Extreme Waves Under Hurricane Ivan

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On 15 September 2004, the center of Hurricane Ivan (Fig. 1A and fig. S1) passed directly over six wave-tide gauges deployed by the Naval Research Laboratory (NRL), at depths of 60 and 90 m, on the outer continental shelf in the northeastern Gulf of Mexico, allowing us to measure the extreme waves directly under a category 4 hurricane (*1*). We calculated significant wave height (H_s) and maximum individual wave height (H_{max}), two parameters commonly used to characterize wave fields (*2*).

During Ivan's approach, H_s and H_{max} rapidly increased and reached peak values when the radial distance between the eye's center and the moorings was ~75 km (Fig. 1B). H_s reached maximum values of 17.9, 16.1, and 17.1 m at moorings 3, 4, and 5, respectively. These H_s values were larger than those measured the same day by National Data Buoy Center (NDBC) buoy 42040 (Fig. 1A), which recorded the largest H_s (15.96 m) ever reported by NDBC. The largest H_{max} reached 27.7 m (91 ft) at mooring 3; out of 146 waves measured at moorings 3, 4, and 5, there were 24 individual waves with heights greater than 15 m (50 ft) (*1*).

The measured values of H_s and H_{max} depict the radial variability of the hurricane wave field in the range $1 \le r/R \le 8$ (Fig. 1C), where r is the radial distance from the moorings to the eye's center and R is the radius of maximum winds (40 km) (*3*). H_s increased rapidly as the normalized radial distance approached 1 (Fig. 1, B and C) and can be approximated by an exponential curve of the form $H_s = a(r/R)^b \exp[-(r/R)^c]$, where $a = 56.61$ m, $b = -0.96$, and $c = -0.94$ (Eq. 1). This compares well with a numerical model (*4*), provided the model's H_s is set to 21 m at $r/R = 1$ (Fig. 1C). Past observations of H_{max} during hurricane-generated seas suggest that H_{max} can reach $1.9H_s$ (*5*), which is consistent with the upper limit of our measurements (Fig. 1B).

The wave-sampling strategy (*1*) employed captured a small segment of the wave field, suggesting our measurements likely missed the largest waves near the storm's eyewall. The largest measured H_s reached 17.9 m at a radial distance of 73 km, about 30 km from the strongest winds. Furthermore, our measurements, from the forward face of Ivan, are likely ~85% of the maximum H_s typically found in the right quadrant (*4*, *6*). These factors strongly suggest the wave field associated with Ivan should generate maximum H_s values greater than 21 m and H_{max} values greater than 40 m at $r/R = 1$.

The values of H_s measured here, possibly reduced by shoaling, are larger than those predicted by several parametric wave models developed for deep water conditions. Young (*6*) proposed a semi-empirical model based on R, maximum wind speed (U_{max}), and hurricane translation speed (V_t); with $R = 40$ km, $V_t = 6$ m s^{-1}, and $U_{max} = 60$ m s^{-1}, the model predicts a maximum H_s of 15.1 m. Hsu (*7*) suggested a simple empirically determined formula, $H_s = 0.2(P_R - P_0)$, where $P_R = 1013$ mbar is the pressure at the edge of the hurricane and $P_0 = 935$ mbar is the central pressure, resulting in an H_s of 15.6 m. Underestimation by these models likely stems from the absence of wave data under intense storms. Measurements of the extremely large waves directly under Ivan may act as a starting point for improving our understanding of the waves generated by the most powerful hurricanes.

