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Increasing Hurricane-Generated Wave Heights along the U.S. East Coast and Their Climate Controls

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ABSTRACT

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Analyses of hourly measurements of ocean wave heights along the U.S. East Coast, collected since the 1970s by three buoys of the National Data Buoy Center, document a progressive increase during the summer months when hurricanes are most important to wave generation. In contrast, the waves measured during the winter, generated by extratropical storms, have not experienced a statistically significant change. Summer waves with significant wave heights greater than 3 m, which can be directly attributed to specific hurricanes, have increased at a rate of 0.059 m/y (1.8 m in 30 years) according to records from buoy 41002 offshore from Charleston, South Carolina, with a lower rate of 0.024 m/y (0.7 m in 30 years) recorded by the Cape Hatteras buoy (41001); both trends are statistically significant at the 90% level. A still lower rate is found for the Cape May buoy (44004), 0.017 m/y, suggesting that there is a systematic latitude variation. Histograms of the ranges of significant wave heights measured during the hurricane season show that the most extreme occurrences during the 1996–2005 decade are both higher and more common than occurred 30 years ago, at the beginning of buoy measurements, having increased from about 7 m to higher than 10 m. The waves recorded by the buoys depend on the annual numbers of hurricanes that followed tracks northward into the central Atlantic, how close their tracks approached the buoys, and the intensities (categories) of those hurricanes. Examinations of the storms that have occurred since 1980 indicate that the primary explanation for the progressive increase in wave heights has been an intensification of the hurricanes, with increased numbers of storms a contributing factor.

ADDITIONAL INDEX WORDS: *Climate change, tropical cyclones, hurricanes, extratropical storms, ocean waves, Cape Hatteras, Gulf of Mexico.*

INTRODUCTION

Research related to the potential impacts of Earth's changing climate on coastal erosion and flooding has been directed almost entirely toward the projected rise in sea level expected this century as a result of global warming. Considerably less attention has been given to the enhancement of storm intensities and the higher waves they generate, which could equally impact shores due to global climate change. Measurements off the coast of England in the northeastern Atlantic (BACON and CARTER, 1991; CARTER and DRAPER, 1988) and along the U.S. West Coast in the Pacific (ALLAN and KOMAR, 2000, 2006) have documented that the heights of waves have been progressively increasing during the past several decades, at sufficiently high rates to be a factor in coastal erosion occurrences. Those studies relate to the waves generated by extratropical storms and their intensification due to the changing climate. More recently, particularly since 2005 with the erosion and flooding produced by Hurricanes Katrina and Rita in the Gulf of Mexico, concern has been directed toward the possible intensification of tropical cyclones as a consequence of global warming: hurricanes in the Atlantic and typhoons in the western Pacific.

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In this study, we have analyzed the waves measured by three National Oceanographic and Atmospheric Administration (NOAA) buoys located along the central U.S. Atlantic shore and one buoy in the Gulf of Mexico. Our initial interest was whether there have been increasing wave heights generated by extratropical storms (nor'easters), comparable to the increase we found in the buoy data along the U.S. Pacific shore. However, in the Atlantic we discovered that the increase in wave heights has been to waves generated during the summer by hurricanes, so they have become the focus of this investigation. This paper is an expansion of an earlier report of this increase, which had been limited to analyses of the NOAA buoy offshore from Cape Hatteras, North Carolina (KOMAR and ALLAN, 2007a).

In addition to the increase in hurricane-generated waves with obvious relevance to potential coastal impacts, it is of interest with respect to the cause being related to Earth's changing climate that has affected both the numbers of storms and their intensities. Therefore, in this study we have compared the decadal variations in measured wave heights to the annual numbers of hurricanes, their intensities (categories), and whether their tracks took them northward into the Atlantic, where their generated waves could be measured by the East Coast buoys, or moved them westward into the Gulf of Mexico. Such analyses lead to a better understanding

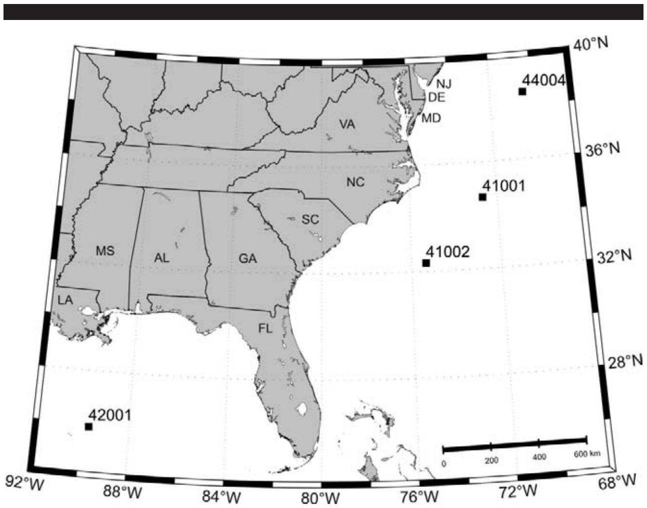

Figure 1. Locations of the NDBC buoys analyzed in this study.

of the factors affecting the East Coast wave climate and address questions related to hurricane intensification that has resulted from global warming.

WAVE DATA SOURCES AND ANALYSES

Measurements of waves along the coasts of the United States are derived primarily from buoys operated by the NATIONAL DATA BUOY CENTER (NDBC, 2007) of NOAA, used to define wave climates important to coastal engineers and scientists. The 25- to 35-year records now available from many buoys have sufficient lengths to permit analyses of potential trends of increasing wave heights, the presence of climate-controlled cycles, or annual variations due to climate events such as a major El Niño.

Our investigations of the U.S. West Coast waves and their climate controls were based on NDBC-buoy data for the changes in significant wave heights and peak-spectral periods (ALLAN and KOMAR, 2000, 2006), including the decadal trends of the winter waves, October through the following March, the season of the greatest storm activity. The present investigation of the East Coast wave climates is similar but requires separate analyses for the winter waves generated by extratropical storms and those of the summer hurricane season. The locations of the four NDBC buoys included in the analyses are shown in Figure 1: in the Atlantic, buoys 44004 (Cape May, New Jersey), 41001 (Cape Hatteras, North Carolina), and 44002 (Charleston, South Carolina); and buoy 42001 in the Gulf of Mexico. The three Atlantic buoys represent a range of latitudes extending along some 800 km of the coast, with Cape Hatteras and its buoy having a central position, of particular interest in that, along with Florida, the Outer Banks of North Carolina has the highest probability for hurricane landfalls, the history of which has been well documented (SMITH, DOLAN, and LINS, 2006). Being well offshore, the Atlantic buoys have wide "windows" seaward, capable of recording waves generated by storms across the full expanse of the ocean basin.

