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Increasing hurricane wave power along the U.S. Atlantic and Gulf coasts

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[1] Although no clear trend in tropical cyclone (TC) generated wave height is observed, a TC wave power index (WPI) increases significantly in the Atlantic during the mid-1990s, resulting largely from an increase in the frequency of middle-to-late season TCs. The WPI is related to TC strength, size, duration, and frequency and is highly correlated with the TC power dissipation index (PDI). Differences between the Atlantic and Gulf of Mexico WPIs reflect systematic changes in TC genesis regions and subsequent tracks, characterized by their relationship with the regional circulation patterns described by the Atlantic Meridional Mode. The annual wave power at near-coastal locations is closely associated with open ocean WPI. The close association of the WPI to hurricane activity implies that under rising sea level, significant coastal impacts will increase as the PDI increases, regardless of TC landfall frequency.

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1. Introduction

[2] The heightened tropical cyclone (TC) activity since 1995 [*Emanuel*, 2005; *Goldenberg et al.*, 2001; *Klotzbach*, 2006; *Webster et al.*, 2005] and extensive damage along the Gulf Coast during the 2005 hurricane season, defined as the period from June through November, have focused attention on potential societal vulnerability from storms along the U.S. Atlantic and Gulf coasts. The damage caused by TCs depends to a large extent on whether they make landfall, when storm surge, high winds, and heavy rainfall combined with high waves cause severe impacts. However, high waves from remote TCs can also have substantial coastal impacts. For example, strong TCs that reach hurricane strength and then track northward along the east coast as they weaken can combine with extratropical systems, such as the 1991 Halloween storm [*Bromirski*, 2001], causing severe coastal erosion and significant economic impacts [*Davis et al.*, 1993; *Dolan et al.*, 1988; *Mather et al.*, 1967]. Observed TC-generated wave heights, typically measured by moored ocean surface buoys, depend on the storm track relative to the buoy, the maximum sustained wind speed, and the area over which sustained high wind speeds persist (the peak fetch), which depends on storm size as well as intensity. The persistence of sustained high wind speeds over a large fetch generates long-period waves that propagate very efficiently for long distances in deep water [*Munk et al.*, 1963]. Thus, distant storms can have impacts at remote coasts and can produce significant TC-generated waves measured at buoys removed from the direct TC track. Extremes in wave power generated by TCs will have an increasingly greater coastal impact as mean sea level rises.

[3] Tropical cyclones are intense "warm core" storm systems that persist for periods from a day or two to about 2 weeks. Not all TCs evolve to hurricane category or make landfall, but lower-intensity systems can still generate high waves that can have significant coastal impacts. For example, waves that have amplitudes of only 1.5 m in deep water have resulted in measurable beach face erosion along the North Carolina coast [*Dolan and Davis*, 1992]. From a coastal management and planning perspective, it is important to know how TC-generated wave energy varies from year to year and whether the intensity, frequency, and seasonal distribution of TC-generated waves are changing. These factors affect the amount and timing of wave power reaching the shore. Although the instrumental record of wave energy is relatively short, the buoy measurement platforms provide consistent hourly wave parameter estimates.

[4] This study examines temporal and spatial variability of TC-generated waves at both open ocean and near-coastal locations along both the Atlantic and Gulf coasts using National Oceanic and Atmospheric Administration (NOAA) buoy data [*Earle*, 1996]. Unlike a recent study by *Komar and Allan* [2007] that restricted TC-generated wave analysis to only a portion of the available data, the National Hurricane Center "best track" record is used to identify all potential significant TC wave events from the available data, giving a more complete characterization of TC wave variability. The open ocean variability is compared with shorter-duration near-coastal buoy data records to demonstrate their relationships. A wave power index (WPI) is presented that characterizes the regional TC wave power variability. Correlations between WPI and the power dissi-

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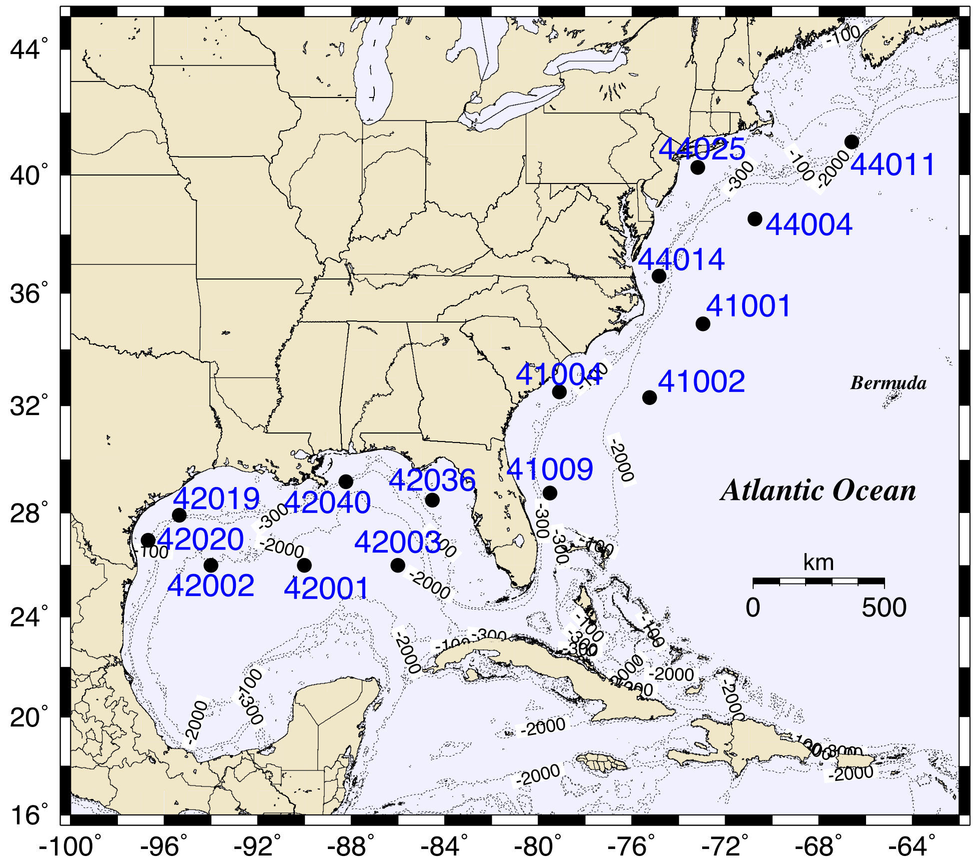

Figure 1. Location of the NOAA buoys providing wave data in this study. Bathymetric contours identify the continental shelf boundary.

pation index (PDI) [*Emanuel*, 2005] and other climate indices give insights into the influence of broadscale climate factors on TC-generated wave variability.

