station 44025 and NAEC6 Top 5 Mean Wave Height. Actual and hindcast data. Note: the USGS warns, with the release of its July 2016 report that its models often fail to capture the most extreme waves. This potentially could affect the results from 1976 - 1990.
### Top 5 Mean Wave Height

<table>
<thead>
<tr>
<th>Buoy and Years</th>
<th>Top 5 Mean Wave Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>44014</td>
<td>1976 - 1995</td>
</tr>
<tr>
<td></td>
<td>1996 - 2015</td>
</tr>
<tr>
<td>44009</td>
<td>1976 - 1995</td>
</tr>
<tr>
<td></td>
<td>1996 - 2015</td>
</tr>
<tr>
<td>44025</td>
<td>1976 - 1995</td>
</tr>
<tr>
<td></td>
<td>1996 - 2015</td>
</tr>
</tbody>
</table>

Table 4: Top 5 Mean Wave Height for Buoys 44014, 44009, and 44025. The asterisk (*) reflects statistical significance at a confidence level of 95% or more.

### 4.5 PROBABILITY OF EXCEEDANCE AND DESIGN WAVE HEIGHT

Given the uncertainty surrounding the rate and degree of climate change, the coastal engineering and management community as well as businesses and homeowners located near the coast must plan for the most aggressive sea level rise scenario. Figure 40 shows the probability of waves exceeding a certain height offshore of Islip, New York. Given the height and frequency of storm waves in this area compared to those in the region of study stretching south to Virginia Beach, the design wave height would be quite similar, but slightly higher at the New York location. The buoys used in this study are many miles offshore. Structures closer to shore would be designed after consideration of shoaling effects, the maximum breaking wave height given water depth and bottom slope, and the return period and risk which the community deemed appropriate.
Figure 40: Exceedance Probability at Station 44025 Using Weibull Distribution.

4.6 COMPARISON WITH EARLIER ANALYSIS IN SIMILAR REGION

The Komar and Allan study of waves off the east coast (recounted in Section 2.1) covers a similar region from Charleston, South Carolina north to Cape May. It includes a buoy off of Cape Hatteras, North Carolina, an area which is especially vulnerable to tropical storms given its elbow-like protrusion into the ocean. The study makes an interesting comparison, since it begins at the same time, but concludes with the peak year 2005. The authors find a flat or even slight downtrend in winter wave heights in this region from 1975 - 2005. During the Atlantic hurricane season, which they define as July - September, the increase in SWH is an order of magnitude more (+0.011 m/year to +0.017 m/year) for the east coast buoys in their study than the findings for the Virginia Beach buoy in this thesis through 2015. Their findings near Cape May are opposite the findings of this thesis, which extends another decade to 2015. When Komar and Allan exclude waves less than 3 meters, in their words eliminating “the dilution
effect of calm periods between storms”, a steeper upward trend in wave heights is visible during this 30-year period. The authors note that these trends are graphed based on a variable number of hours in each year and thereby are dependent on storms and their tracks.

4.7 COMPARISON WITH USGS RESULTS

Results from this thesis are consistent with a historical analysis of waves from 1976 - 2005 and dynamical downscaling going forward, conducted by the United States Geological Survey and reported in July 2016. USGS researchers project mean wave heights on the U.S. east coast to decrease by 20 – 30 cm during the winter months of December – February in the period from 2026-2045 under RCP4.5 and to undergo no change during the other seasons. Under RCP8.5, mean wave heights through 2045 are expected to decrease by even more than 30 cm. During this same time period and RCP4.5, the Top 5 percent or the extreme waves are projected to decrease by the same 20 – 30 cm during the winter months of the 2026 - 2045 period, but to increase by 10 - 20 cm during the rest of the year (including spring) in the latitude near 40 degrees North. Under RCP8.5, similar to the trend in mean waves, the Top 5 percent of waves are expected to decrease by more than 30 cm during the winter months with little or no change during the rest of the year.