The buoy in the Gulf of Mexico was selected for its central position within that body of water, located 335 km south of the Louisiana shore (Figure 1). It has been included in the study to provide a comparison with the Atlantic buoys in terms of the existence of decadal trends and to permit comparisons of any outliers during specific years from their respective trends, the expectation being that the outliers will in part be governed by the numbers of hurricanes that passed westward into the Gulf as opposed to those that moved northward into the North Atlantic. All of the buoys are in deep water, so the data have not been affected by shoaling, refraction, or bottom friction. The buoys selected for analysis also have relative long records, having begun the collection of wave data during the mid-1970s or no later than the mid-1980s, providing sufficient record lengths to document whether decadal trends of change have occurred.

In 1984, the NDBC modified its analysis procedures to improve the inclusion of long-period motions in the wave spectra. The details of this change and how it has affected the spectra and derived significant wave heights have been analyzed by EARLE, STEELE, and HSU (1984) and were considered in our analyses of the West Coast wave climates (ALLAN and KOMAR, 2006). The change is important only where there is a strong mix of swell derived from distant storms and locally generated sea with a wide spectrum of lower wave periods, causing the fixed-hull accelerometers commonly used by the NDBC to introduce spurious energy into the combined spectra. EARLE, STEELE, and HSU (1984) provide wave spectra analyzed by both the pre- and the post-1984 procedures to illustrate the potential differences, and their examples indicated that after 1984 the reported significant wave heights could in the most extreme cases be increased by roughly up to 10%, the actual increase depending on the relative proportions of swell and sea being measured. According to M.D. EARLE (personal communication), this difference can be expected to be most important in analyses of specific storm-wave events with broad spectra but would likely have only a small effect on waves dominated by swell and on monthly to yearly averages needed in wave climates, the focus of our analyses. In both our U.S. West Coast and our U.S. East Coast wave analyses, we have not found upward "steps" in the data trends at 1984, which might have indicated that the modification in NDBC procedures had a significant effect.

A basic change made by the NDBC in their wave-measurement program occurred in August 1979, prior to which the data were collected on 3-hour intervals, while since that time the measurements are hourly. In general, this change should have minimal consequences in studies of wave climates; it is mainly important in this study, where we contrast histograms of the ranges of wave heights measured early in the buoy operation (the 1970s and 1980s) compared with the most recent decade of data collection, the desire being to have approximately the same numbers of measurements represented in the two histograms. Also of potential significance are the intervals of missing data within the records due to downtime in the buoy's operation. It is standard procedure to discount the results if 20% or more of the potential data record for the year is missing (ALLAN and KOMAR, 2000, 2006; BACON and CARTER, 1991), and that is the approach we have used here. This resulted in a few gaps in the graphs of decadal trends of annually averaged wave heights but was minimized by our selection of NDBC buoys to be included in the study.

The present examinations of the U.S. East Coast wave climates are more complicated than those for the West Coast in that the waves generated by extratropical storms vs. those from tropical cyclones (primarily hurricanes) in effect represent separate components in the wave climates, which need to be analyzed individually due to the expectation that they will respond differently to Earth's changing climate. To accomplish this, our analyses have been separated into summer and winter seasons, the "summer" including the months of July through September, approximately the maximum of the hurricane season, while the "winter," with extratropical storms, is the subsequent months of November through March. The omitted months, *e.g.,* October, have not been included as they are transitional, with a high probability of waves being generated by both types of storms. This separation also minimizes the potential effects of an expansion of the respective wave-generation seasons due to the changing climate. It has been found in this study that there has not been a change in the heights of waves generated by extratropical storms during the winter, so its season would not be expected to have expanded into July through September, the "summer" season analyzed for changes in the hurricane-generated waves, and affected the analyses presented here.

SUMMER HURRICANE WAVES: ANALYSIS RESULTS

In this section we present analyses of the significant wave heights measured by the NDBC buoys, beginning with an example of the recorded hourly wave heights during the hurricane season of 1995. That is followed by documentation of trends in the annually averaged significant wave heights spanning the decades of buoy operations and by presentations of the ranges of wave heights as histograms that permit examinations of the most extreme significant wave heights that have been measured and how they have increased with time.

Hourly Measurements of Significant Wave Heights

Figure 2 provides an example of the hourly significant wave heights measured by the Cape May and Cape Hatteras buoys during the summer of 1995; the July records have not been included in the diagram due to the absence of high wave events that month. The 1995 hurricane season began in early July with the development of Hurricane Allison in the Gulf of Mexico, later to cross the southeast United States and pass into the Atlantic as a tropical storm; the season ended in late October with Hurricane Tanya, which passed through the central Atlantic. For the entire hurricane season, eight tropical storms and 11 hurricanes occurred. Our analyses for the limited summer hurricane season, July through September, omitted two tropical storms and 4 hurricanes, but 3 of those hurricanes occurred in the Gulf, which commonly is the case for early- and late-season hurricanes due to the presence of warm water in the Gulf and Caribbean, when the Atlantic has generally become too cold to fuel hurricane generation.

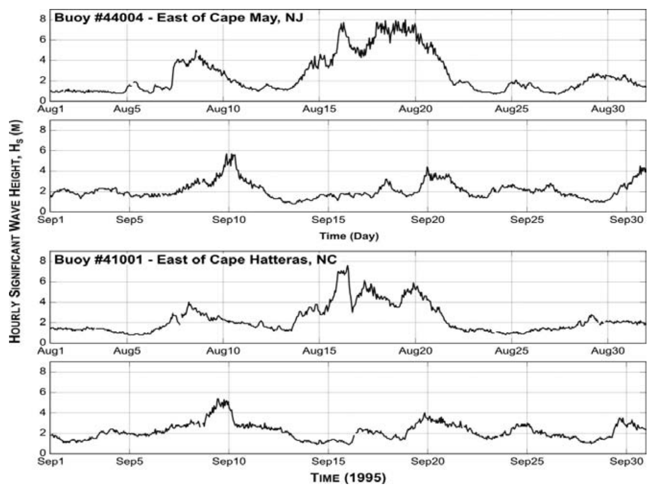

Figure 2. The hourly significant wave heights measured by the Cape May and Cape Hatteras buoys during the summer hurricane season of 1995.

