

## Extreme Waves Under Hurricane Ivan

David W. Wang,\* Douglas A. Mitchell, William J. Teague, Ewa Jarosz, Mark S. Hulbert

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 (*I*). 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  $\sim 75$  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) (*I*).

The measured values of  $H_s$  and  $H_{\max}$  depict the radial variability of the hurricane wave field in the range  $1 \leq r/R \leq 8$  (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 (*I*) 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  $\sim 85\%$  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<sup>-1</sup>, and  $U_{\max} = 60$  m s<sup>-1</sup>, 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.

### References and Notes

1. Materials and methods are available as supporting material on Science Online.
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### Supporting Online Material

[www.sciencemag.org/cgi/content/full/309/5736/896/DC1](http://www.sciencemag.org/cgi/content/full/309/5736/896/DC1)

Materials and Methods  
Fig. S1

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Naval Research Laboratory, Stennis Space Center, MS 39529, USA.

\*To whom correspondence should be addressed.  
E-mail: [dwang@nrlssc.navy.mil](mailto:dwang@nrlssc.navy.mil)

**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) as a function of normalized radial distance ( $r/R$ ). The red dashed line represents the exponential relation (Eq. 1); digitized values of a segment  $15^\circ$  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).