Moving into the next period of projection, 2081 - 2100, the findings for mean wave heights are quite similar, expected to decline 20 - 30 cm on the U.S. east coast during the December – February period and to remain the same during the rest of the year under RCP4.5. Extreme waves, those in the top 5 percent, are expected to decrease by more than 30 cm during the winter months, but also to decrease during the rest of the year by an estimated 10 – 20 cm in the mid- and northern sections of the east coast. Similarly, under the RCP8.5 scenario, mean waves are expected to decrease by 20 cm to more than 30 cm in the winter and by an estimated 20 cm during the rest of the year, while the top 5 percent are projected to decrease by more than 30 cm during the winter and by 10 – 30 cm during the other seasons. One finding to single out is that mean winter wave heights on the northern part of the east coast are projected to see the largest decline, in excess of 40 cm under RCP8.5 toward the end of the 21st century.
CHAPTER 5
SUMMARY, IMPLICATIONS, AND FUTURE RESEARCH

5.1 SUMMARY

The wave climate of the region of the U.S. mid-Atlantic between Virginia Beach, VA and Islip, NY is affected both by latitude and seasonality especially with respect to larger waves. The trend in significant wave heights is virtually flat to slightly lower across the region both when actual hourly wave heights are considered as well as when the wave height record is extended and partly reconstructed with hindcast data from USGS output points collocated with or near the actual buoys. Summer and winter means as well as the means of storm wave heights follow a similar trend. Where a flattening in the downtrend is visible, there is a possibility that it is the result of comparing early years of purely hindcast data, skewed lower due to the model’s potential failure to account for larger storm waves, with the combination of actual/hindcast data and purely actual data. The largest change visible in the study comes from analysis of the mean wave height throughout the region during the transitional months of October and November. While these months both technically are considered part of the Atlantic hurricane season, in many previous studies, they have not been included in traditional calculations of “summer” waves which are those most considered to be affected by tropical storms in this region. In fact, the summer months of July - September recorded less than a quarter of the extreme actual waves seen at any buoy in this study while the months of October and November saw at least as many as during the summer months and in some cases, more than double the number. For that reason, the “summer” season is defined in this thesis as July-November.

When the data are explored on an annual basis, it is clear that the early 1990s saw several years during which both summer and winter storms brought waves in excess of 7 meters to most of the mid-Atlantic region. That sort of consecutively active period has not occurred since. This sort of monitoring of trends in mean wave heights is important in understanding the
overall wave climate and how global warming may be affecting the distribution of waves. But it is the patterns of extreme waves that shed light on whether and how tropical and extra-tropical storm seasons are developing and changing.

The objective of this thesis has been to analyze wave heights in the mid-Atlantic region, an area of accelerated sea level rise, and to understand any effect that climate change may be having. Well-cited previous research, which used wave data only through 2005 which had one of the most intense tropical storm seasons on record, had led to conclusions that gradual warming of the Earth’s climate is leading to more frequent and intense tropical storms which are generating increasingly large waves. Since 2005, a hurricane of Category 3 or above has yet to make landfall on the U.S. Atlantic coast. Now, current predictions of tropical cyclone activity from forecasting models for the most part indicate fewer tropical storms as the 21st century progresses, though an increase in intensity of the average tropical cyclone as well as the number of occurrence days of high category hurricanes toward the end of the century is expected to occur. Most forecasting models now predict a decrease in wave heights in the North Atlantic with even greater decreases at higher latitudes. These projections appear consistent with the trends that are beginning to appear in this research.

This study extends past regression analysis a decade forward. A goal of this and similar analysis is to present the coastal management and engineering community along the U.S. east coast with a meaningful connection between climate change and wave height trends so that we can design, plan, and budget for current and future shoreline protection as well as for offshore projects and safe navigation.

This study relied on data from three buoys owned and maintained by the National Data Buoy Center, a division of the National Oceanic and Atmospheric Administration’s (NOAA) National Weather Service. The buoys were chosen for the length and completeness of their data records, 1986 - 2015, and for their location in deep water with closer proximity to shore than those used in past analyses. Data were studied during the full extent of the time period but also segmented by time, location, and magnitude of wave height in attempts to discern whether ongoing climate change was affecting tropical storm formation and resultant wave generation. Both mean wave height and extreme wave heights, annually and seasonally, were
analyzed using least squares regression and comparison of number distribution. Additional hindcast data from the U.S. Geological Survey became a welcome substitute for large gaps in the actual data record. It also allowed the extension of the wave record back to 1976, providing a far larger data set to be used for the comparison of mean annual statistics.