Therefore, during most years relatively few hurricanes have been missed in our analyses of the Atlantic buoys because we have limited them to July through September. Also, there are only rare occurrences of wave events of significant magnitudes during the summer that cannot be attributed to having been generated by specific hurricanes, so there is a minimal degree of contamination of the analyzed summer hurricane-wave records by extratropical storms.

Most apparent in the wave records for 1995 (Figure 2) are the waves in mid-August that achieved significant wave heights of just under 8 m on the Cape May buoy and 5 to 7 m on the Cape Hatteras buoy, having been generated by Hurricane Felix. Its recorded waves first appeared on August 13 and lasted until August 22 but with complex variations within those 10 days, evident in the records of both buoys. This storm became a Category 1 hurricane early August 11, with its intensity rapidly increasing so that it achieved Category 4 late August 12 while still in the mid-Atlantic, but began it to decrease the next day. The waves recorded by the buoys during August 13–15, reaching 4-m significant wave heights, were generated by that Category 4 phase of the storm, with the heights having been reduced during their travel to the coastal buoys. On the Cape Hatteras buoy record (Figure 2), waves with 7-m significant wave heights occurred as a sharp increase on August 16 when Felix came close to that buoy's location, at which time the intensity of the storm had dropped to Category 2. This was followed by a 1-day decrease in measured waves as the storm moved northward to offshore from Cape May, where 8-m significant wave heights were recorded. The storm then moved offshore, with its intensity reduced to Category 1, where it stalled and its path made a curious clockwise loop, accounting for the multiple wave-height maximums, most apparent in the Cape Hatteras record. After August 20, Felix moved rapidly away from the coast, with the wave measurements decreasing to calm-period levels, 1 to 2 m. From these records, the prolonged period of high waves generated by Hurricane Felix can be attributed to its close approach to the Cape May and Cape Hatteras buoys, even though the storm's intensity had decreased.

Four other episodes of hurricane-generated waves were recorded by the Atlantic buoys during the 1995 season (Figure 2): Hurricane Humberto, a Category 1 to 2 storm in the central Atlantic (August 9); Hurricane Luis, a Category 3 storm in the western Atlantic (September 9); Hurricane Maryland, Category 2, in the western Atlantic (September 20); and Hurricane Noel in the eastern Atlantic, which occurred at the end of September and into early October. Of these, Luis is most prominent in the buoy records, with recorded significant wave heights of 5 to 6 m. Luis was a Category 3 storm for most of its life as it moved in northwest across the Atlantic, taking it toward the U.S. East Coast, with its closest approach having been on September 9 east of Georgia, after which it followed a north–northwest path approximately parallel with the coast, passing Cape May on September 10. This path accounts for its high recorded waves (Figure 2), first by the Charleston and Cape Hatteras buoys and followed a day later by the Cape May buoy.

The waves recorded by the Atlantic buoys during the summer of 1995, and in other hurricane seasons, demonstrate that the heights attributable to tropical storms are generally small, mere "blimps" of 2- to 3-m significant wave heights above the relatively calm intervals between storms, when the heights are 1 to 2 m. The measured significant wave heights directly attributable to hurricanes are generally higher than 3 m and, as will be seen in the analyses that follow, have ranged up to extremes of 10 to 11 m. In general, the recorded significant wave heights generated by distant hurricanes are in the range 3 to 5 m, having been reduced to those heights for even the highest-category storms during wave passage across the ocean to the buoys; it will be seen that this range dominates the decadal increases in annual averages of the summer hurricane wave heights. Recorded waves larger than about 5 to 6 m generally require the hurricane to pass reasonably close to the buoy, with a few storms having generated recorded significant wave heights of 8 to 11 m in such circumstances; these represent the most extreme wave heights measured, but with their rarity they tend to produce scatter in the analyses of decadal trends while being the most important component in the histograms of the wave climates due to their potential impacts on the U.S. Atlantic shore.

Decadal Trends of Annually Averaged Wave Heights

Of primary interest in this study is whether there have been trends of progressively increasing wave heights recorded by the East Coast buoys, much as we found in our studies of the West Coast waves. Figure 3 contains the results of our analyses for the three Atlantic buoys, graphs of the annual averages of the measured significant wave heights during the summer and winter as defined earlier. The dark symbols are for the years when more than 80% of the record was available to be analyzed, with the linear regressions being based on those years; the open symbols represent years that technically are gaps, with 20 to 30% of the record missing. While there is a hint of meaningful downward trends for the winter waves generated by extratropical storms, with nearly identical rates measured by the Cape Hatteras and Charleston buoys, these trends are not statistically significant. This result differs from what we found on the U.S. West Coast (ALLAN and KOMAR, 2000, 2006), where increases have occurred since at least the mid-1970s, particularly at the higher latitudes of Washington and Oregon. It is possible that analyses of the Atlantic Coast winter waves will similarly reveal an increase at the higher latitudes of New England and Canada.

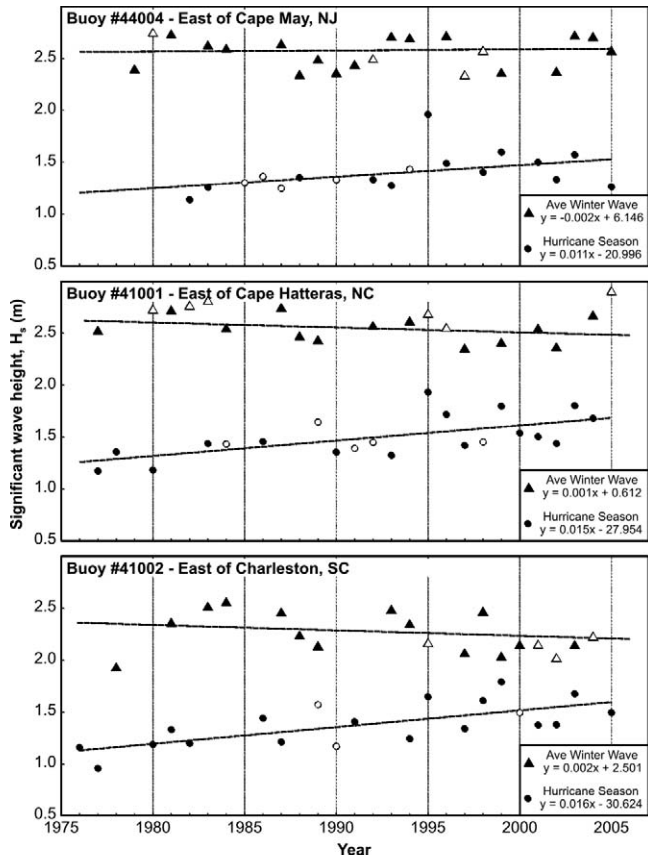

Figure 3. Trends in the annual averages of the "winter" and "summer" significant wave heights. Closed symbols meet the criterion of there being less than 20% missing data, with the regressions based only on those years; open symbols did not meet that criterion.