2. Data Overview: Occurrence of Significant TC Wave Events

[5] The western North Atlantic and Gulf of Mexico TC-associated wave variability from 1978 to 2006 are characterized from ocean surface buoy measurements collected by seven open ocean NOAA National Data Buoy Center buoys (Figure 1). The data are generally sampled hourly, although data collected from 1978 to 1980 and during parts of the 1980s employed an eight sample per day collection methodology. Wave data from the National Oceanographic Data Center (NODC) (http://www.nodc.noaa.gov/BUOY/buoy.html) for four western North Atlantic open ocean buoys (from north to south: 44011, 44004, 41001, and 41002, offshore about 400 km) and three open ocean Gulf of Mexico buoys (from east to west: 42003, 42001, and 42002) were examined. All buoys are in deep water (depths >1000 m) except northernmost buoy 44011 (whose record begins in 1984), likely causing wave amplitudes at 44011 to be affected by shoaling and refraction. The record lengths of the eight near-coastal buoys are of much shorter duration, beginning about 1990, but are useful for assessing the relationship between open ocean and nearshore wave variability. Key wave parameters measured at each buoy are the significant wave height, H_S, the average of the highest third of the waves, and the dominant wave period, T_P, the period of the waves having the greatest energy.

[6] The magnitude of the coastal impact from TCs depends on the wave power, which is proportional to $H_S^2 T_P$. The highest waves with the longest periods are generated while the storm intensity remains high, observed in buoy records to typically last at most 2–4 days. So although a TC can maintain its warm core integrity for as much as 2 weeks, commonly, the most powerful waves are generated during only a fraction of the storm's duration. To accurately assess wave variability associated with TCs, wave height data need to be examined only for the time that waves from each TC are observed at the buoys, thus ensuring the exclusion of extratropical storm waves resulting from nor'easters that can produce significant (extreme) wave events during the hurricane season, especially at the three northernmost buoys. Because severe coastal erosion results from high-amplitude H_S events, significant open ocean TC wave events were defined as those having H_S that exceeded 3 m (slightly less than the 98th percentile of all hurricane season waves for the Gulf of Mexico group and slightly greater than the 90th percentile for the Atlantic group). The difference in 3 m percentile levels indicates that the east coast is generally impacted by higher-amplitude TC waves, likely related to the longer fetches possible in the Atlantic.

[7] Not all tropical storms intensify sufficiently to generate significant H_S events, and not all hurricanes generate

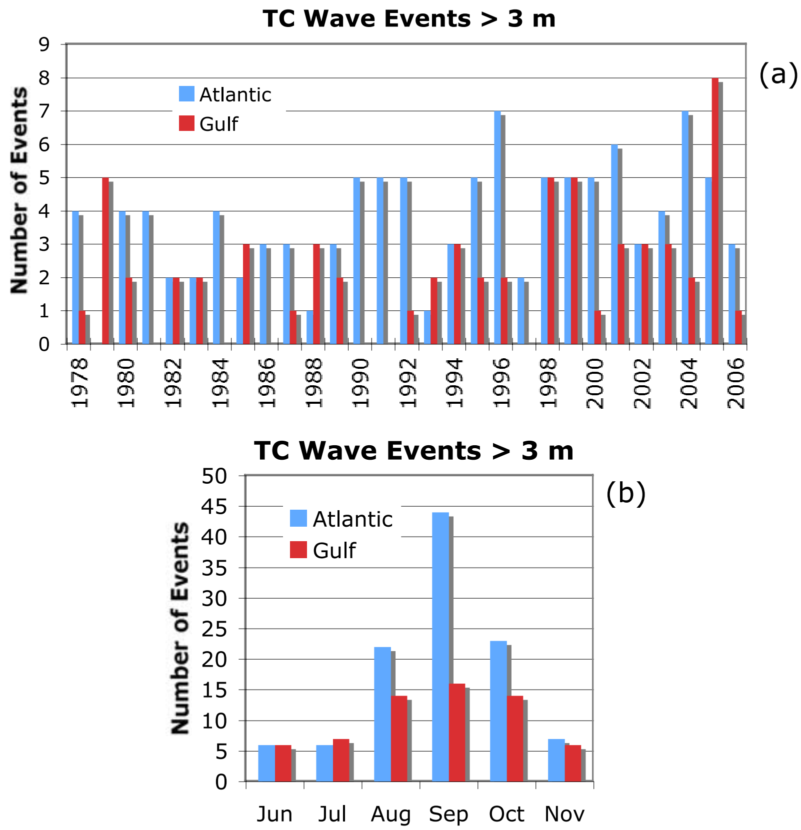

Figure 2. (a) Total number of events per hurricane season. (b) Total number of wave events identified during each month of the June–November hurricane season for all buoy data available from NODC from 1978 to 2006. Shown are the number of wave events associated with tropical cyclone (TC) storm systems with H_S that exceeded 3 m at a minimum of one of the buoys in each group. Each event was counted only once, even if it was observed at multiple buoys in a group. No data were available from NODC for any of the Atlantic buoys during the entire 1979 hurricane season.

significant waves that reach the locations of the buoys studied. Major hurricanes confined to the Gulf of Mexico, such as 2005 Hurricane Katrina, do not produce significant waves along the U.S. Atlantic coast. The Gulf of Mexico region is shielded from the impact of waves from many TCs that track farther eastward by Cuba, other Caribbean islands, and Florida. So the Gulf of Mexico and Atlantic buoys, to some extent, can be treated as separate groups to coarsely assess the spatial variability of significant TC wave event variability. Additionally, some TCs are short-lived low-intensity storms and/or have tracks confined to the eastern Atlantic and thus generate no significant waves along the U.S. Gulf and Atlantic coasts.

[8] To assess the differences in significant TC wave variability in the Gulf of Mexico and western North Atlantic and to ensure that non-TC waves were excluded, the time periods that TC-generated storm waves were observed at the buoys for all storms in the National Hurricane Center best track record from 1978 onward were identified separately as Atlantic and Gulf of Mexico events on the basis of their storm tracks. TCs that tracked from the Atlantic to the Gulf of Mexico and vice versa, such as Hurricane Wilma during late October 2005, and generated high waves along both coasts were included in both regions' analyses. Because the number of TCs that produce significant wave events that reach anywhere along the Atlantic or Gulf coasts determines whether there is potential for societal impact, an event observed at more than one buoy within each group was counted only once, allowing for regional coverage for significant wave event identification.

[9] Each of the buoy records has significant data gaps. But there is considerable redundancy in the wave events within the Atlantic and Gulf of Mexico groups; that is, strong TCs produce waves that are observed over the relatively broad region covered by the buoys. So there is great value in examining them collectively as groups in order to cover the entire record period and make an accurate assessment of TC-associated wave variability along the U.S. Atlantic and Gulf coasts.