5.2 IMPLICATIONS

Many challenges exist both in analyzing existing data and projecting forward. Currently, it is risky, if not impossible, (with the exception of tropical and extra-tropical storms) to say with certainty whether the winds that have generated surface waves are local or from propagating swell. With gradients in SST affecting wind patterns and atmospheric circulation and the strong correlation between SSTs and tropical storm formation in the various ocean basins, long-term analysis needs to have a global as well as regional focus. Trustworthy projections of future sea level rise as well as trends in future wave heights are key to planning for and designing coastal structures, beach management projects, and offshore activities that will withstand extreme conditions and protect the property and livelihood of communities along the coasts.

5.3 FUTURE RESEARCH

Given the variability associated with climate changes and the uncertainty about its rate, it is believed that stationary analysis, such as that performed in this thesis, would be better replaced with non-stationary analysis, though that is beyond the scope of this thesis. Since so much of variation in the wave climate revolves around its extremes and using the annual maxima method ignores important information, analysis that can better assess extreme waves using statistical models and fitting extreme-value distribution curves would best serve the coastal engineering community.

Tracking whether and how wind direction is shifting near the recording buoys may also help the understanding of changes in extreme wave patterns. Though both local winds and remotely-generated swell can affect surface waves, comparing changes in wind direction to
storm tracks would be a logical step. There is a large amount of ongoing research into the effects of local winds, global wind fields, and wave—climate projections.

Finally, a better understanding of the anthropogenic influences that are affecting climate change is just one part of the global warming puzzle. If the gradients in relative SST change are affecting atmospheric circulation, the result is likely to be a stronger interconnection and variation among ocean basins. Knowing whether human-induced global warming in turn is affecting atmospheric oscillations and weather patterns will be a powerful tool in the future projection of tropical and extra-tropical storms and the waves they generate.
REFERENCES


4 ibid


6 National Ocean Economics Program, Middlebury Institute of International Studies at Monterey.

7 ibid


NASA Global Climate Change website.


NASA Sea Level Change Portal.

Intergovernmental Panel on Climate Change. 2014. Summary for Policymakers.


24 Geophysical Fluid Dynamics Laboratory website.


28 ibid


ibid


Reportingclimatescience.com website. Atlantic Cooling.

National Center for Atmospheric Research, Climate and Global Dynamics.


IPCC 2013. Working Group 1: The Scientific Basis. Section 2.7.3.


U.S. Environmental Protection Agency website. Climate-Indicators/Oceans.


ibid

Personal email exchange with Li Erikson, USGS, July 12, 2016.

USGS, Study Area Section. USGS Table, Figure 14.