In contrast to the winter waves generated by extratropical storms, the Atlantic buoys document clear trends of increasing wave heights during the summer, the hurricane season (Figure 3). The trends for the three buoys are similar, with the regression for the Cape May data yielding a rate of increase of 0.011 m/y, while the Cape Hatteras and Charleston buoys have rates of 0.015 and 0.017 m/y, respectively, a net increase of about 0.5 m for their 30-year records. This degree of increase is substantial for the summer in view of the low values for those averages, in the range of 1.25 m increasing to about 1.75 m over the decades. These low values reflect the "dilution" of the summer data by waves during calm periods between storms, evident in Figure 2, where the significant wave heights are in the range 1 to 2 m or less while the

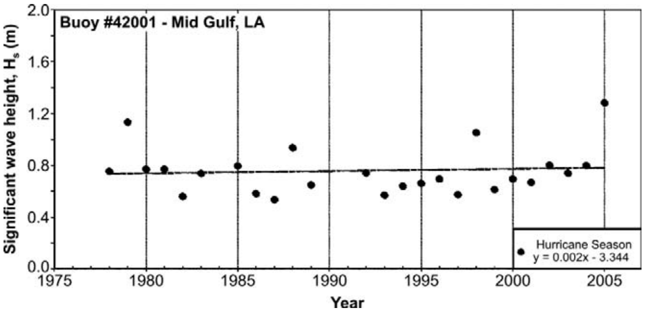

Figure 4. Annual averages of the summer significant wave heights measured by the NDBC buoy in the Gulf of Mexico.

hurricane-generated waves reach 3 to 11 m. In this respect, the wave-height magnitudes in Figure 3 are misleading, giving the mistaken impression that the winter wave heights generated by extratropical storms are substantially higher than the summer waves of hurricanes. Our continuing analyses have shown that they are in fact comparable in the magnitudes of their extreme occurrences, both being in the range 8 to 11 m for these three buoys. The differences seen in Figure 3 for the annual averages result from the dominance of low waves during calm periods during the summer, whereas calm periods in the winter are rare, their dilution effect being less.

The regressions in Figure 3 for the summer waves are all statistically significant at the 95% level using the Wilcoxon nonparametric rank-sum test for the presence of a trend, and the rare outliers can be accounted for by the annual variability in the storms. There is only one significant outlier within the summer annual averages for the three buoys: that in 1995, when the average for the Cape May buoy exceeded the regression line by about 0.5 m; the departure from the regression for the Cape Hatteras buoy is less but still noticeable, while it is in line with the other data for the Charleston buoy. This outlier during the 1995 summer season can be attributed to the occurrence of Hurricane Felix, examined in Figure 2, mainly to its having stalled off the coast of New Jersey for several days, during which it generated high waves, rather than to its having produced unusually extreme wave heights.

Also of interest are the waves recorded by the Atlantic buoys during the summer of 2005, the extreme hurricane season with a record number of high-category hurricanes. That season unexpectedly recorded an unusually low summer average for the Cape May buoy, a mild outlier, in spite of the severity of that hurricane season. This can be attributed to the higher-category storms having followed tracks into the Gulf of Mexico. The results for similar analyses of buoy 42001 in the Gulf are given in Figure 4. Unlike the Atlantic buoys, there is not a trend of increasing (or decreasing) annually averaged significant wave heights for the summer hurricane season in the Gulf. There is instead considerably more variation from year to year, with 1979, 1998, and 2005 being outliers with exceptionally high averages. The last, 2005, is when Hurricanes Katrina and Rita entered the Gulf with

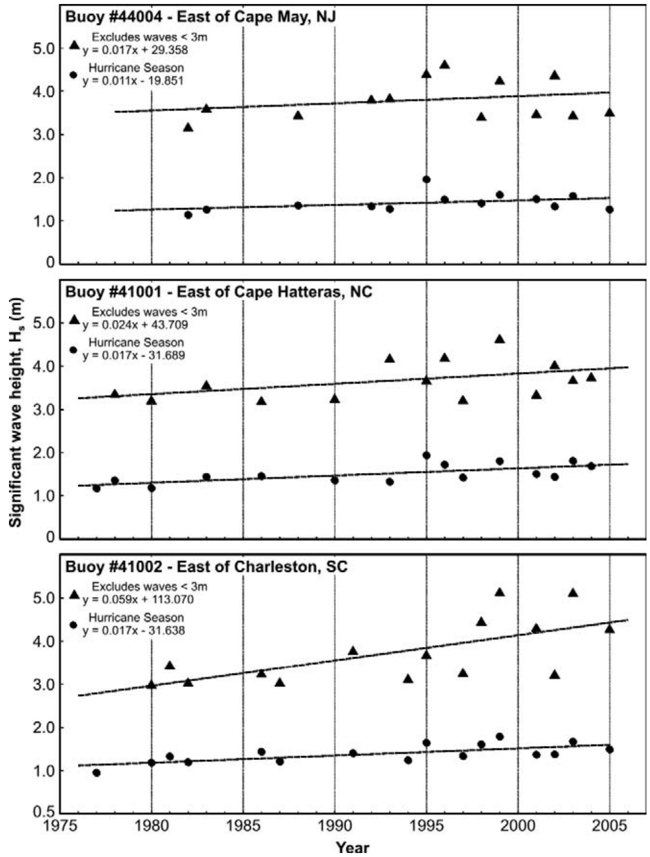

Figure 5. Trends in annual averages of the significant wave heights higher than 3 m, those generated by hurricanes and recorded by the East Coast buoys.

devastating consequences, both having achieved Categories 4 and 5 while over water generating waves. It is seen in Figure 4 that 2005 created an outlier well above the regression line. This contrast in the records between the Atlantic and the Gulf for the 2005 hurricane season illustrates the control on the wave climates from year to year by the intensities of the storms and their tracks, which takes them either northward into the Atlantic or westward into the Gulf and/or Caribbean. Both the high variability and the lack of a trend in the Gulf data can be attributed to the differences from year to year in the numbers and intensities of tropical cyclones that pass through the Gulf, with many of those storms having come in proximity to the recording buoy due to the small aerial extent of that body of water.