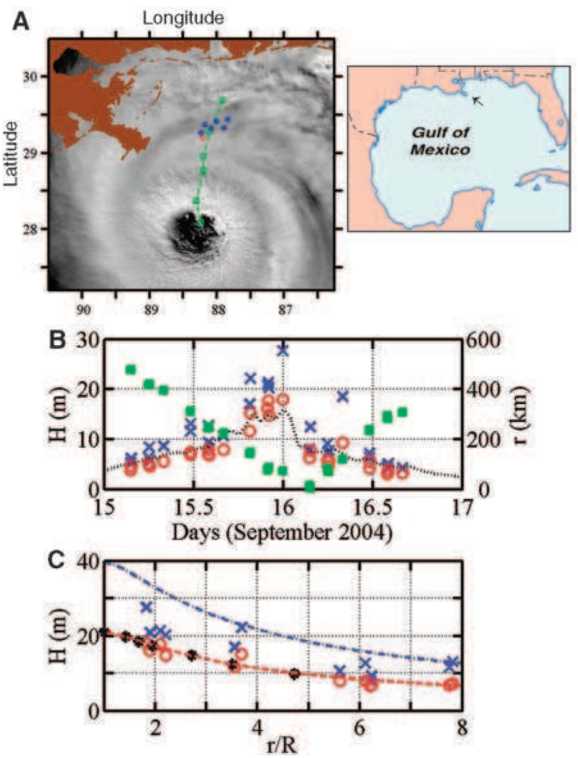

Fig. 1. (**A**) Satellite image of Hurricane Ivan from the Moderate Resolution Imaging Spectroradiometer (MODIS) at 1850 universal time, 15 September 2004 (provided by NRL's Ocean Optics Group). The eye of Hurricane Ivan is clearly shown just southeast of the boot of Louisiana. NRL moorings are shown as blue dots [northern line (60 m), moorings 1, 2, and 3; southern line (90 m), moorings 4, 5, and 6]. The NDBC buoy is shown as a red circle, and the track of Hurricane Ivan is shown as a green dashed line with squares marking the hurricane's center every 3 hours. (**Inset**) Location of Ivan at the time of measurement. (**B**) Time evolution of H_s (circles) and H_{max} (crosses) for the six NRL moorings, H_s for NDBC buoy 42040 (dotted line), and radial distance to Ivan's center (squares). (**C**) H_s and H_{max} as a function of normalized radial distance (r/R). The red dashed line represents the exponential relation (Eq. 1); digitized values of a segment 15° clockwise from the forward direction of a numerically simulated wave field are denoted by black asterisks. The blue dashed line represents $H_{max} = 1.9H_s$, and circles and crosses are as in (B).

References and Notes

1. Materials and methods are available as supporting material on *Science* Online.
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8. Supported by the Office of Naval Research as part of the NRL's basic research project "Slope to Shelf Energetics and Exchange Dynamics (SEED)" under program element 0601153N (NRL–Stennis Space Center contribution no. NRL/JA/7330–05–5172), by the Minerals Management Service Environmental Studies Program, and by the Minerals Management Service Technology Assessment and Research Program on Hurricane Ivan.

Supporting Online Material
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Materials and Methods
Fig. S1

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Supporting Online Material

A category 4 hurricane has maximum sustained wind speeds between 59 to 69 m/sec. More details can be seen in (http://www.nhc.noaa.gov/aboutsshs.shtml).

Sea-Bird Electronics Wave and Tide Recorders (SBE 26 SEAGAUGE) measured near-bottom pressure at the six moorings on the continental shelf. Wave-induced dynamic pressure data (P_w) were collected at each instrument by burst-sampling every 8 hours for 512 seconds with a 1 Hz sample rate. Based on linear wave theory, sea surface wave elevation (η) was calculated from P_W by applying the frequency-dependent pressure response factor (*1*) that compensates for exponential depth attenuation and projects the near-bottom pressure field to the surface. The time series of η from moorings 3, 4, and 5 are shown in Fig. S2. Based on the time series, significant wave height was calculated as 4 times the root-mean-square of η. Individual wave heights in the η time series are defined to be between two zero up-crossings of the mean water level. The individual crest-to-trough wave height is defined as the elevation range between two zero up-crossings. A constant water density 1025 kg/m^3 was used.

A cut-off frequency was chosen to avoid contamination due to spurious high frequency pressure noise amplified by the response factor. An attenuation threshold of 1.5% was empirically chosen for the cut-off frequency, thus, high-frequency wave components with an attenuation factor smaller than 1.5 % were excluded. The cut-off frequencies were 0.14 and 0.12 Hz for water depths of 60 and 90 m, respectively. An example of the spectra of P_w and derived η are shown in Fig. S3. Estimations of wave nonlinearity or the presence of breaking waves from wave profiles were not made due to the exclusion of high-frequency wave energy. This exclusion could also underestimate wave heights, but is likely insignificant during high seas when most of the wave energy has a frequency less than 0.08 Hz. Corrections taking into account the effects from wave nonlinearity (*2, 3*) and water density changes due to the presence of bubbles from breaking waves were not considered here.