### Table 5: Atlantic Hurricanes and Tropical Storms in the Region 1976-2015

<table>
<thead>
<tr>
<th>Year</th>
<th>Date in Study Area</th>
<th>Name</th>
<th>Highest Cat in Study Area</th>
<th>Lat/Lon in Study Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>Aug 6-10</td>
<td>Belle</td>
<td>H3</td>
<td>26.0, -72.8 – 42.6, -72.4</td>
</tr>
<tr>
<td>1977</td>
<td>Sept 6 – 9</td>
<td>Clara</td>
<td>H1</td>
<td>34.2, -76.4 – 34.8, -63.5</td>
</tr>
<tr>
<td>1978</td>
<td>Nov 3 - 4</td>
<td>Unnamed</td>
<td>TD</td>
<td>30.0, -75.0 – 37.0, -71.0</td>
</tr>
<tr>
<td>1979</td>
<td>Aug 3 – 5</td>
<td>Unnamed</td>
<td>TD</td>
<td>30.2, -68.5 – 40.5, -66.5</td>
</tr>
<tr>
<td>1980</td>
<td>July 23 – 26</td>
<td>Unnamed</td>
<td>TD</td>
<td>34.0, -75.8 – 37.6, -64.0</td>
</tr>
<tr>
<td>1981</td>
<td>June 30 – July 1</td>
<td>Bret</td>
<td>TS</td>
<td>36.0, -69.0 – 37.4, -76.0</td>
</tr>
<tr>
<td></td>
<td>Aug 7 – 22</td>
<td>Dennis</td>
<td>H1</td>
<td>10.5, -25.7 – 38.1, -65.4</td>
</tr>
<tr>
<td></td>
<td>Nov 12 – 16</td>
<td>Unnamed</td>
<td>TS</td>
<td>31.0, -74.0 – 40.7, -68.5</td>
</tr>
<tr>
<td>1983</td>
<td>Sept 27 - 30</td>
<td>Dean</td>
<td>TS</td>
<td>28.0, -73.0 – 37.5, -75.8</td>
</tr>
<tr>
<td>1984</td>
<td>Sept 8 – 15</td>
<td>Diana</td>
<td>H4</td>
<td>28.5, -77.4 – 41.0, -66.0</td>
</tr>
<tr>
<td></td>
<td>Oct 7 – 15</td>
<td>Josephine</td>
<td>H2</td>
<td>24.1, -68.9 – 36.2, -68.4</td>
</tr>
<tr>
<td>1985</td>
<td>Aug 10 - 12</td>
<td>Claudette</td>
<td>TS</td>
<td>32.5, -77.5 – 34.5, -66.4</td>
</tr>
<tr>
<td></td>
<td>Aug 19 – 20</td>
<td>Danny</td>
<td>H1/ET</td>
<td>37.5, -75.3 – 40.4, -69.4</td>
</tr>
<tr>
<td></td>
<td>Sept 25 -27</td>
<td>Gloria</td>
<td>H2</td>
<td>26.9, -73.0 – 41.9, -72.8</td>
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<tr>
<td></td>
<td>Sept 21 – 25</td>
<td>Henri</td>
<td>H1</td>
<td>29.6, -74.3 – 41.3, -71.8</td>
</tr>
<tr>
<td></td>
<td>Oct 12-15</td>
<td>Isabel</td>
<td>TD</td>
<td>31.7, -79.0 – 35.8, -72.7</td>
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<tr>
<td>Year</td>
<td>Month</td>
<td>Name</td>
<td>Type</td>
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<td>----------</td>
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<td>-----------</td>
</tr>
<tr>
<td>1986</td>
<td>Aug 15 – 19</td>
<td>Charley</td>
<td>H1</td>
<td>32.3, -80.0 – 40.9, -67.5</td>
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<tr>
<td>1988</td>
<td>Aug 5 – 7</td>
<td>Alberto</td>
<td>TD</td>
<td>32.0, -77.5 – 41.5, -69.0</td>
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<tr>
<td>1991</td>
<td>Oct 31 – Nov 2</td>
<td>Unnamed</td>
<td>TS</td>
<td>40.0, -68.5 – 39.5, -65.7 (circular)</td>
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<tr>
<td>1991</td>
<td>Aug 16 – 19</td>
<td>Bob</td>
<td>H3</td>
<td>25.6, -74.3 – 41.4, -71.4</td>
</tr>
<tr>
<td>1993</td>
<td>Aug 28 – Sept 2</td>
<td>Emily</td>
<td>H3</td>
<td>26.6, -65.2 – 39.2, -66.0</td>
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<tr>
<td>1995</td>
<td>July 5 - 9</td>
<td>Barry</td>
<td>TS</td>
<td>32.0, -72.0 – 40.5, -64.6</td>
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<td>Aug 13 – 21</td>
<td>Felix</td>
<td>H4</td>
<td>25.1, -61.6 – 40.6, -63.3</td>
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<tr>
<td>1996</td>
<td>Oct 8 -9</td>
<td>Josephine</td>
<td>ET</td>
<td>36.0, -76.0 – 42.5, -68.0</td>
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<td>1997</td>
<td>July 24 – 26</td>
<td>Danny</td>
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<td></td>
<td>Aug 31 – Sept 3</td>
<td>Danielle</td>
<td>H2</td>
<td>30.0, -73.7 – 39.9, -60.1</td>
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<tr>
<td></td>
<td>Sept 4 - 5</td>
<td>Earl</td>
<td>TS</td>
<td>36.5, -75.0 – 40.0, -65.5</td>
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<td>1999</td>
<td>Oct 16 - 19</td>
<td>Irene</td>
<td>H2</td>
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<td></td>
<td>Sept 19 - 20</td>
<td>Gordon</td>
<td>ET</td>
<td>38.5, -76.0 – 41.5, -72.0</td>
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<td>2002</td>
<td>July 14 - 16</td>
<td>Arthur</td>
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<td>34.3, -76.8 – 40.5, -57.9</td>
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<td>Sept 8 – 11</td>
<td>Kyle</td>
<td>H2</td>
<td>29.0, -71.0 – 40.3, -66.8 (H2)</td>
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<td>Sept 8 - 11</td>
<td>Gustav</td>
<td>H1</td>
<td>29.0, -71.0 – 40.3, -66.8</td>
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Table 5 (continued)