In our examination in Figure 2 of the hourly records of the measured significant wave heights during the 1995 hurricane season, it was concluded that the waves clearly attributable to hurricanes had heights greater than 3 m. Figure 5 therefore presents analyses for the three Atlantic buoys where recorded significant wave heights lower than 3 m have been omitted in calculating the annual summer averages, this in effect having eliminated the dilution effect of calm periods between storms. As expected, the graphed averages have shifted to higher values compared with the results where the entire summer records are analyzed, now achieving average heights on the order of 4 to 5 m that are more realistically expected to have been generated by hurricanes according to the record seen in Figure 2. With the omission of the lower waves the trends have also steepened, most notably in the Charleston record, where the regression is 0.059 m/y, an increase of about 1.8 m in 30 years. The rate of increase for the Cape Hatteras data is somewhat less at 0.024 m/y, an increase of 0.7 m in 30 years. This apparent latitude change continues with the record from the Cape May buoy being still lower at 0.017 m/y, an increase of 0.5 m in 30 years. Due to the episodic nature of hurricane occurrences, particularly those that generated the most extreme recorded wave heights, the scatter in the data has increased in Figure 5 compared with the analyses in Figure 3, where the entire summer records are included; however, the Wilcoxon test remains statistically significant at the 90% level for the Charleston and Cape Hatteras buoys but not for the Cape May buoy due to the limited data available from early in its record.

The results in Figure 5 for the recorded significant wave heights above 3 m provide a superior assessment of the increases in hurricane-generated waves having reached the U.S. Atlantic shore during the past 30 years, since it includes both the waves in the 3- to 5-m range derived from distant hurricanes and the more extreme waves generated by storms whose tracks took them into the western Atlantic, bringing them into proximity with the NDBC buoys and the U.S. shore. However, it needs to be recognized that the averages graphed in Figure 5 represent variable numbers of hours of waves exceeding 3 m from year to year, whereas Figure 3 considers roughly the same number of hourly measurements even though the majority are for calm periods between storms. It is seen in Figure 5 that there are several years in which the annual averages barely exceed the 3-m threshold; an analysis presented later in this paper shows that these are years when there were few hurricanes passing through the North Atlantic, where they could generate waves recorded by these buoys, generally with none passing into the Western Atlantic, where the storms could generate extreme waves in the buoy records. Thus, built into Figure 5 is a dependence on the annual numbers of hurricanes and their tracks, as well as their intensities, whereas Figure 3 is valuable in having providing assessments of the annual averages of all measured summer waves during the summer hurricane seasons. Taken together, the results of these analyses at the latitudes of Cape Hatteras and Charleston document that the increase in wave heights generated by hurricanes since the mid-1970s has been substantial, whereas it has been more moderate at the higher latitude of Cape May and presumably farther north.

Histograms of Wave-Height Occurrences

Wave climates are generally based on the cumulative records of daily wave measurements collected by buoys over a number of years, with the analyses including graphical depictions of the full range of measured significant wave heights as a frequency distribution in the form of a histogram. The histograms are traditionally graphed as the percentages of occurrence for each wave height, it having been normalized to the total number of measurements collected over the years. As an alternative approach, we have found that there are advantages in graphing the raw data for the actual numbers of wave-height occurrences, using a log scale that emphasizes the rare but most extreme measured waves, even the maximum single occurrence that plots as $10^0 = 1$. We have discussed this approach in detail elsewhere, as well as the advantages and potential misunderstandings in using this depiction (Komar and Allan, 2007b).

Such analyses become complicated when the wave climate is changing with time, as found in this study for the summer hurricane-generated waves. Accordingly, for each buoy we have separately analyzed a wave-height histogram for an early portion of the record and for the recent decade, 1996–2005, the objective being to examine the changes in ranges of wave heights that correspond to the trends in the annual averages seen in Figures 3 and 5. The specific years selected from early in the records differ somewhat for each buoy, depending on when it became operational, and with the record analyzed having been lengthened where it extends back prior to 1979, when the measurements were at 3-hour intervals, in an attempt to obtain recorded numbers of measurements comparable to those in 1996–2005. The resulting pairs of histograms for the summer hurricane-generated waves recorded by the three Atlantic buoys are presented in Figure 6, with the results for the Gulf of Mexico buoy given in Figure 7.

It is seen in Figure 6 that the pairs of histograms are similar for the three Atlantic buoys in having documented increases in the numbers of higher waves during the recent decade compared with early in their records, including marked shifts in the heights of the most extreme measured waves. However, the pairs of histograms suggest that the areas beneath the 1996–2005 histograms are much larger than those for the earlier records, the tendency being to attribute this to more data having been included in the more recent histograms. As indicated on the diagrams, the early records are based on fewer observations even though we attempted to include more years to increase their numbers. However, this generally is not the primary cause for the apparent increase in areas beneath the curves for the 1996–2005 decade compared with the earlier recorded periods. As discussed in Komar and Allan (2007b), this difference persists even when the data are graphed as percentages, normalized to the numbers of observations so that the areas beneath both curves represent 100%. The differences in areas are instead caused by the use of the log scale that emphasizes the low numbers of extreme wave heights, which thereby warps the areas beneath the curves even though these extremes represent a very small percentage of the total number of observations (Komar and Allan, 2007b). With greater numbers of rare extreme waves having occurred during 1996–2005 for the three Atlantic buoys, the areas under their histograms are larger than those for the early years of buoy operations. Of the pairs of histograms given in Figure 6, only those for the Charleston buoy have been significantly affected by differences in numbers of measurements, with far fewer repre-