References

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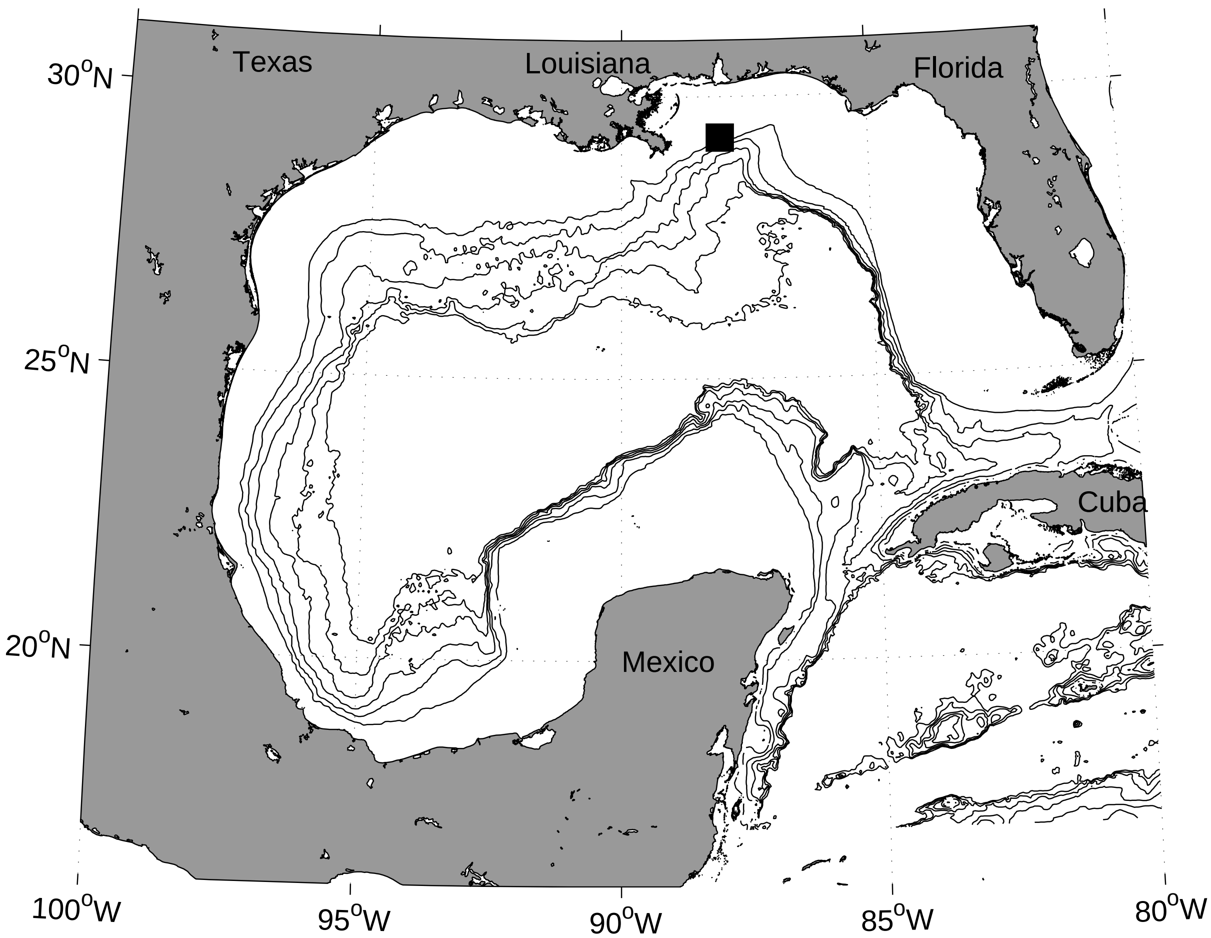

Fig. S1 Map showing bathymetry and the location of the measurement area (solid black square) in the Gulf of Mexico. Contour interval is 500 m.