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<td>July 31 – Aug 5</td>
<td>Alex</td>
<td>H3</td>
<td>30.3, -78.3 – 40.8, -59.6 (H2)</td>
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<td>Bonnie</td>
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<td>TS</td>
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<td>Aug 28 - 31</td>
<td>Hermine</td>
<td>TS</td>
<td>29.0, -65.7 – 41.5, -70.9</td>
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<td>TS</td>
<td>37.0, -80.5 – 31.0, -77.5</td>
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<td>Sept 7 - 17</td>
<td>Ophelia</td>
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<td>27.4, -78.5 – 37.3, -72.7</td>
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<td>Oct 10 – 14</td>
<td>Twenty-two</td>
<td>TS</td>
<td>31.6, -67.5 – 39.6, -73.8</td>
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<td>Beryl</td>
<td>TS</td>
<td>32.3, -73.3 – 41.0, -70.5</td>
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<td>Gabrielle</td>
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<td>2008</td>
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<td>TS</td>
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<td>Earl</td>
<td>H4</td>
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<td>23.5, -75.1 – 40.3, -74.1</td>
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<td>2012</td>
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<td>Sandy</td>
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<td>2015</td>
<td>July 12 - 14</td>
<td>Claudette</td>
<td>TS</td>
<td>n/a</td>
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Table 5: Atlantic hurricanes and tropical storms passing within 100 nautical miles of 37.5 N and 73.0 West during the months of July-November 1976-2015. Source: NOAA.
APPENDIX B
MAPS OF HURRICANES THROUGH THE STUDY AREA

JULY – NOVEMBER, 1976 - 2015

Figure 41: Hurricanes through the Study Area. July-November 1976-2015. Source: NOAA.
APPENDIX B: HURRICANES THROUGH THE STUDY AREA (continued)
JULY – NOVEMBER, 1976 - 2015

Figure 28: Hurricanes through the Study Area. July-November 1976-2015. Source: NOAA.
VITA

Hillary Lane
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Norfolk, Virginia 23529

EDUCATION

THE WHARTON SCHOOL, UNIVERSITY OF PENNSYLVANIA, PHILADELPHIA, PA
Bachelor of Science in Economics, 1988, cum laude

INTERNSHIPS AND WORK EXPERIENCE

WOODS HOLE OCEANOGRAPHIC INSTITUTE, WOODS HOLE, MA, SUMMER 2015
Prepared and deployed current profilers and pressure gauge instruments. Studied movement and closing of the Katama Bay inlet.

STEVENS INSTITUTE OF TECHNOLOGY, HOBOKEN, NJ, SUMMER 2013
Analyzed effects of sea level rise on future storm surge with FEMA models. Analyzed floodwater velocities and forces on areas of the NYC shoreline.

LAMONT DOHERTY EARTH OBSERVATORY, COLUMBIA UNIVERSITY, 2009
Analyzed sediment cores for shock impact. International team sought to prove hypothesis that meteoric impact generated catastrophic tsunamis centuries ago.

Correspondent and anchor.
Live and taped reporting for NBC Nightly News, The Today Show, MSNBC, CNBC, and NBC-affiliated stations around the world.

CNN, NEW YORK, NY
Correspondent, 2001-2002