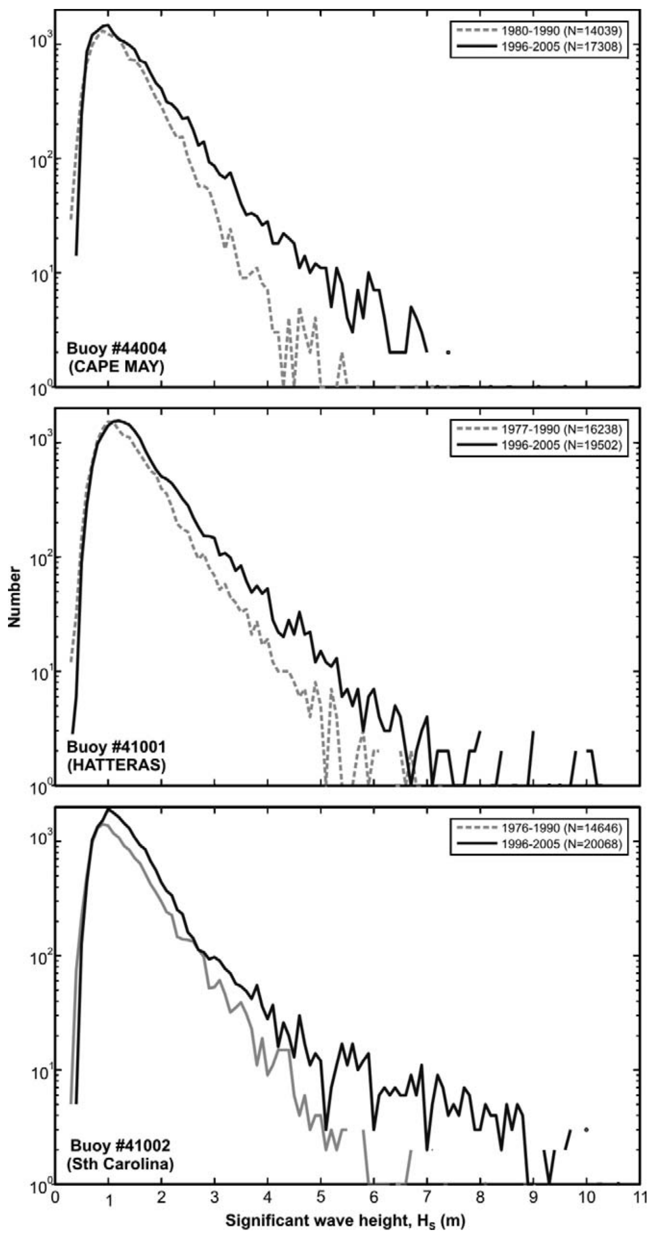

Figure 6. Histograms for the numbers of significant wave heights measured by the three East Coast buoys, comparing decades of measurements early and recently in the buoy records.

sented in the early record because there were two complete years of missing data when the buoy was not operational; even in this example, however, the contrast in the histograms for the numbers of most extreme measured waves can be attributed to the marked increase in wave heights generated by hurricanes over the decades, corresponding to the trends in the annual averages seen in Figures 3 and 5 for the Charleston buoy.

Examining the details of the histograms for the Atlantic buoys (Figure 6), it is seen that each has its maximum centered on about 1 m, this representing the near-calm periods of the summer between hurricanes. The curves are fairly regular up to wave heights of 4 to 5 m, attributable to the relatively large numbers of occurrences having been measured in this range, generated by virtually all of the hurricanes that passed through the North Atlantic during those decades. For example, at the 4-m height for the Cape Hatteras buoy, there were about 15 occurrences during 1977–1990, nearly tripling to about 45 in 1996–2005, which represented sufficient numbers to yield fairly stable records and documented the increase in high-wave occurrences over the span of that record. Above 5-m significant wave heights, the numbers of occurrences generally involve fewer than 10 for a specific height, often only 1 or 2. The irregularities in the histograms resulted from the sensitivity on the log scale to these low numbers of occurrences for the rare, extreme waves. However, those extremes are of greatest interest to coastal scientists and engineers as causes of coastal erosion and in the design of ocean structures. In Figure 6 it is seen that for the Cape Hatteras histograms in the 1977–1990 record, the highest significant wave height recorded had been 7.2 m; for the 1996–2005 decade, it had increased to 10.2 m. An examination of the hourly recorded significant wave heights from 1996 through 2005 indicates that several hurricanes generated waves on the order of 6 to 7 m. Those above 8 m can be attributed to just a few hurricanes of high intensities whose tracks took them into proximity with the buoy; in the case of the Cape Hatteras buoy, Hurricanes Dennis (August 31, 1999), Floyd (September 17, 1999), and Isabel (September 19, 2003) generated the most extreme waves, the 8- to 10-m values seen in the 1996–2005 histogram.

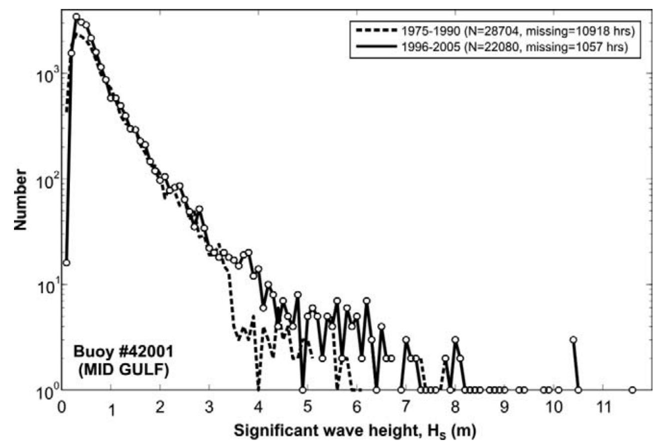

Figure 7. Histograms of the significant wave heights measured by the NDBC buoy in the Gulf of Mexico.

The histograms for the significant wave heights recorded by the buoy in the Gulf of Mexico (Figure 7) show somewhat different results from those in the Atlantic. Here the modes for both the early period of buoy operation and the recent decade are centered on about a 0.5-m significant wave height, the calm periods between storms being represented by lower waves than in the Atlantic, as expected. From that mode up to about the 3.0-m wave height, the histograms for the early period and recent decade are nearly congruent, differing from the Atlantic wave histograms, where this intermediate range of wave heights can be attributed to hurricanes whose tracks were distant from the recording buoys, their generated heights having been reduced to this range as the waves crossed the wide expanse of the Atlantic. With the Gulf being a smaller body of water, this process of wave reduction prior to being recorded by the buoy has been much less important, With the absence of change within that medium range of wave heights, there was not a discernable trend of increase in the annually averaged summer wave heights (Figure 4), there only being large variations from year to year. In the range of more extreme measured significant wave heights, 5 to 8 m, the Gulf histograms show considerable irregularities with fewer than 10 occurrences and without a distinct difference between the 1975–1990 and the 1996–2005 periods. The main difference is in the highest measured significant wave heights, having increased from about 8 m in the early records to 11.6 m in the recent decade, attributable to the recent high-category hurricanes such as Katrina and Rita in 2005.