[10] Importantly, both Atlantic and Gulf of Mexico regions show a general tendency for more significant TC-associated wave events since 1995 (Figure 2a), consistent with increasing overall counts of named storms during recent years. As would be expected by considering the tracks within the Gulf of Mexico of tropical storm Arlene, Hurricane Cindy, and major hurricanes Dennis, Emily, Katrina, Rita, and Wilma, the 2005 hurricane season had the highest incidence of significant H_S events over the data record in the Gulf of Mexico. Since 1978, there were substantially more significant H_S events along the Atlantic coast than in the Gulf of Mexico, with almost three times as

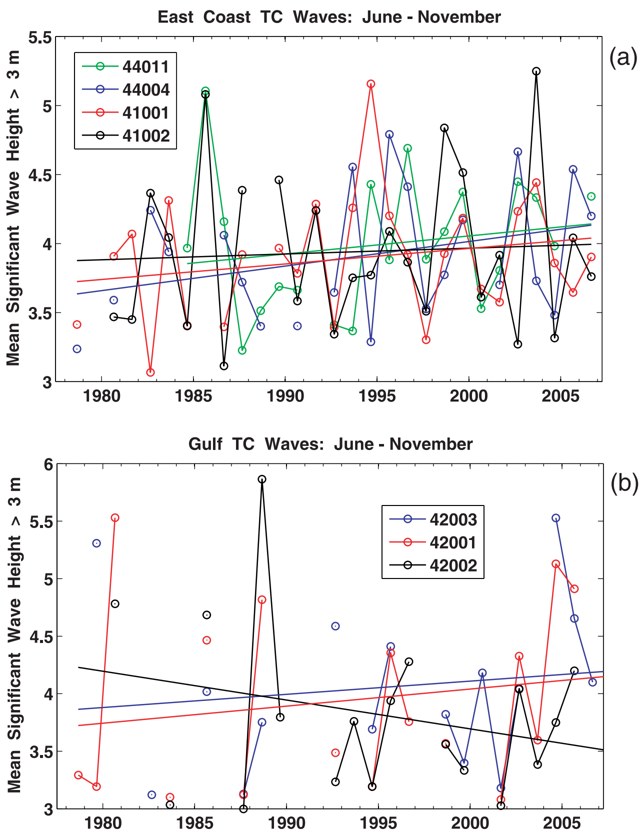

Figure 3. Mean of all tropical cyclone–associated H_S measurements that exceeded 3 m during June–November hurricane seasons for (a) western North Atlantic buoys along the U.S. east coast and (b) Gulf of Mexico buoys. Significant TC-associated H_S events do not occur at all buoys every year. Least squares trends shown are not statistically significant, with the upward trend at 41001 less than half of that determined by *Komar and Allan* [2007].

many events during September (Figure 2b). The prevailing storm tracks in September apparently favor the Atlantic over the Gulf of Mexico for generation of significant H_S events. The monthly distribution along both coasts peaks in September, with an equally likely chance of a significant TC wave event occurring during October as during August over the 1978–2006 data record.

3. Open Ocean TC Wave Height Variability

[11] Because wave power is proportional to the square of the wave height, H_S variability is a more important wave parameter than wave period variability for coastal impacts. The mean of TC-associated H_S measurements above the 3 m threshold provides a measure of changes in strong TC events. The mean of all TC wave events during each hurricane season (Figure 3) shows considerable variability between buoys in each group and between the two coasts. Differences within each group are partly explained by buoy location relative to storm track and other storm characteristics. Other differences are explained by missing data, underscoring the importance of making a collective comparison to obtain a more reliable assessment of TC wave variability over time from the network of available buoy data.

[12] The mean H_S estimates can be strongly affected by a few extreme wave events from individual high-intensity TCs that track nearby. Because TCs generally originate at low latitudes, it would be expected that TC-associated H_S amplitudes would be higher at the southernmost buoys. Indeed, Figure 3a suggests that it is more likely to observe high wave amplitudes at the southernmost Atlantic buoy, 41002, confirming expectations. However, TCs traveling northward along the east coast can be sustained by warm Gulf Stream waters and can also develop an expanded fetch as the surface wind field expands because of the increasing ambient Coriolis force [*Kossin et al.*, 2007], resulting in the generation of high wave amplitudes near Cape Hatteras (buoy 41001) and northward.

[13] Because of the substantial year-to-year variability in TC frequency and their June–November distribution, the buoy records were examined over the entire hurricane season. Linear least squares analysis of mean H_S for observations exceeding 3 m indicates that there are no statistically significant trends in extreme H_S (at the two-tailed t test $\alpha = 0.25$ level) for the open ocean buoys in Figure 3 (except buoy 44004, which shows the greatest increase of the Atlantic group), indicating that TC wave heights on average have not substantially increased along the U.S. east or Gulf coasts since 1978. Differences with results reported by *Komar and Allan* [2007] arise because they based their estimate on only 13 hurricane seasons, excluded all TCs during the important October and November months, and included non-TC nor'easter events in their estimate. Trend estimates at 41001 are also likely affected by being out of service during Hurricane Gloria in September 1985, when the highest-amplitude TC H_S measurement (14.3 m) observed at any of the open ocean buoys along the east coast since 1978 was recorded at 41002 to the south and would likely have produced some of the most extreme waves at 41001 over the past four decades.

[14] The duration that extreme H_S occurs is an important factor in characterizing TC-generated wave power variability over time. Similar to extreme H_S in Figure 3, there is no statistically significant trend in the duration of best track–identified events exceeding 3 m in the open ocean along either the U.S. Atlantic (Figure 4) or Gulf coasts (Figure 5). This indicates that although the number of observed extreme TC events has increased (Figure 2), neither their average extreme wave height nor their associated duration have increased appreciably.

