EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 88 NUMBER 30

24 JULY 2007

PAGES 301–308

# Higher Waves Along U.S. East Coast Linked to Hurricanes

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Ocean wave heights measured by buoys along the U.S. Atlantic coast document an increase during the summer months when hurricanes are most important to wave generation. Wave heights greater than 3 meters, which can be attributed to specific hurricanes, have increased on average by 0.7–1.8 meters in the past 30 years, with the southernmost buoy that is offshore of Charleston, S.C., experiencing the highest rate of increase. The most extreme hourly averaged wave heights generated by major hurricanes have increased from about 7 meters early in the records of the buoys to more than 10 meters during the most recent decade. This increase in wave heights can be attributed in large part to a progressive intensification of the hurricanes, which *Emanuel* [2005] has documented through his analyses of hurricane wind speeds.

Measurements of ocean waves by buoys that are part of NOAA's National Data Buoy Center (NDBC) were initiated during the 1970s, and there now are 30 years of wave records. These records are sufficiently long to detect trends and variations that can be related to the storms responsible for their generation, and to climate controls including global warming. Our previous investigations analyzed buoy data collected along the U.S. Pacific coast [*Allan and Komar*, 2000, 2006], where we found trends of progressively increasing wave heights attributed to the intensification of extratropical storms. Our focus in this article is on the U.S. Atlantic coast, providing an examination of whether there has been an increase in the heights of waves generated by hurricanes, which could have resulted from hurricane intensification, as indicated by *Emanuel*'s [2005] analyses of the wind velocities within the storms. *Landsea et al.* [2006] have argued, though, that the apparent increase in storm intensities is an artifact of the improved technology used to monitor the storms.

Our analyses have included wave measurements from four NDBC buoys, three of which are along the U.S. Atlantic shore and one of which is in the Gulf of Mexico. The three Atlantic buoys are 44004, seaward of Cape May, N.J.; 41001, offshore of Cape Hatteras, N.C.; and 41002, seaward of Charleston, S.C. (P. D. Komar and J. C. Allan, manuscript in preparation, 2007). All four buoys are in deep water beyond the edge of the continental shelf, and their records have not been affected by wave shoaling or bottom friction. The results from the three Atlantic buoys are similar, and this article presents results mainly from the buoy offshore of Cape Hatteras (CH). The record from the CH buoy is of particular interest because it is seaward of the North Carolina coast, which, along with Florida, has the highest probability in the United States for hurricane landfalls [*Smith et al.*, 2006]. This buoy also has the longest record of the three Atlantic buoys, with fewer data gaps. The data reported each hour by the buoy include the significant wave height, defined as the average of the highest one third of the measured wave heights; the heights discussed in this paper represent that commonly used average.

The North Atlantic season of tropical storms and hurricanes (collectively termed tropical cyclones) generally extends from July through October. There is some overlap with the season of waves generated by extratropical storms (e.g., nor'easters), which occur mainly during the winter. In order to investigate the contributions of tropical cyclones to the wave climates, we have limited analyses of their waves to the 'summer' months of July through September, and we have omitted October when both types of storms have likely occurred. Inspections of the wave records demonstrate that this seasonal segregation largely has been successful.

Figure 1 contains an analysis of the annually averaged significant wave heights measured by the CH buoy during the summer months—the hurricane season—showing a persistent increase spanning three decades; the linear regression yields 0.017 meters per year for the rate of increase, statistically significant at the 95% level determined with a Wilcoxon rank-sum nonparametric test that in essence statistically compares the first half of the record with the second half to confirm that there is a trend. The trends for the other two Atlantic buoys are nearly the same, but the analysis for the buoy in the Gulf of Mexico showed more variation from year to year, without a statistically significant trend.

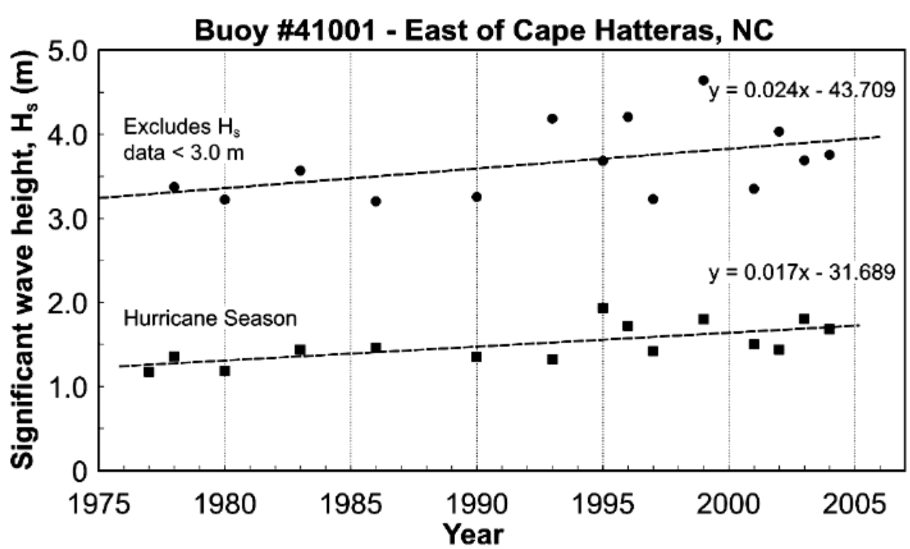


*Fig. 1. Trends in the annual averages of the summer hurricane-generated significant wave heights measured offshore of Cape Hatteras, N.C. Best fit lines are provided.*