CLIMATE CONTROLS ON HURRICANE WAVES

The wave heights generated by a hurricane and later recorded by a buoy depend on the intensity (category) of the storm, its overall track through the North Atlantic, and how close its track brings it to the buoy. As seen in Figure 2 for the daily wave measurements recorded by the Cape May and Cape Hatteras buoys during the summer of 1995, the waves derived from Hurricane Felix lasted for several days, during which their heights varied as this storm crossed the Atlantic, generally increasing as it came nearer the buoy even though the storm's intensity was gradually decreasing. When considering the annual averages of the wave heights measured by the buoys throughout the summer hurricane season, the number of storms that occurred is obviously important, with the resulting average being the integration of the wave-height variations recorded for each of those storms, determined by their varying intensities. It is apparent that unraveling the storm-related causes of the decadal increases in recorded wave heights, found in the analyses presented here, will not be simple. However, any effort directed toward accomplishing this is important, as it serves to better define the wave climate at that site and its expected future changes.

Such analyses are of additional interest in that the wave records derived from the buoys can potentially serve as a proxy to examine the recent history of the climatology of hurricanes in the North Atlantic. Of interest in this respect is the study by EMANUEL (2005), who concluded from analyses of wind speeds measured within hurricanes in the North Atlantic that their intensities have increased due to the elevated ocean-water temperatures that fuel the storms. While there is general agreement that the intensities of hurricanes have increased in the Atlantic since the 1970s, thanks to the advent of satellite monitoring of the storms, debate remains as to whether this increase extends back through earlier decades when changes in the technology used to monitor the storms likely affected the measurements (LANDSEA *et al.,* 2006).

It is noteworthy that the heights of waves generated by hurricanes appear to be highly sensitive to the intensities of the storms, *i.e.,* to their categories in the Saffir-Simpson classification, where the central atmospheric pressures are progressively reduced for the more intense, high-category hurricanes, with the associated wind speeds responsible for the wave generation increasing (SIMPSON and RIEHL, 1981). The correlation between the generated wave heights and the central atmospheric pressures is seen in the empiric formula of HSU, MARTIN, and BLANCHARD (2000),

$$H_{s\,\max} = 0.2(P_n - P_c), \tag{1}$$

where P_c is the atmospheric pressure in the eye of the hurricane and $P_n \approx 1013$ mbar is the normal atmospheric pressure beyond the effects of the storm; $H_{s\,\max}$ is the significant wave height—specifically, its greatest value that is generated close to the wall of the hurricane's eye, in its right-hand quadrant, where the wind speeds are highest (in the Northern Hemisphere) due to being enhanced by the forward movement of the storm. According to this formula, Category 1 hurricanes are expected to generate significant wave heights on the order of 6 to 7 m, while a Category 5 storm ($P_c < 920$ mbar) could generate significant wave heights of 20 m or greater. The wave heights, therefore, increase markedly with the intensity of the hurricane, such that only a modest increase in their average intensities over the decades could result in a measurable increase in the wave heights recorded by buoys. However, the value of $H_{s\,\max}$ given by Equation (1) is not fully representative of the waves being generated by the hurricane as a whole, since it correlates with the maximum wind speeds in the eye wall of the storm, whereas the wind speeds progressively decrease outward from that maximum, as do the generated waves. HSU, MARTIN, and BLANCHARD (2000) also analyzed this outward decrease, finding that the significant wave height is reduce to approximately half the value of $H_{s\,\max}$ at a distance of five times the radius of the eye, typically occurring about 250 km outward from the storm's center.

The results of our analyses of the wave-buoy records have shown that the most extreme significant wave heights measured are on the order of 10 to 11 m, well below the potential values of $H_{s\,\max}$ for an intense hurricane, but those potential extremes would be recorded only if the eye wall of the right-hand quadrant of the hurricane passed directly over the recording buoy. According to Equation (1), a hurricane of Category 3 could account for an $H_{s\,\max}$ value on the order of 10 m as measured by the buoys, but it is more likely that those heights were generated by higher-category storms with some reduction as the waves traveled to the buoy. Even then, the storm could not have been too distant from the buoy.

It is apparent that the potential correlation between the recorded waves and the storm intensity is affected by the track of the storm and how close it comes to the recording buoy. In an attempt to provide an initial assessment of the roles of these factors, we have categorized the tracks of tropical cyclones to determine which storms followed northward paths that take them into regions of the North Atlantic, where their generated waves could be recorded by the East Coast buoys, vs. those that entered the Caribbean or Gulf of

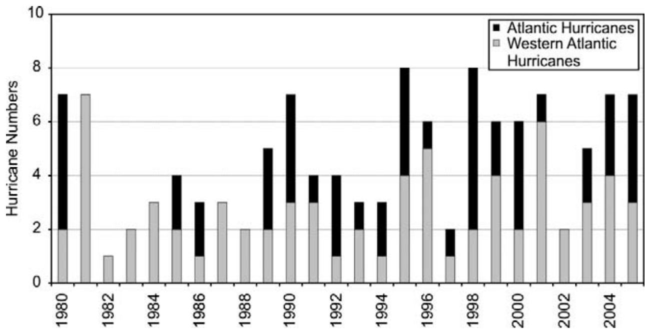

Figure 8. Bar graphs for the annual numbers of tropical cyclones (tropical storms and hurricanes) that followed northward tracks into the North Atlantic, and the subset of those storms that passed through the Western Atlantic, bringing them into proximity with the recording buoys.

Mexico or originally formed there. Furthermore, we categorized the storms that followed northward tracks as having entered the eastern, central, or western Atlantic (west of 60° W longitude), the last category being of particular interest as its track could then have brought the storm into proximity with the NDBC buoys that recorded the highest generated waves.

During the 26 years from 1980 through 2005, our analyses found that 168 (6.5 per year) hurricanes had developed in the Atlantic, 122 (4.7 per year) of which followed northward tracks, with 69 (2.7 per year) having passed through the Western Atlantic. We then separately analyzed the 1980–1989 and the 1996–2005 decades, finding that there had been a significant increase during the more recent decade: 37 (3.7 per year) hurricanes followed northward tracks during 1980–1989, vs. 56 (5.6 per year) during 1996–2005, with similar increases in the occurrences of Western Atlantic tracks (23 increasing to 32). This decadal increase is evident in Figure 8, which presents bar graphs for the numbers of tropical cyclones each hurricane season that followed tracks taking them into the North Atlantic, where they generated waves that could have been recorded by the U.S. East Coast buoys, and the subset of those numbers that entered the Western Atlantic, the hurricanes expected to have generated the highest recorded significant wave heights. This graph reinforces the preceding assessments for the 1980–1989 and the 1996–2005 decades, with the more recent decade on average having produced greater numbers of storms following northward tracks, as well as the numbers having entered the Western Atlantic.