4. Open Ocean Wave Power Variability

[15] Differences in H_S variability observed at different buoys are highly sensitive to storm track. The impact of buoy location on assessing TC wave variability can be reduced somewhat by comparing wave power variability collectively during each hurricane season. The TC wave power per event, P_E, in deep water along a unit length of wave crest can be estimated from the significant wave height, H_S, and the dominant wave period, T_P, measured at the buoys over the wave event duration, τ, as

$$P_E \approx \frac{1}{2} Ec = \frac{\rho g^2}{32\pi} \int_0^\tau H_S^2 T_P dt, \quad (1)$$

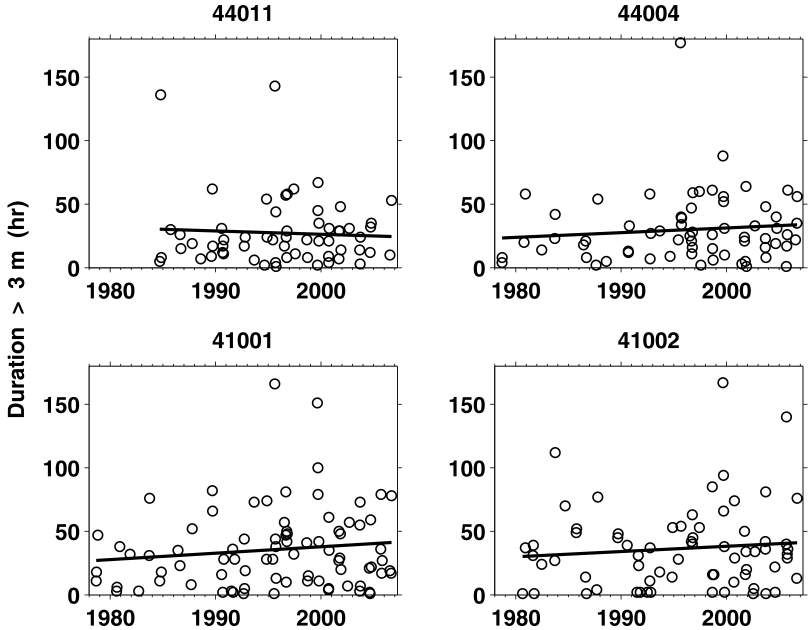

Figure 4. Duration that wave heights exceeded 3 m for best track identified wave events along the Atlantic coast at NOAA open ocean buoys 44011, 44004, 41001, and 41002 (north to south; see Figure 1). Linear least squares trends shown are not statistically significant at the two-tailed t test $\alpha = 0.25$ level.

where E is the wave energy and c is the wave phase speed. T_P is sensitive to the duration and size of the fetch over which strong winds persist, i.e., the storm's size. Thus, P_E, formed from the H_S and T_P wave parameters, gives a better measure of hurricane strength than H_S alone, which can be large for relatively small, short-duration but intense nearby storms that have relatively short T_P. To make comparisons across the entire record length valid, data sampled at eight samples per day were linearly interpolated to hourly sampling. T_P data were not available prior to 1980. Analogous to the PDI, interannual wave power at each buoy, P_A, is obtained as the sum of P_E for all TC wave events during a hurricane season. Here P_E is obtained over the entire TC wave event duration, not just for waves greater than 3 m.

[16] A regional WPI for each coast is formed from the average of P_A at the three deep water buoys in the Atlantic and the Gulf of Mexico, respectively. Even though proximity to storm track and wave directionality issues are not resolvable and the data gaps are problematic, the long-distance propagation characteristics of long-period gravity waves generated by strong storms allow the use of widely separated buoys to obtain a wave power estimate that enables a useful comparison of the regional WPI variability over time. In addition, many TCs in the Atlantic track northward and thus approach each of the Atlantic buoy locations, while the Gulf of Mexico is constrained by surrounding landmasses to the extent that TC-generated waves are generally observed throughout that region.

[17] In general, the Atlantic buoys show a significant increase in annual P_A since 1995 (Figure 6a). P_A during six of the hurricane seasons since 1995 exceeds all prior years at a minimum of one of the Atlantic group buoys. This increase is mirrored in the Atlantic WPI (Figure 5c), indicating that TC wave energy variability impacts the entire region. Because no significant trends in either H_S (Figure 3) or event duration (Figures 4 and 5) were observed, the increase in the Atlantic WPI likely results primarily from the increased number of TC-associated wave events along the east coast since 1995.

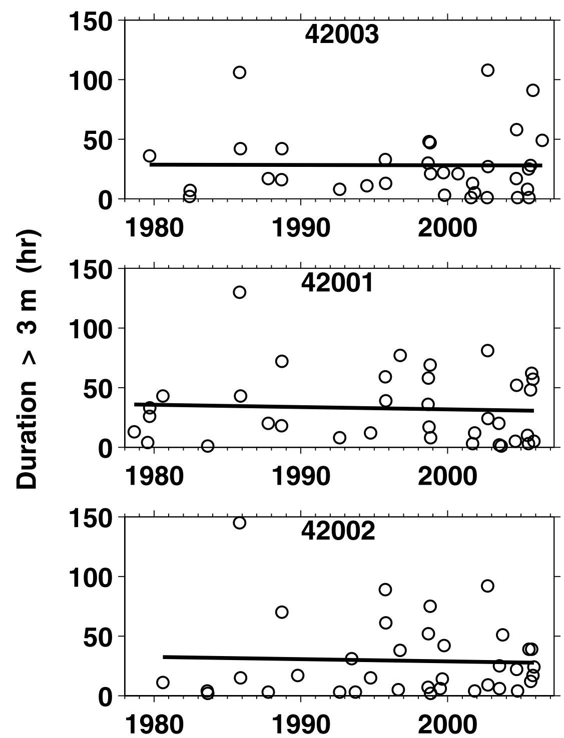

Figure 5. Duration that wave heights exceeded 3 m for best track identified wave events in the Gulf of Mexico at NOAA open ocean buoys 42003, 42001, and 42002 (east to west; see Figure 1). Linear least squares trends shown are not statistically significant at the two-tailed t test $\alpha = 0.25$ level.