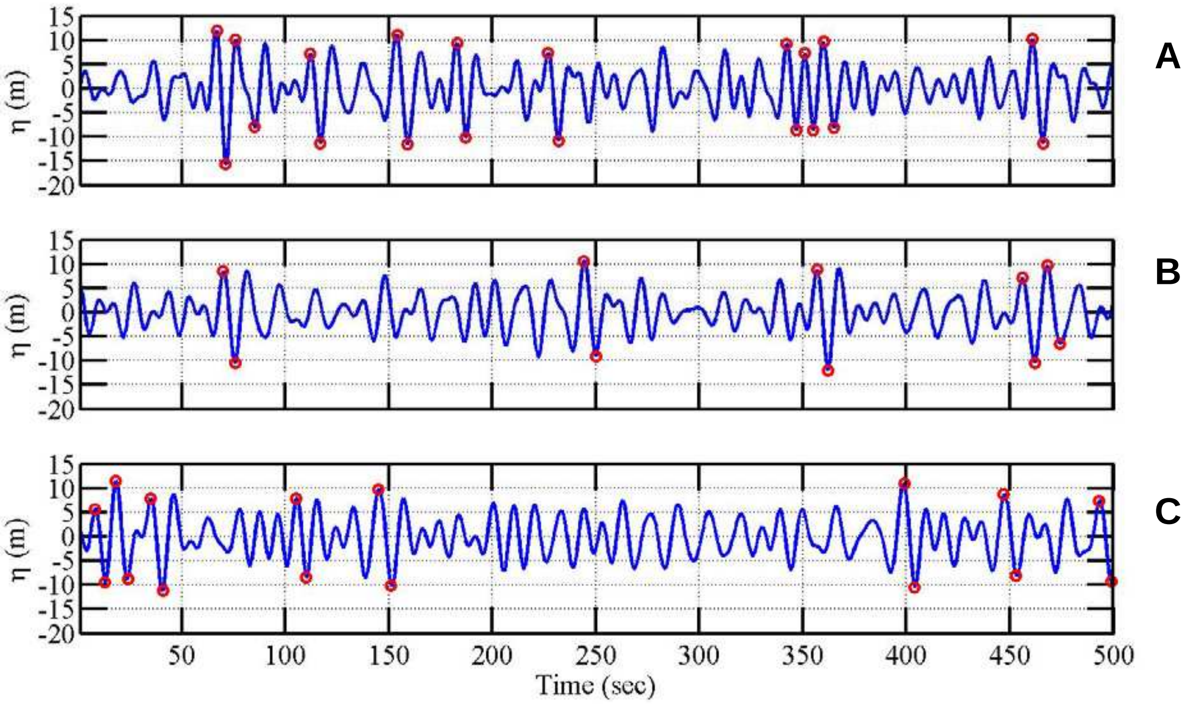

Fig. S2 Time series of wave measurements from NRL (A) mooring 3, (B) mooring 4, and (C) mooring 5. The crests and troughs of individual wave heights larger than 15 m are marked (o).

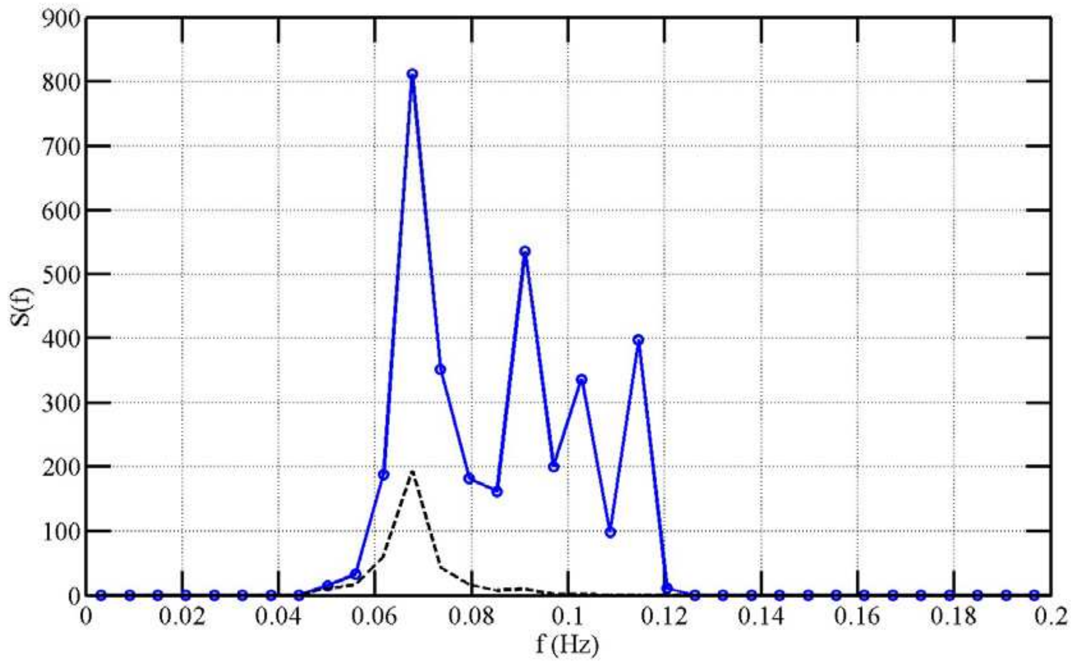

Fig. S3 Energy density spectrum of surface wave (solid) and bottom pressure (dashed) from NRL mooring 5. The units are m^2/Hz and psi^2/Hz, respectively, for surface wave and bottom pressure.