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The hurricane season averages graphed in Figure 1 for the CH buoy are diluted by the low waves of calm periods between hurricanes, when the significant wave heights are of the order of 1–2 meters, whereas identifiable hurricane waves typically range from about 3 meters to the extremes of 8–10 meters. Figure 1 therefore also includes a plot of the CH data where this dilution is eliminated by having omitted all measurements less than 3 meters. The new averages are accordingly shifted to higher values, more representative of having been generated by hurricanes, with a clear trend of increasing wave heights spanning the 30-year record of the buoy. The regression now yields a rate of increase of 0.024 meters per year, an increase of 0.72 meters in 30 years, which provides a better assessment of the decadal increase in wave heights generated by hurricanes. The rate of increase for the Charleston buoy to the south of the CH buoy is greater (0.054 meters per year; 1.8 meters in 30 years), while that to the north offshore of Cape May is less (0.017 meters per year), indicating that there likely is a regular along-coast variation. The Wilcoxon test of the increase remains statistically significant at the 95% level for the CH and Charleston buoys.

The change over the decades of the full range of wave heights generated by tropical cyclones, including the most extreme measured significant wave heights, is revealed when the data are graphed as a histogram (Figure 2), based on all of the summer data from the CH buoy. Figure 2 includes two histograms—the first for the waves measured early in the buoy's record (1977–1990), the second for 1996–2005—analyzed separately to further document the decadal increase seen in Figure 1. Rather than graphing the percentages of wave-height occurrences, the histograms are the actual numbers of occurrences for the complete range of significant wave heights, and a log scale is used that magnifies the most extreme occurrences so their numbers are readily evident. Both histograms have maximums centered on 1- to 2-meter wave heights, which represents the nearly calm periods between the higher waves generated by hurricanes.

It is evident that there has been a shift in the range of higher waves during the 1996–2005 decade compared with the earliest buoy measurements, with there being greater numbers of waves higher than 3 meters and a substantial increase in the most extreme significant wave heights that had been measured; the highest recorded waves during 1977–1990 had been 7.2 meters, while for the 1996–2005 period they had increased to 10.2 meters. A storm-by-storm analysis of the recorded waves showed that those in the range of 2–5 meters were for the most part generated by distant hurricanes, with the wave heights having decreased as they traveled across the ocean from their area of generation to the recording buoy; the rare but more extreme wave heights required that the storm pass in reasonably close proximity to the buoy. An examination of the hourly recorded CH significant wave heights showed that a number of hurricanes generated waves of the order of 6–7 meters during the 1996–2005 decade. The most extreme waves were generated by hurricanes Dennis (31 August 1999), Floyd (17 September 1999), and Isabel (19 September 2003), yielding the 8- to 10-meter values in the histogram.

The waves recorded by the Atlantic buoys depend on the annual numbers of tropical storms and hurricanes that followed tracks northward into the central Atlantic, how close their tracks approached the buoys, and the intensities (categories) of those hurricanes. Our examinations of the storms that occurred during the past 30 years indicate that the numbers of storms and their tracks cannot account for the fairly uniform trends of increasing wave heights seen in Figure 1. Although there has been a general increase in the numbers of hurricanes, there is considerable variation from year to year (P. D. Komar and J. C. Allan, manuscript in preparation, 2007). The most likely explanation for the increasing wave heights is that there has been a progressive intensification of the hurricanes, as documented in the study of *Emanuel* [2005] based on analyses of the wind speeds measured within the storms, the primary factor important to the generation of waves. With the increase in hurricane intensities and wind speeds having likely been a response to higher ocean-water temperatures brought about by global warming, the heights of the waves they generate can be expected to continue to increase into the future, just as they have for the past 30 years, bringing greater hazards to communities along the shores of the western Atlantic.

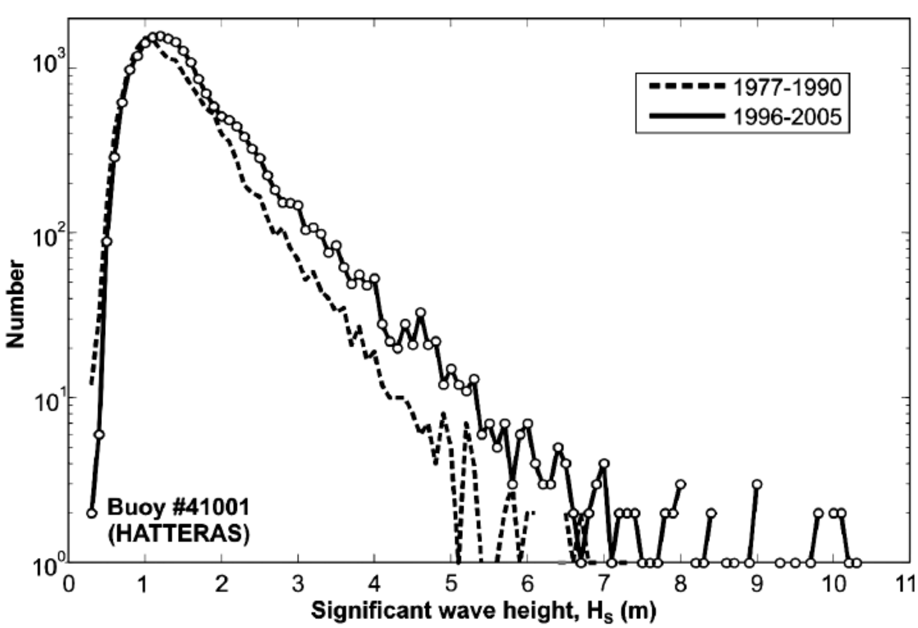


*Fig. 2. Histograms of the numbers of occurrences of 'summer' significant wave heights measured by the Cape Hatteras buoy during early (1977–1990) versus recent decades*

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