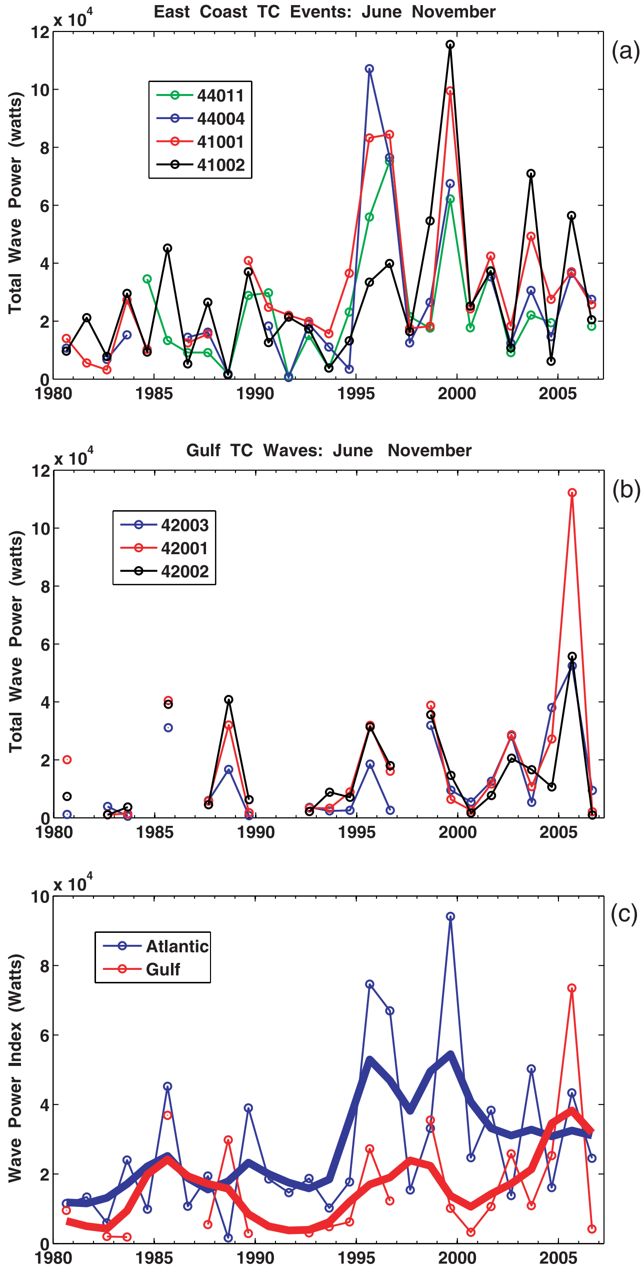

Figure 6. Total wave power, P_A, for all tropical cyclone–associated wave events during June–November hurricane seasons identified at (a) western North Atlantic open ocean buoys and (b) Gulf of Mexico open ocean buoys. Note that missing data at buoy 41002 during 1995 and 1996 excluded important events, resulting in an underestimation at 41002 for those years. (c) Mean of the available annual deep water wave power data shown in Figure 4 (the wave power index (WPI)). Wave period data are not available prior to 1980. Longer-period variability is emphasized by low-pass filtering the annual data with a 1-4-6-4-1 binomial filter, giving the Atlantic and Gulf of Mexico region WPI (thick lines).

[18] In contrast to the Atlantic buoys, the Gulf of Mexico buoys (Figure 6b) show exceptional P_A levels only during the 2005 hurricane season when major hurricanes Dennis, Emily, Katrina, Rita, and Wilma tracked through the Gulf of Mexico. It should be noted that the exceptional P_A levels observed in the Gulf of Mexico during 2005 were exceeded in the Atlantic at 41002 during 1999 and were approached during 1995 and 1996 at more northern buoys 41001 and 44004 (Figure 6a), attesting to a greater frequency of extreme TC-associated wave events along the east coast compared to the Gulf of Mexico during the last four decades.

[19] The Atlantic WPI is generally much higher than the Gulf of Mexico WPI (Figure 6c), reflecting the greater number of significant H_S events in the Atlantic (shown in Figure 2). The Atlantic WPI about doubles from the 1980s to the late 1990s, comparable to the relative increase in the PDI [*Emanuel*, 2005]. It is noteworthy that even though the Atlantic WPI has declined from its peak in the late 1990s, its level during 2000–2006 shows an increase of about 50% over the 1980s. The Gulf of Mexico WPI (Figure 6c) suggests a pattern of longer-period variability that appears to be partly in tune with Atlantic TC activity.

5. Near-Coastal Wave Power Variability

[20] The magnitude of coastal impacts from TCs depends on the amount of wave energy reaching the shore, which is greatest during TC landfalls. The number of landfalls along the U.S. Atlantic and Gulf coasts has increased since the mid-1990s (Figure 7), with substantially more landfalls along the Gulf Coast. About as many landfalls occur along the western Gulf Coast as the eastern, with a recent tendency for increased numbers of western Gulf of Mexico landfalls. For the entire Gulf Coast, the extreme 2005 hurricane season stands out. Along the Atlantic coast, not surprisingly, most landfalls occur south of Cape Hatteras. Landfalls north of Cape Hatteras are infrequent, with the pattern in Figure 7 essentially unchanged since 1900 (not shown).

[21] Although TC landfalls are of primary concern because of associated storm surge, high–wave power events associated with TCs that do not make landfall can also cause significant coastal erosion that can also result in long-term changes in coastlines [*Dolan and Davis*, 1992; *Dean and Dalrymple*, 2002]. As the occurrence of relative extreme water levels increases nonlinearly with rising mean sea level [*Cayan et al.*, 2008], the characteristics of near-coastal wave power variability will become increasingly important and will have greater societal impact as mean sea level rises. Significant H_S events occur at coastal locations for TC events that never make landfall, such as Hurricane Felix in August 1995. Felix reached Category 4 strength over open water and was heading toward the Carolina coast when it encountered a midlatitude trough that caused a reversal in direction, sending Felix back out to sea and resulting in the extended two-phase extreme wave event observed near Cape Hatteras (Figure 8). Waves from Felix caused extensive beach erosion and damage along the North Carolina and New Jersey coasts.

[22] To establish the relationship between open ocean and near-coastal wave power, and thus the coastal erosion potential, available H_S and T_P data from NOAA near-coastal buoys distributed along both the U.S. Atlantic and Gulf coasts (see Figure 1 for locations) were obtained to determine the near-coastal P_A for the same events identified at the open ocean buoys (Figures 3–6). Both the Atlantic (Figure 9a) and Gulf of Mexico (Figure 10a) near-coastal buoys