These increases in the numbers of storms between the two decades can in part account for the differences in the histograms in Figure 6 of the ranges of measured wave heights, with both more extreme and greater numbers of high waves having been measured during 1996–2005 compared with early in the buoy records. However, the overall numbers of hurricanes from year to year have varied considerably (Figure 8), so the numbers of storms alone cannot account for the fairly uniform trends of increasing annually averaged significant wave heights seen in Figures 3 and 5. For example, during each of the years 1980, 1981, 2004, and 2005, at the beginning and end of the analyzed decades (Figure 8), identical numbers (seven each year) of hurricanes followed northward tracks, with more having entered the Western Atlantic during 1980–1981 (nine) than in 2004–2005 (seven). The increases in the annually averaged wave heights during 2004–2005 at the end of the buoy record, compared with 1980–1981 early in the record, seen in Figures 3 and 5 as part of the decadal trends of increasing wave heights, must therefore be attributed primarily to increases in the average intensities of the hurricanes as found in the study of EMANUEL (2005), based on his analyses of the wind speeds measured within the storms.

The evidence from our analyses of the hurricane occurrences, therefore, is that the primary factor governing the increase in the Atlantic summer wave heights has been the parallel increases in ocean-water temperatures and intensities of the resulting hurricanes. This conclusion is supported by the sensitivity of the heights of the waves expected to have been generated by hurricanes for the range of intensities (categories), as predicted by Equation (1) from HSU, MARTIN, and BLANCHARD (2000). It was to be expected that had there been an increase in the intensities of the storms over the decades, as found in the analyses of EMANUEL (2005), we would expect to find a measurable increase in the heights of the waves generated by those storms, which we have.

SUMMARY AND DISCUSSION

In this study, we have analyzed the daily measurements of ocean wave heights recorded by three NDBC buoys along an 800-km stretch of the central U.S. East Coast and one buoy with a central position within the Gulf of Mexico. Separate analyses were undertaken for the summer months of July through September to document the waves generated by hurricanes and for the subsequent winter months of November through March, when the waves along the Atlantic shore would have been generated by extratropical storms (nor'easters). From these analyses, we have reached the following conclusions:

- There has not been a statistically significant change in the winter significant wave heights measured by the three Atlantic buoys, waves that were generated by extratropical storms.
- The waves during the summer hurricane seasons, recorded by the three Atlantic buoys, document that there has been a trend of increasing significant wave heights since at least the mid-1970s, with the trends being statistically significant at the 95% confidence level.
- In the summer records, the measured significant wave heights greater than 3 m can in nearly all cases be directly associated with having been generated by specific hurricanes, with the maximum recorded significant wave heights having achieved 10 to 11 m, generated by hurricanes whose tracks took them into proximity with the recording buoys.
- Analyses of the recorded significant wave heights 3 m and greater therefore provide the best assessments for the decadal increases in hurricane-generated waves. The Charleston buoy data showed the highest rate of increase,

0.059 m/y (1.8 m in 30 years); the Cape Hatteras buoy showed somewhat less, 0.024 m/y (0.7 m in 30 years); and the Cape May buoy data showed a trend of 0.017 m/y, suggesting that there is a systematic latitude variation, increasing toward the south.

- Histograms of the ranges of significant wave heights measured by the Atlantic buoys during the hurricane seasons show that the most extreme occurrences during 1996–2005 are both higher and more common than occurrences 30 years ago at the beginning of buoy measurements, having increased from about 7 m to higher than 10 m.
- Similar analyses of the summer waves measured by the buoy in the Gulf of Mexico show large variations from year to year, depending on the numbers of hurricanes and their intensities (categories), storms that were either generated in the Gulf or entered by following westward tracks from the Atlantic; this variability precluded the detection of a net trend of changing wave heights over the decades, but the histograms of recorded significant wave heights show a dramatic increase in the most extreme measured waves, from about 8 m during 1975–1990 to 11.6 m during 1996–2005, reflecting the recent occurrence of high-category storms such as Hurricanes Katrina and Rita in 2005.

The measured increases in wave heights during the summer hurricane seasons, recorded by the NDBC buoys along the U.S. East Coast since their deployment in the 1970s, must reflect a parallel change in Earth's climate that has affected the capacity of the hurricanes to generate those higher waves. Our analyses of the histograms for the entire ranges of recorded significant wave heights (Figure 6) demonstrate that there has been a net increase in the numbers of occurrences of waves higher than 3 m, those generated by hurricanes, and in particular the most extreme significant wave heights recorded. The analyses of the annual averages of the summer significant wave heights (Figures 3 and 5) demonstrate that this increase has been reasonably uniform over the decades, suggesting that it has been produced by a reasonably gradual change in the climate. Our examination of the tropical cyclones that have occurred since 1980 indicates that the most likely explanation for this progressive increase in wave heights has been an intensification of the hurricanes as found by EMANUEL (2005), with increased numbers of storms having been a contributing factor. However, our analysis of the numbers of storms supporting this conclusion did not provide a direct comparison between the intensities of the hurricanes that have occurred since 1980 and the waves recorded by the NDBC buoys. This should be undertaken in order to more positively link the buoy records to changes in the climatology of the hurricanes, their annual numbers, intensities, and tracks. This could be accomplished through applications of wave-hindcast models that predict the heights of waves and the spectrum of wave energy for the storm as determined by its wind speeds, fetch area, *etc.,* followed by analyses of the transformations of those waves as they traveled across the ocean from the area of the storm to the recording buoys. Such analyses would necessarily including every tropical storm and hurricane that has occurred since 1980, for the full hurricane seasons since the origin of each wave event could be identified in the transitional months, an improvement over our approach of having separated the waves generated by hurricanes from those generated by extratropical storms by analyzing the limited summer and winter seasons. Furthermore, if the wave-buoy records are to be used as a proxy to determine the changes in hurricane intensities, such analyses would then be the inverse of this conventional approach, beginning the analyses instead with the waves recorded by the buoys, reverse-tracking them back to the hurricane that had generated them, and finally analyzing the intensity of that hurricane and the other factors that had been important to wave generation.

Whatever the ultimate answers are to the decadal changes in the climatology of hurricanes due to Earth's evolving climate, the bottom line is that it is already clear from our analyses that the heights of waves generated by hurricanes reaching the Atlantic shores of the United States have been increasing for the past 30 years and are likely to continue to do so in response to global warming, bringing still greater hazards to communities along those coasts.

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