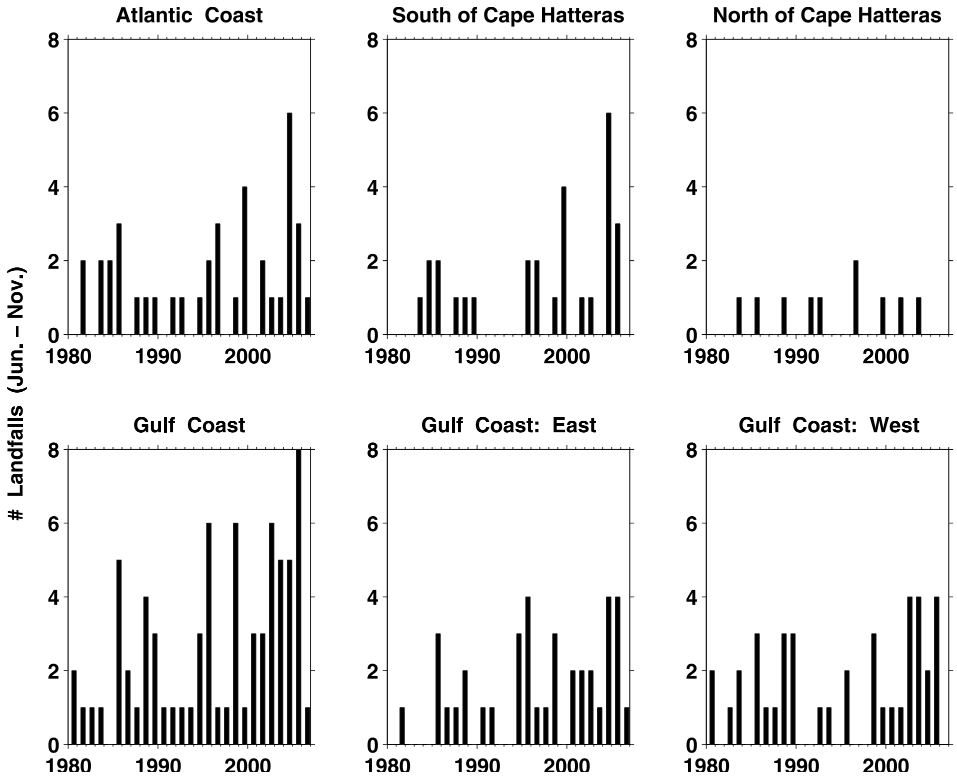

Figure 7. Landfall counts along the U.S. Atlantic and Gulf coasts for the entire coast and for north-south and east-west subregions. Landfall counts along the Atlantic coast were determined for subregions 25°–36°N and 36°–47°N. Gulf region landfalls were constrained to the region north of 23.5°N, with the east-west boundary at −89.5°W. Each event was counted only once for each region and subregion, even if multiple landfalls occurred. However, landfalls for the same event were included in the subregion counts; thus the sum of subregion landfalls along a coast in a season could exceed the number of occurrences for the entire coast.

show peaks in P_A that mirror those observed at corresponding open ocean buoys (Figures 6a and 6b, respectively), showing a direct relationship between open ocean and near-coastal wave power. The observed similarities also suggest that the open ocean buoys, which provide measurements over a longer time span, can be used as reasonably reliable indicators of long-term near-coastal wave power variability.

[23] To estimate the importance of TC landfall to coastal wave activity, near-coastal P_A was determined only for the TC events that did not make landfall; that is, events common with Figure 7 were excluded. Comparing Figures 9b and 10b to Figures 9a and 10a, respectively, shows that a greater proportion of the wave energy is excluded for the Gulf of Mexico, indicating that landfalls in the Gulf of Mexico occur more in concert with open ocean wave power events, not surprising when TC track and the relatively small size of the Gulf of Mexico basin are considered. Comparison of Figures 6a and 9b indicates that substantial wave power reaches the coast north of Cape Hatteras in the absence of landfalls, as characterized by nonlandfall P_A observed at buoy 44014. It is important to note that P_A observed along the Atlantic coast for nonlandfall events often exceeds that for all events at near-coastal locations in the Gulf of Mexico (including landfalls), attesting to the typically greater TC wave energy along the Atlantic coast. Surprisingly, Atlantic TC events that do not make landfall have a tendency to produce greater wave power at more northern coastal locations, evidenced especially prior to 2000. This tendency is likely related to track and the longer fetches associated with northward traveling TCs. In addition to being the northernmost buoy, wave

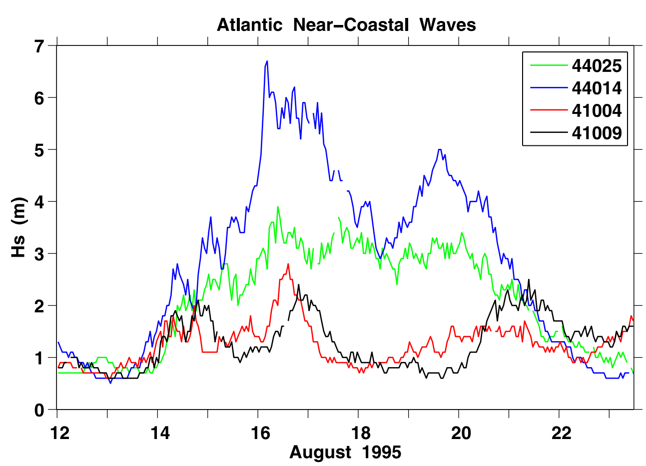

Figure 8. Significant wave height, H_S, observed at NOAA near-coastal buoys 44025, 44014, 41004, and 41009 during Hurricane Felix in August 1995, a tropical cyclone that did not make landfall. Note that near-coastal H_S was higher north of Cape Hatteras during this event.

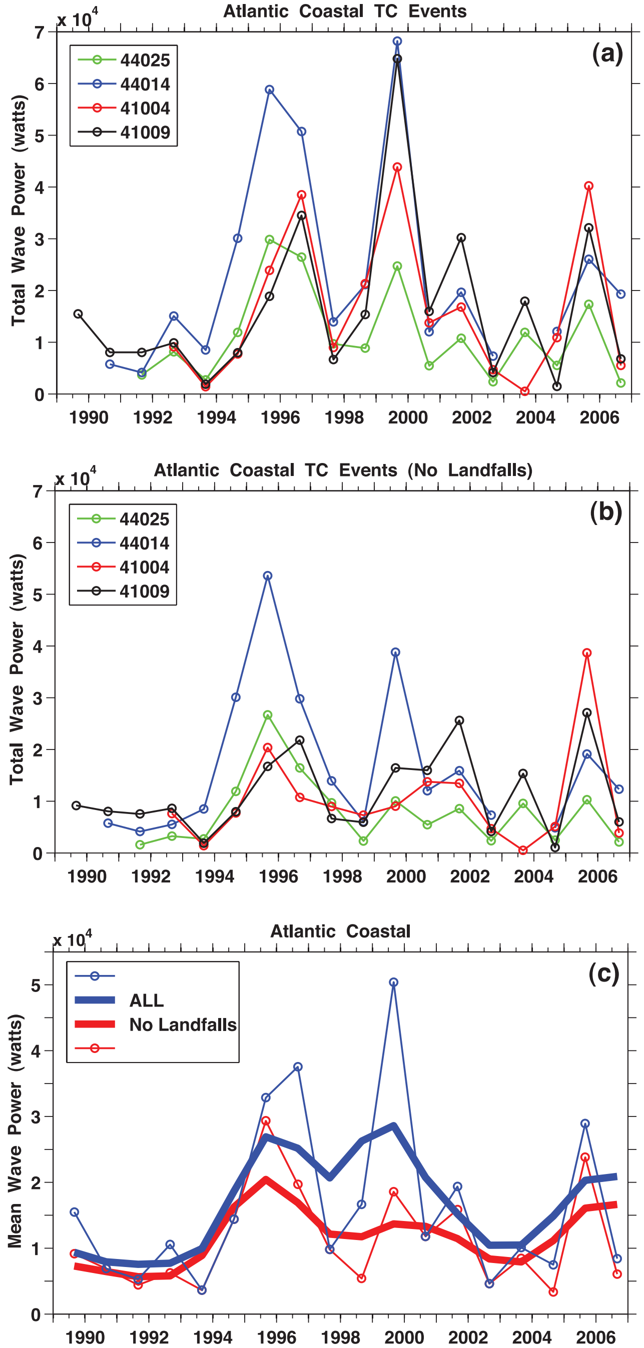

Figure 9. Total P_A for all tropical cyclone–associated wave events during June–November hurricane seasons identified at near-coastal western North Atlantic buoys for (a) the same events studied in Figure 6a and (b) subset of events in Figure 9a formed by excluding those events that made landfall. (c) Mean of the available annual wave power data shown in Figures 9a and 9b. Longer-period variability in Figure 9c is emphasized by low-pass filtering the annual data with a 1-4-6-4-1 binomial filter, as for the WPI in Figure 6c.

power at 44025 is likely reduced by bottom interaction for waves crossing the comparatively wider shallow-water shelf.

[24] Comparing the mean wave power (Figures 9c and 10c) with the WPI (Figure 6c) indicates that open ocean and near-coastal wave power covary. This similarity indicates that the WPI gives a reliable measure of wave power variability across the western North Atlantic and Gulf of Mexico regions and can be used as an indicator of near-coastal wave activity during earlier years when the near-coastal buoys were not in service. The upward biases in both the Atlantic WPI and mean near-coastal TC wave

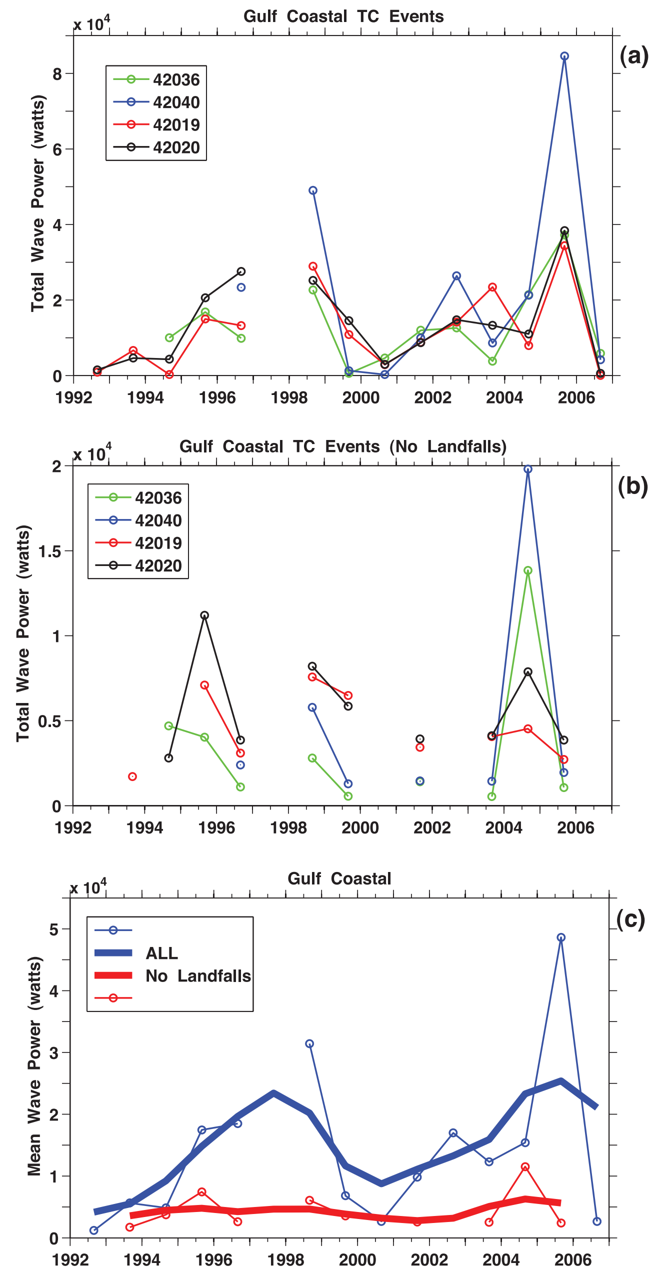

Figure 10. Total P_A for all tropical cyclone–associated wave events during June–November hurricane seasons identified at near-coastal Gulf of Mexico buoys for (a) the same events studied in Figure 6b and (b) subset of events in Figure 10a formed by excluding those events that made landfall. (c) Mean of the available annual wave power data shown in Figures 10a and 10b. Longer-period variability in Figure 10c is emphasized by low-pass filtering the annual data with a 1-4-6-4-1 binomial filter, as for the WPI in Figure 6c.

Table 1. Correlation of WPI With PDI and Climate Indices[a]

	Atlantic		Gulf	
	Interannual	5-year Mean	Interannual	5-year Mean
PDI	**0.58 (0.001)**	**0.72 (<0.001)**	**0.57 (0.007)**	**0.66 (<0.001)**
AMM	0.30 (0.191)	**0.51 (0.011)**	**0.72 (<0.001)**	**0.63 (<0.001)**
AMO	0.27 (0.239)	**0.52 (0.011)**	0.46 (0.060)	**0.78 (<0.001)**
NINO3.4	**−0.48 (0.046)**	−0.03 (0.905)	−0.20 (0.502)	0.39 (0.073)

[a]Correlation coefficients, *R*, between WPI and the PDI, the AMM and AMO modes of climate variability over the North Atlantic, and the NINO3.4 SST index from the Pacific on interannual (hurricane season, June–November) and 5-year seasonal running mean timescales. Associated *t* test–derived *p* values (in parentheses) <0.05 indicate that the associated *R* (in bold) are statistically significant.

power since the mid-1990s indicate that the potential for severe coastal erosion is increasing.

6. Discussion

[25] Both the annual TC wave power and the PDI (which is related to the cube of the maximum sustained surface wind speed of the storm [*Emanuel*, 2005]) depend largely on the duration, frequency, and intensity of the strongest TCs. Additionally, other important modulators of Atlantic and Gulf of Mexico region WPI are storm size and the variability of storm tracks, which determine the region of significant coastal impact. These various TC measures are potentially associated with climate factors such as the Atlantic Multidecadal Oscillation (AMO) [e.g., *Goldenberg et al.*, 2001], the Atlantic Meridional Mode (AMM) [*Vimont and Kossin*, 2007; *Kossin and Vimont*, 2007]), and the El Niño–Southern Oscillation (ENSO).

[26] As would be expected from the direct relationship between wind speed and wave power, WPI (Figure 6c) is well correlated with PDI both in the Atlantic and Gulf of Mexico regions on interannual and longer-period timescales (Table 1). Because of the close association of WPI and near-coastal wave power, this relationship indicates that increases in the PDI will have associated increased coastal impact, whether or not landfalls increase. Both the Atlantic and Gulf of Mexico WPIs are highly correlated with 5-year running means of the AMO over the 1978–2006 period (Table 1). This is expected since the AMO is known to modulate Atlantic TC frequency on longer timescales [*Goldenberg et al.*, 2001] and thus will affect WPI on these timescales. The AMM, which describes the leading mode of coupled ocean-atmosphere variability in the Atlantic [*Chiang and Vimont*, 2004], has also been shown to modulate TC frequency, as well as track location and duration. During positive AMM

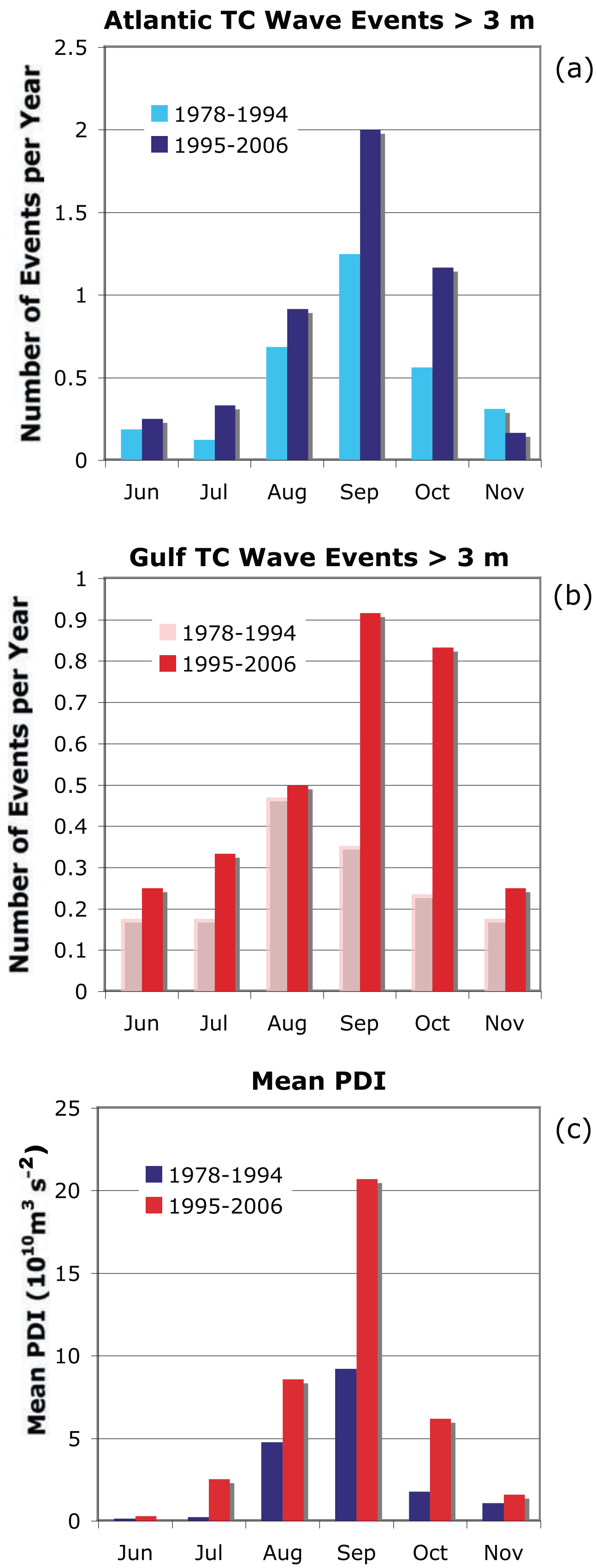

Figure 11. Changes, by month, in the number of significant H_S wave events per year observed by (a) Atlantic and (b) Gulf of Mexico buoys before and after 1995. Increases are observed in every month except for the relatively quiescent November Atlantic. The greatest increases have occurred during September–October, particularly in the Gulf of Mexico. (c) Mean monthly PDI for the same time periods as for the wave event counts in Figures 11a and 11b, showing the increases in overall hurricane activity for the entire Atlantic basin.

phases, TCs generally develop and track through the Atlantic main development region between 5°N and 25°N latitude, while negative AMM phases are generally associated with TC development in the subtropical Atlantic [see *Kossin and Vimont*, 2007, Figure 3]. During negative phases, then, very little Gulf of Mexico activity is expected. This is consistent with Table 1, which shows a significant positive correlation between Gulf of Mexico WPI and the AMM.

[27] The NINO3.4 index is the average sea surface temperature (SST) anomaly over the equatorial eastern Pacific (5°N–5°S, 170°W–120°W) and characterizes Pacific tropical SST variability associated with El Niño. The suppressing effect of El Niño on Atlantic TC activity [*Gray*, 1984] is apparent by the strong interannual correlation of NINO3.4 with WPI, which surprisingly is manifested for the Atlantic region but not the Gulf of Mexico. The observed differences between correlations of climate indices with the Gulf of Mexico and Atlantic WPIs in Table 1 demonstrate the importance of separate WPIs for assessing the potential for increasing destructiveness of TCs along both coasts in the future.

[28] Changes in the distribution of TC events on interannual timescales are also observed. The number of significant H_S events for the 1978–1994 and the 1995–2006 epochs shows an increase in extreme events in the September and October months along both the Atlantic and Gulf coasts (Figures 11a and 11b), suggesting that the increase in total annual TC wave power since 1995 results from an increase in middle-to-late season high-intensity TCs. The change in the mean monthly PDI between the 1978–1994 and the 1995–2006 epochs (Figure 11c) shows similar variation. Comparing the PDI change with TC wave event changes, it is clear that the large increases in hurricane activity during September–October have had a greater impact on the relative frequency of Gulf Coast wave events than the Atlantic. This is again well aligned with the relationships in Table 1, which show that the AMM is apparently modulating Gulf of Mexico WPI through its effect on TC genesis location and track.

7. Conclusions

[29] Wave observations since 1980 along the U.S. Atlantic and Gulf coasts indicate that TC-generated wave power in the western North Atlantic has increased significantly since the mid-1990s, both at open ocean and at near-coastal locations. This increase is well correlated with the observed increase in the Atlantic PDI and appears to be modulated by the AMM. Because relative extreme coastal water levels increase nonlinearly with rising sea level, lower-energy TC wave events will become increasingly important whether or not the recent upward trend in TC-generated wave power continues (and irrespective of hurricane landfall frequency). Total wave power from TCs, as well as the regional and seasonal wave power distributions, is thus an important consideration. In the future, the coastal erosion potential from increased coastal wave power will be further enhanced by rising sea level, which allows more wave energy to reach farther shoreward.

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